Journal of Coastal Research

SPECIAL ISSUE NO. 51 (pages 1-226) **SUMMER 2010**

CONTENTS

European Marine Sand and Gravel Resources: Evaluation and Environmental Impacts of Extraction - an Introduction .... **Wendy M.I. Bonne** i

European marine aggregates resources: Origins, usage, prospecting and dredging techniques ... **Adonis F. Velegrakis, Arnaud Ballay, Serafim E. Poulos, Rolandas Radzevičius, Valérie K. Bellec, and Faustino Manso** 1

Marine Aggregate Extraction Regulation in EU Member States ... **Rolandas Radzevičius, Adonis F. Velegrakis, Wendy M.I. Bonne, Stella Kortekaas, Erwan Garel, Nerijus Blažauskas, and Regina Asariotis** 15

Morphodynamic models used for studying the impacts of offshore aggregate extraction: a review ... **Déborah Idier, Saskia Hommes, Christophe Brière, Pieter Roos, Dirk-Jan R. Walstra, Michiel A.F. Knaapen, and Suzanne J.M.H. Hulscher** 39

North Sea

Aggregate extraction from tidal sandbanks: is dredging with nature an option? Introduction ... **Vera R.M. Van Lancker, Wendy M.I. Bonne, Adonis F. Velegrakis, and Michael B. Collins** 53

Geo-environmental Characterization of the Kwinte Bank ... **Valérie K. Bellec, Vera R.M. Van Lancker, Koen Degrendele, Marc Roche, and Sophie Le Bot** 63

Morphological Evolution of the Kwinte Bank Central Depression Before and After Cessation of Aggregate Extraction ... **Koen Degrendele, Marc Roche, Patrik Schotte, Vera R.M. Van Lancker, Valérie K. Bellec, and Wendy M.I. Bonne** 77

Tidally-averaged Currents and Bedload Transport over the Kwinte Bank, Southern North Sea ... **Erwan Garel** 87

A. Grain-Size Trend Analysis for the Determination of Non-Biogenic Sediment Transport Pathways on the Kwinte Bank (southern North Sea), in Relation to Sand Dredging ... **Serafim E. Poulos, and Arnaud Ballay** 95

Modelling the Effects of Sand Extraction on Sediment Transport due to Tides on the Kwinte Bank ... **Dries Van den Eynde, Alessio Giardino, Jesús Portilla, Michael Fettweis, Frederic Francken, and Jaak Monbaliu** 101

Modelling the Morphodynamics of the Kwinte Bank, Subject to Sand Extraction ... **Christophe Brière, Pieter C. Roos, Erwan Garel, and Suzanne J.M.H. Hulscher** 117

Wave effects on the morphodynamic evolution of an offshore sand bank ... **Alessio Giardino, Dries Van den Eynde, and Jaak Monbaliu** 127

Macrobenthos characteristics and distribution following intensive sand extraction on a subtidal sandbank ... **Wendy M.I. Bonne** 141

Recommendations for the sustainable exploitation of tidal sandbanks ... **Vera R.M. Van Lancker, Wendy M.I. Bonne, Erwan Garel, Koen Degrendele, Marc Roche, Dries Van den Eynde, Valérie K. Bellec, Christophe Brière, Michael B. Collins, and Adonis F. Velegrakis** 151

Baltic Sea

Aggregate Resources And Extraction In The Baltic Sea – An Introduction ... **Klaus Schwarzer** 165

Last Quaternary Evolution of Gravel Deposits in Tromper Wiek, Southwestern Baltic Sea ... **Valérie K. Bellec, Markus Diesing, and Klaus Schwarzer** 173

Nearshore dredging in the Baltic Sea: Condition after cessation of activities and assessment of regeneration ... **Faustino Manso, Rolandas Radzevicius, Nerijus Blažauskas, Arnaud Ballay, and Klaus Schwarzer** 187

Wave-Induced Sand Re-suspension At Dredged Gravel Pits Based Upon Hydrodynamic Measurements (Tromper Wiek, Baltic Sea) ... **Erwan Garel and Alice Lefebvre** 195

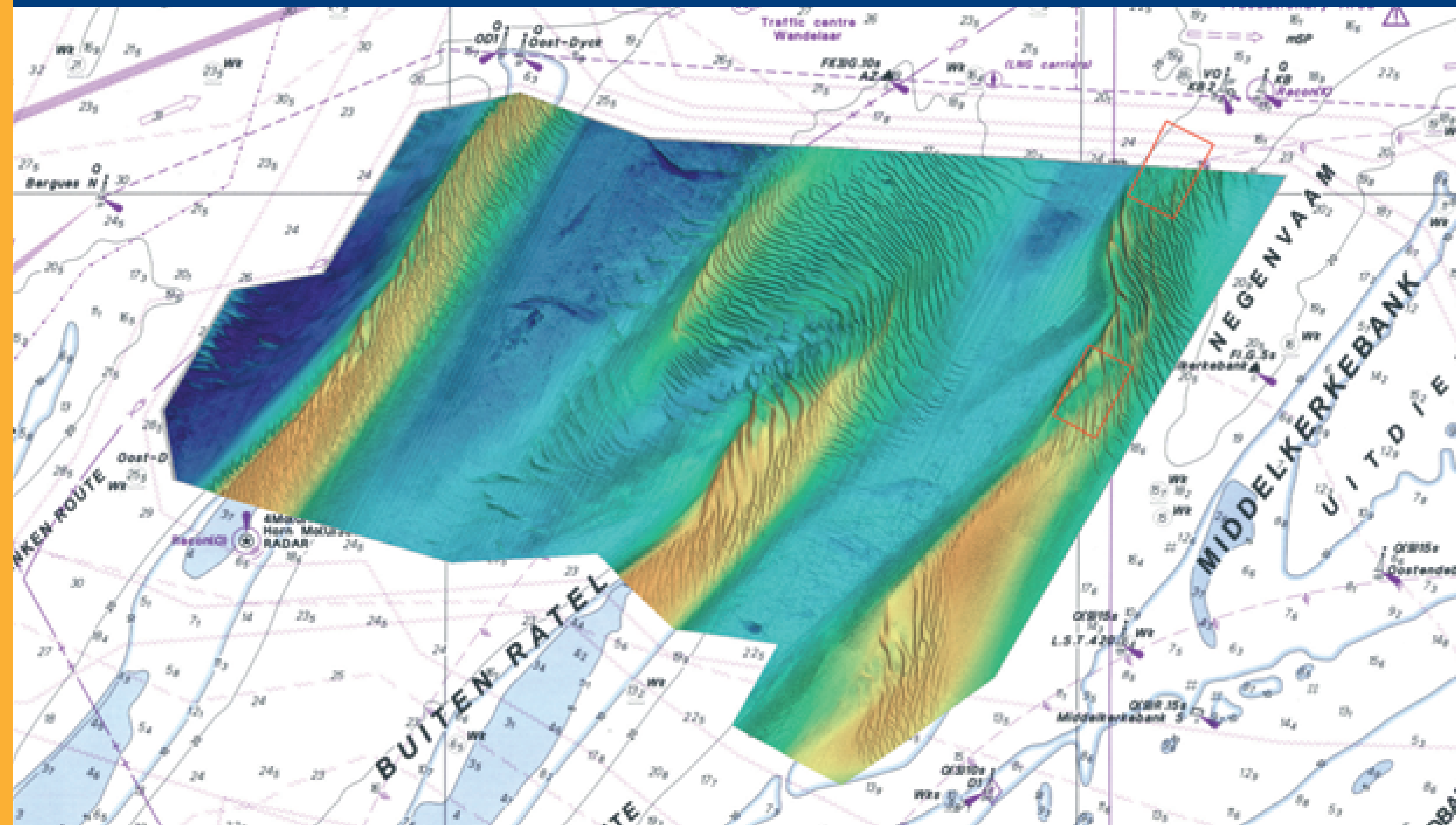
Assessment of the Effects of Marine Aggregate Extraction on the Coastline: an Example from the German Baltic Sea coast .. **Stella Kortekaas, Ingrida Bagdanaviciute, Paolo Gyssels, Jose M. Alonso Huerta, and Arnaud Héquette** 205

The Physical and Biological Impact of Sand Extraction: a Case Study in the Western Baltic Sea ... **Jochen C. Krause, Markus Diesing, and Günther Arlt** 215

CERF JOURNAL of COASTAL RESEARCH SI 51

EUMARSAND: European Marine Sand and Gravel Resources

Editors: Vera Van Lancker, Wendy Bonne, Adolfo Uriarte and Michael Collins



Journal of Coastal Research

Special Issue #51

EUSKO JAURLARITZA GOBIERNO VASCO
HEZKUNTZA, UNIBERTSITATE ETA IKERKETA SAILA
DEPARTAMENTO DE EDUCACIÓN, UNIVERSIDADES E INVESTIGACIÓN
azti tecnalia

Published by:

JOURNAL OF COASTAL RESEARCH

An International Forum for the Littoral Sciences

The ***JOURNAL OF COASTAL RESEARCH*** (ISSN 0749-0208) is the official publication of The Coastal Education and Research Foundation *[CERF]* and is published bimonthly in January, March, May, July, September, and November. The journal is available online at www.jcronline.org and subscriptions can be placed through www.CERF-JCR.org. Publishing services are currently available through CERF, 1656 Cypress Row Drive, West Palm Beach, FL 33441. Calender-year (2011) print and online subscription prices for the JCR are: $115.00 for US CERF members/$125.00 for International CERF members ($95.00 for online only), and $519.00 for US Institutions/$541.00 for International Institutions ($437.00 for online only). Additional surface charges may apply to subscribers located outside of the USA. For additional subscription information, please go to www.CERF-JCR.org. Subscriptions, changes of address, and requests for missing issues should be sent to the JCR Subscriptions Office, Allen Press, P.O. Box 7065, Lawrence, Kansas 66044 or CERF@allenpress.com. Claims for copies lost in the mail must be received within 90 days (180 days foreign) of the issue date to insure replacement at no charge. Access to the archived JCR is available through JSTOR at http://www.jstor.org/.

Periodicals postage paid at Lawrence, KS, and additional mailing offices. POSTMASTER: Send address changes *Journal of Coastal Research*, Allen Press Association Management, P.O. Box 1897, Lawrence, KS 66044.

THE COASTAL EDUCATION AND RESEARCH FOUNDATION

1656 Cypress Row Drive
West Palm Beach, FL 33411, U.S.A.

The Coastal Education and Research Foundation *[CERF]* is a nonprofit corporation dedicated to the advancement of the coastal sciences. The Foundation is devoted to the multi-disciplinary study of the complex problems of the coastal zone. The purpose of CERF is to help translate and interpret coastal issues for the public and to assist professional research and public information programs. The Foundation specifically supports and encourages field and laboratory studies on a local, national, and international basis. Through the medium of scientific publications, television, and radio CERF brings accurate information to the public and coastal specialists on all aspects of coastal issues in an effort to maintain or improve the quality of shoreline resources.

Because CERF is concerned with broad environmental issues, our efforts concentrate on significant problems such as maintenance of good quality (potable) water with adequate supply, and hazards associated with potential beach erosion, flooding, and susceptibility of developed shorelines to storm surge and wave attack. By focusing attention on these potential man-made and natural hazards, it is hoped that our research efforts will help others improve the quality of life in diverse coastal areas. CERF thus aims to stimulate awareness of coastal (marine and freshwater shorelines) land and water problems; initiate and foster research and innovation to promote long-term coastal productivity; establish an educational forum for the debate of contentious coastal issues; and develop new principles and approaches for enlightened coastal management, and encourage their adoption and use.

CERF is associated with the Department of Geosciences at Florida Atlantic University (FAU) in Boca Raton, Florida. This association provides a basis for cooperative investigation, in private and public sectors, of biophysical resources found in open and naturally protected coastal regions, estuaries, large inland bodies of water bounded by shorelines, wetlands, and other coastal environments. Scientific investigative efforts by faculty, students, and staff span a wide and diversified range of interrelated topics that are relevant to solutions of today's dynamic problems. It is hoped that these combined attempts to better understand that nature of coastal processes will help forestall what may become contentious issues of tomorrow.

The FAU Center for Hydrology and Water Resources (CHWR) pursues excellence in theoretical and applied research in hydrology, water resources (freshwater, coastal, and marine), and related geoscience topics. Research at the CHWR focuses on developing more complete understanding of surface and subsurface hydrological processes, including practical applications to subtropical coastal environments in southern Florida. The CHWR focuses on educational activities by providing funding and training of graduate students in hydrology, water resources, and hydrological modeling *via* various real-world applications. Multidisciplinary studies at the CHWR bring together experts from various fields in remote sensing and geographic information science, environmental studies, biology, geology, geography, and engineering.

☐ CERF MEMBERSHIP ☐

Members are individuals that support the aims of the foundation through personal and group efforts or by donations. Memberships are available in different categories with privileges.

Subscription information is available online at www.cerf-jcr.org. Subscriptions office: Allen Press, Inc., PO Box 1897, Lawrence, KS 66044 U.S.A.

Editor-in-Chief

Charles W. Finkl Ph.D., CSci, CMarSci, FIMarEST, CPGS, CPSSc, PWS

Dr. Charles W. Finkl is President and Executive Director of the Coastal Education & Research Foundation *[CERF]*, publisher of the JCR. Charlie, a founding editor of the *Journal of Coastal Research*, has served as Editor-in-Chief for the past 26 years. He is a Research Professor in the Department of Geosciences at Florida Atlantic University in Boca Raton, Florida. He received his Bachelor and Master of Science degrees from Oregon State University and the Ph.D. from the University of Western Australia. He is a member of more than 20 professional societies and has published more than 200 professional papers, books, and reports. He is a Chartered Marine Scientist (CMarSci) [Institute of Marine Engineering, Science and Technology], Certified Professional Geological Scientist (CPGS) [American Institute of Professional Geologists (AIPG),], Certified Professional Soil Scientist (CPSSc) [American Registry of Certified Professionals in Agronomy, Crops, and Soils], and a Professional Wetland Scientist (PWS) [Society of Wetland Scientists]. Charlie has field experience in parts of the USA, Caribbean area, Brazil, Honduras, Russia, South Africa, Western Europe, Australasia, and South Pacific islands. He is also the Series Editor of the Encyclopedia of Earth Sciences Series that is published by Springer (Germany). There are more than twenty-eight volumes in the Series and about twenty-five are available online. Charlie also serves on the Editorial Board of the *International Journal of Environmental Studies* (Routledge) and is an occasional peer reviewer for many other professional journals.

Charlie has interests and expertise in the general areas of surficial geology, coastal and marine geomorphology (including coastal classification), coastal/marine biophysical environments, exploration geochemistry, soils and weathering (regolith geology), coastal zone management and engineering applications or impacts on natural systems (including erosion control and shore protection), coastal hydrology including submarine freshwater and mineralized seeps, subaerial and marine structural geology, natural hazard mitigation in coastal zones, marine environments and coastal wetland protection and restoration, and remote sensing (*e.g.* land cover classification in coastal wetlands, advection-diffusion turbidity plumes in coastal waters, delineation of bottom types and sand resources), effluent disposal and pollution of wetlands and estuaries, water resources mapping and conservation, time series studies of wetland hydroperiod and soil moisture.

Foundation Meetings

International Coastal Symposiums (ICS)

The International Coastal Symposium (ICS) was set up by Per Bruun (deceased) and Charlie Finkl, the first meeting being held in Hilton Head, South Carolina, in 1993. Since then these CERF meetings were held a second time in Hilton Head and then in Palm Beach, Florida. With the success of these meetings, CERF moved the ICS to the international scene holding meetings in conjunction with local sponsors in Australia, Brazil, Iceland, New Zealand, Northern Ireland, and Portugal. Forthcoming meetings will be held in Szczecin, Poland (11th ICS hosted by Dr. Kazimierz Furmanczyk at the University of Szczecin), and Plymouth, United Kingdom (12th ICS hosted by Dr. Gerd Masselink at the University of Plymouth). The ICS deals with all aspects of the coastal zone and attracted more than 600 delegates to the 10th ICS, organized by the Faculdade de Ciências Sociais e Humanas – UNL in Lisbon, Portugal.

Acknowledgment Front Cover:
Multibeam imagery of the Flemish Banks, superimposed on a nautical chart of the region, Belgian part of the North Sea. Multibeam imagery: Belgian Federal Public Service Economy, SMEs, Self-employed and Energy – Continental Shelf - Fund for Sand Extraction.
Nautical Chart: Agency for Maritime and Coastal Services, Coastal Division, Flemish Hydrography

Journal of Coastal Research	SI	51	i-vi	West Palm Beach, Florida	Summer 2010

European Marine Sand and Gravel Resources: Evaluation and Environmental Impacts of Extraction - an Introduction

Wendy M.I. Bonne

AZTI Foundation
Marine Research Division
Herrera Kaia, Portualdea s/n
20110, Pasaia, Spain

Present address:
Marine Environment Service, Directorate General Environment,
Federal Public Service Health, Food Chain Safety and Environment,
Federal Government of Belgium
Victor Hortaplein 40 box 10
1060 Brussels, Belgium
Wendy.Bonne@health.fgov.be

INTRODUCTION

Marine aggregates (sand and gravel) have emerged as a strategic mineral resource; this is due to an increasing general demand and to stricter regulations on the exploitation of land-won aggregates, in EU Member States. Annually, approx. 40 million m^3 of marine sand and gravel are extracted, alone, from the North European inner (<60m water depth) continental shelf (www.sandandgravel.com/extraction). In the near future, the extraction will increase significantly, to provide vast quantities of material needed for the realisation of large-scale infrastructure projects, planned for Europe's coastal areas; this is combined with the burgeoning general urbanisation of the coastal zone. At the same time, European coastal zones are under increasing pressure from coastal erosion. Thus, beach replenishment and other coastal defence schemes, requiring large quantities of suitable aggregate material, are necessary to manage such coastal retreat and accommodate the development (Selby and Ooms, 1996; Humphreys *et al.*, 1996).

Such increasing demand, together with the conservation of coastal ecosystems and diverse stakeholders' interests, require that resource sustainability, environmental prudence and careful management are crucial components of the practice and regulation of marine aggregate operations. There is an urgent need for integrated and coherent approaches to the effective prospecting of commercially-viable marine sand and gravel deposits, the development of a science-based approach to their sustainable management, together with an environmental impact assessment of their exploitation. Such objectives require an interdisciplinary approach, to develop a thorough understanding of the sedimentary, hydrodynamic and ecological conditions of the inner continental shelf and adjacent coasts. Likewise, the use of 'state-of-the-art' approaches and instrumentation is needed.

DOI: 10.2112 / SI51-001.1 received 9 January 2008; accepted in revision 1 April 2008.

The main objectives of the RTN project EUMARSAND were: (a) to train young European researchers in individual research approaches; and (b) to provide them with an integrated and balanced view of the diverse and complex issues involved, through the application of a wide range of scientific approaches. As such, close co-operation between marine geologists, biologists, hydrodynamic and morphodynamic modellers and coastal engineers was established. The task of such a grouping was to integrate the research approaches involved in marine aggregate prospecting. Likewise, the undertaking of the assessment of the environmental impacts of offshore mining activities, using 'state-of-the-art' approaches and instrumentation.

Nine Partners, from 8 countries, have been involved in the project, as listed in Table 1.

SCOPE OF THE EUMARSAND SPECIAL ISSUE

The objectives of the project EUMARSAND comprised: (a) an estimation of the usage, assessment of resource availability and the provision of a critical review of the licensing procedures, at an European level; (b) the investigation of the impact of marine aggregate extraction, on the environment; and (c) the provision of recommendations on the integration of the research approaches involved.

A considerable amount of effort was placed into the provision of a critical review of the licensing procedures, at an European level. The compatibility of the different national licensing/regulatory regimes was compared, with the present European Environmental Legislation (e.g. EIA Directives, Habitats Directive) and International Conventions.

In relation to the field studies, two sites were investigated: the Kwinte Bank (Belgian part of the southern North Sea), which represents a modern deposit in a relatively high energy tidal environment; and Tromper Wiek (German Baltic Sea); which represents a relict deposit, located within a non-tidal setting. The deposits are representative of commonly-occurring, European aggregate extraction sites.

Table 1. *Participants in the EUMARSAND Programme*

Project Partners [(1)]		
Marine Research Division - AZTI Foundation (Technological Institute for Fisheries and Food), Spain	Dr. Wendy Bonne Dr. Adolfo Uriarte Marine ecology (and coordination)	Wendy.Bonne@health.fgov.be aduriarte@pas.azti.es
School of Ocean and Earth Science - University of Southampton, United Kingdom	Dr. Erwan Garel Prof. Michael Collins Sediment dynamics	egarel@ualg.pt mbc@noc.soton.ac.uk
Renard Centre of Marine Geology (RCMG) - Ghent University, Belgium	Dr. Valérie Bellec Dr. Sophie Le Bot Dr. Vera Van Lancker Marine geophysics, North Sea	valerie.bellec@ngu.no sophie.lebot@univ-rouen.fr vera.vanlancker@mumm.ac.be
Department of Geography and Climatology - National & Kapodis-trian University of Athens, Greece	Dr. Arnaud Ballay Dr. Serafim Poulos Seabed characterisation	arnaudballay@yahoo.fr poulos@geol.uoa.gr
Marine Science Department - University of The Aegean, Greece	Dr. Rolandas Radzevičius Prof. Adonis Velegrakis Legislation	rolandas.radzevicius@geo.lt afv@aegean.gr
Maritime Institute - Gdansk (MIG), Poland	Dr. Nerijus Blažauskas Ms. Ingrida Bagdanavičiūtė Mr. Juliusz Marek Gajewski Information systems	nb@geo.lt ingrida@geo.lt julgaj@im.gda.pl
Coastal Geomorphology and Shoreline Management Unit - Université du Littoral-Côte d'Opale, France	Dr. Stella Kortekaas Prof. Arnaud Hequette Coastal impact	s.kortekaas@fugro.nl hequette@univ-littoral.fr
Water Engineering and Management, Civil Engineering Department - University of Twente, The Netherlands	Dr. Christophe Brière Dr. Déborah Idier Prof. Suzanne J.M.H. Hulscher Morphodynamic modelling	christophe.briere@deltares.nl d.idier@brgm.fr S.J.M.H.Hulscher@ctw.utwente.nl
Institute of Geosciences, Marine Geology, Coastal and Continental Shelf Research - Christian-Albrechts-University Kiel, Germany	Dr. Faustino Manso Dr. Klaus Schwarzer Marine geophysics, Baltic Sea	f.manso@fugro.it kls@gpi.uni-kiel.de

[(1)] Note: with recent e-mail addresses incorporated.

Investigation of the Kwinte Bank focussed upon a particular area of the seabed that had been exploited intensively for dredging, since the 1970's. It has been transformed now into a depression, from which sand extraction has been prohibited, since February 2003. In the Baltic Sea, gravel and sand extraction areas have been investigated within the German Tromper Wiek area; these have been subjected to different aggregate extraction techniques, i.e. anchor and trailer suction hopper dredging, respectively. Both areas under investigation have been surveyed using 'state-of-the-art' geophysical/geological techniques and instrumentation (acoustical data from seismic profiles, multibeam and side-scan sonar surveys; ground-truthing sediment samples, from Van Veen grabs and boxcores; and video imagery of the seabed). The physical impacts of the extraction on the seabed have been assessed also using hydro-, sediment- and morpho-dynamic modelling, calibrated and validated by high quality *in-situ* measuring instrumentation (bottom- and hull- mounted ADCP, electromagnetic current meters (S4), and Autonomous Benthic Landers). Ecological impacts have been investigated, whereas the physical effects on the adjacent coastline are assessed only for the Baltic Sea, between Warnemünde and Darss.

RESULTS OF THE EUMARSAND RESEARCH

The first three contributions in the Special Issue explain some general aspects of the exploitation of marine sands. Firstly, Radzevičius *et al.* (this volume) address the range of legislative arrangements, for the different Member States. Secondly, Velegrakis *et al.* (this volume) summarise the origin and use of marine aggregates and the processes involved in marine aggregate extraction. The synthesis demonstrates that the industry faces several problems, which hinder its sustainable development, including (amongst others): lack of standardisation of the relevant information; difficulties in the access to information; and limited collaboration/coordination between the marine scientific research establishments and the marine aggregate industry. The third review relates to modelling research methodologies, to investigate the impact of aggregate extractions (Idier *et al.,* this volume). Based upon a series of examples, this paper provides an overview on the three main morpho-dynamic modelling approaches used for offshore marine aggregate extraction impact assessments: (1) full process-based; (2) idealized process-based; and (3) conceptual models. It illustrates also the way in which these models, applied to extractions on a flat bed or from sandbanks, complement each other, towards the establishment of Coastal State Indicators.

Subsequent papers in the Issue address the field studies undertaken in the North and Baltic Seas (see below).

North Sea – Kwinte Bank

The research activities undertaken on the Kwinte Bank are introduced in the paper of Van Lancker *et al.* (this volume). This contribution sets the scene for the evaluation of aggregate extraction from tidal sandbanks; likewise, it summarises the evolution of research activities carried out on the Kwinte Bank, together with the main conclusions arising from previous studies, into the effects of sand extraction from the sandbank. The history of the 'follow-up monitoring' of the extraction effects highlights that information availability/discontinuity, together with the temporal and spatial scales over which observations are obtained and interpreted, can significantly influence the assessment of the impacts of aggregate extraction.

(a) Geophysics and sedimentology

The morphology and sedimentology of the central depression on the Kwinte Bank and its immediate surroundings are described, in detail, in Bellec *et al.* (this volume). The depression could be distinguished clearly from its surroundings, based upon acoustic imagery obtained from multibeam and side-scan sonar data, together with automated seabed classification. The analysis of sediment samples (collected using Van Veen grab), has shown that the depression was characterized by a high variability of medium to fine-grained sediments, containing variable shell contents. Morphological and sedimentological differences were detected on both sides of the depression; these are the result of reworking of the bed by tidal currents. The elongated very-large dunes of the western side of the bank are related directly to the stronger flood current, whereas the large dunes on the eastern side are related to the longer ebb current. Remarkably, the temporal differences in mean grain-size, between surveys, has revealed the same trend for the depression and in the Kwinte swale. This trend differed from those observed for other areas of the sandbank, with very-large and compound dunes.

(b) Sediment dynamics, derived from in-situ hydrodynamic measurements

Garel investigated the short-term hydro-sediment dynamic processes, acting on the depression and its immediately surrounding area. These was identified through the use of *in-situ* current measurements, together with a one-dimensional sediment transport model. Hull-mounted ADCP data were acquired, across the bank and during a nominal spring tidal cycle. Two self-recording current meters (S4 and ADCP) were moored, on the bank and within the central depression. The results indicate that net sand transport, over a tidal cycle, converges from both flanks, towards the crest of the bank. This sediment transport pattern relates to the veering of the peak (ebb and flood) currents, when passing over the bank, due to enhanced frictional drag. Variability in the tidal flow induces fluctuations in the extension and location of the net sand transport convergence zone. During the tidal cycle experiment with the hull-mounted ADCP, divergence of net sand transport has been observed inside the depression, which in indicative of erosion. Differences in the tidal ellipses and the across-bank component of the peak currents, during the ebb and flood, have been observed inside the depression, compared to over the crest of the bank.

(c) Grain-size trend analysis

An alternative approach to defining sediment transport pathways is grain-size trend analysis (McLaren and Bowles, 1985; Gao and Collins, 1991). Based upon a grid of samples, two main transport pathways have been identified (Poulos and Ballay*,* this volume): over the central depression and its western part, directed towards the northeast; and towards the southwest, over the gentle eastern slope of the Kwinte Bank.

(d) Morphodynamic modelling

In order to investigate the sea bed dynamics, in general, and to predict the long-term morphodynamic impact of sand extraction from tidal sandbanks, in particular, process-based modelling is a commonly-used method. Herein, different approaches can be considered: (i) based upon complex numerical simulation; or (ii) by applying an idealised model, designed specifically to describe sandbank dynamics. The first of these approaches has been applied to the Kwinte Bank (Brière *et al.,* this volume). The short-term modelling was set up with the complex full process-based model, Delft 3D – Online. The numerical results obtained, together with the field measurements, showed good agreement. Sand transport is directed towards the northeast, along the western flank of the bank; it is southward along the eastern part. In the area of the depression, the residual sediment transport direction is opposed to that of the residual currents, i.e. directed towards the east, suggesting deepening of the depression (at least, under the conditions of the field measurements). The long-term impact of sand extraction is assessed, considering complementary approaches (combining the benefits from the complex numerical modelling and the idealised model). From the idealised model, the anticipated long-term trend of an excavated area is the recovery of the depression, resulting in a new equilibrium of the sandbank. However, the modelling approaches assume an infinite source of sand which, in reality, may not be the case. No clear trend in the evolution of the depression area can be deduced from the long-term full process-based modelling, whilst the short-term observations and modelling results suggest a deepening of the depression area.

(e) Benthic ecology

In order to establish the nature and vulnerability to aggregate mining, of the benthic communities on the Kwinte Bank, macrobenthic fauna have been investigated in the central depression and its surrounding areas; these are compared with the adjacent Middelkerke Bank, where no exploitation takes place (Bonne*,* this volume). Compared with historical data available for the Kwinte Bank, together with the reference stations on the Middelkerke Bank, crustaceans and echinoderms have become now more important over the area of the depression; this suggests higher similarity to the swale environment, than was the case previously. However, the species composition difference has been observed within the wide niche width of the sandbank transitional species assemblages, described earlier for the Kwinte Bank and the Belgian subtidal sandbanks. Sand extraction has created a locally-different habitat on the Kwinte Bank, to which the benthic fauna has adapted. However, the change is not significant over the larger scale of the sandbank system, one year after cessation of the intensive anthropogenic disturbance (see above).

(f) Synthesis of results

Van Lancker *et al.* (this volume) have integrated the different research results and discussed these within the perspective of sustainable exploitation. A suite of criteria are proposed (geographical, geological, morphological, sediment dynamical, ecological and exploitational) that can assist in limiting the environmental impact of extraction. A methodological framework for research is put forward, whilst recommendations for future monitoring schemes are highlighted. The information provided can guide decisions on the management of the impact of aggregate extraction, within the marine environment.

Baltic Sea – Tromper Wiek and the Warnemünde, the Darss Coastal Zone

The research activities undertaken on the Baltic Sea are introduced in the paper of Schwarzer (this volumen)**.** This contribution explains the background to the extraction of sand and gravel resources.

Likewise, emphasis is placed on the diversity of the Baltic Sea, in relation to its geological, environmental and ecological settings; its area is around 4 x 10^5 Km^2 , with a volume of approx 2 x 10 Km^3. Detailed information is provided on the geological developments, environmental conditions, aggregate resources and their exploitation; these serve as a background to the subsequent detailed, in terms of process and locations, investigations.

(a) Geophysics

The Tromper Wiek area was selected as the study area, for geophysical and sedimentological research, undertaken in the Baltic Sea. Tromper Wiek is a semi-enclosed embayment of the Western Baltic Sea, lying to the NE of Rügen Island.

Based upon boomer data, the late Quaternary history of the Tromper Wiek was reconstructed within the framework of the evolution of the Baltic Sea. Bellec *et al.* (this volume) describe the formation of gravel bars on the seabed, at particular locations within Tromper Wiek. Different periods of drainage led to the formation, or the re-activation of, channels that were infilled with coarse-grained material (in some places) during lower sea level. The gravels present originated from the erosion of the cliffs and till outcrops, on the seabed. After the formation of the barrier/bar and back-barrier system of gravel deposits covering the channels, sea level rose. Waves and currents eroded, in part, the barrier system that evolved into submerged bars. This pattern of evolution explains the direction of the steep slope towards the coast. The rapid rise in sea level, together with the coarse granulometry of the deposits, has permitted their preservation.

Using hydro-acoustic survey techniques (side-scan sonar and multibeam), high-resolution bathymetric and acoustic images (sonographs) of former marine aggregate extractions were obtained from the Tromper Wiek area (Manso *et al.,* this volume). These data, together with ground-truthing (underwater video and seabed sediment samples) were used to describe the present condition of marks on the sea bed generated by mining, in terms of their morphology and superficial grain size distribution. Different features (pits and furrows), generated by different extraction techniques (anchor suction dredging and trailer hopper suction dredging, respectively) were detected at both of the study sites: Tromper Wiek 1 (a sandy gravel seabed); and Tromper Wiek East (a sandy seabed). Regeneration varies, depending upon the material extracted and the mining technique applied. In general, it is rapid during the first years following the extraction, becoming almost undetectable over a longer period of time. However, the marks are still detectable after more than 10 years, since they were initially generated.

(b) Sediment dynamics

Sand lying at the bottom of the gravel pits is remobilized episodically; it is transported partially into and out of the pits. However, the long-term balance of sand within the dredging craters has not been established. Within the context of the low sand supply and intense coastal erosion, it is of importance to determine if the pits act as sediment traps; thus, reducing the overall sediment budget towards the coast and, as such, enhancing erosion.

Garel (this volume) and Lefebvre (this volume) investigate the above issue, based upon hydrodynamic measurements obtained within and outside of an isolated pit, over a 4-day period; this included a storm event, with significant wave heights of up to 1.2 m. The dataset consists of current magnitude and direction, water level variations and turbidity. Re-suspension events have been observed within and outside of the crater, during the storms. The currents are relatively weak, but reveal significant differences within and outside of the pit; these are indicative of a decoupling of the flow. Although the bed shear stress is greater outside of the pit, the suspended sediment concentration is higher within the pit; it increases earlier than outside the pit, before the storm event. As there is no evidence for significant additional turbidity inside the pit, the higher suspended sediment concentration is the result of the advection of fine-grained sediment towards, then captured, by the pit. Over the long-term (a year), fine sand is trapped preferentially; this is in response to the dominance of moderate storm activity, throughout the year. In relation to sediment transport out of the pit, no evidence is available for sand re-suspension above the crater rim, during moderate storm events; nonetheless, this is possible during more severe storms. The study has emphasised the need to investigate, in greater detail, the flow structure inside the pits; this is to assess the sediment balance within the pits, based upon the prevailing long-term wave climate over the area. Such an approach would assist in the provision of guidelines for gravel removal over the area, in terms of the water depth for extraction and the dimension of the pits.

(c) Coastal impact

Offshore sediment extraction may affect the coastline in different ways: cause beach draw-down; change tidal currents; affect sediment transport; modify nearshore wave conditions; or reduce shelter provided to the adjacent coastline. KORTEKAAS *et al.* (this volume) investigated an area located on the German Baltic Sea coast, between Warnemünde and Darss. The coastline here is eroding rapidly and extensive offshore sand extraction is taking place. Sand resources, of Holocene sedimentary material, are limited over the area and are restricted to a layer of < 2 m in thickness. To investigate the effect of sand extraction on the coastline, bathymetric data obtained from 2 different periods were compared; this was in addition to establishing the location of the coastline, during 5 different years, over a time-span of 50 years. Waves and wave-induced sediment transport were simulated, using an integrated coastal zone model (Sistema de Modelado Costero-SMC (Coastal Modelling Aid System, 2002), developed by the Ocean and Coastal Research Group from the University of Cantabria with the support of the Directorate General to the Coast in the Environmental Ministry of Spain).

Because of the extensive shore protection structures, it is difficult to distinguish between natural and artificially-induced coastal change. As such, no direct relationship was established between changes in the coastline and the bathymetric alteration at the extraction sites. However, the results obtained indicate some primary areas of concern, i.e. very small changes in bathymetry are sufficient to cause significant modifications in the sediment transport potential at the coast, causing variations in the patterns of erosion and accretion. Sediment transport by both wave action and currents (induced by the inflow of North Sea waters) is in a NE direction, towards Darss; here, deposition takes place in a National Park where dredging is prohibited. There is very little input of sediment into the system. Any sand that is removed by marine aggregate extraction, for industrial use, is likely to have a negative effect on the total sediment budget at the shoreline.

Invited Papers

This Special Issue includes also some Invited Contributions; these have been selected to enable an overview to be provided of research relevant to the study of the environmental impact assessments (EIA's), of the two field sites. For the Kwinte Bank, this consists of the work of DEGRENDELE *et al.* (this volume), on the morphological evolution of the Kwinte Bank central depression, before and after the cessation of aggregate extraction. The results show that two years after the closure, the site has not undergone sedimentation, nor has there been a significant change in the nature of the sediments. The morphological changes, identified during the extraction, have ceased, but no significant regeneration took place following cessation of the dredging. If the sediment volume variation, during extraction, is compensated for the amount of extracted sediments, the resulting sediment volume variation is similar to the natural evolution of a non-exploited sandbank; this would imply that marine aggregate extraction has only a local impact.

VAN DEN EYNDE *et al.* (this volume) contribute to the modelling of the effects of sand extraction on sediment transport, due to tides. Numerical models are used to simulate the response of the sediment transport pattern, to extensive sand extraction of the sandbank. A 'worst-case' scenario, together with (two) 'more likely' scenarios, were simulated. Likewise, the effect of the bathymetric changes, on sediment transport, was studied. The results reveal that the intense sand extraction does not appear to affect the stability of the sandbank. Although erosion and deposition is decreasing, a regeneration mechanism appears to be present; this could cause the sandbank to rebuild, on the condition that sand resources are available elsewhere, to be transported to the bank (which has not yet been confirmed). A trench depression, perpendicular to the crest of the sandbank, could be slowly infilled. However, the time-scale of the regeneration process is still uncertain.

GIARDINO *et al.* (this volume) have modelled the interaction between wave activity and tidal currents; this has revealed a high increase in sediment transport, but also a change in direction of the net flux of sediments. In particular, the crests of the shallow sandbanks are highly vulnerable and erosion as deposition as patterns may change, according to the wave activity. In addition, the dominance of the ebb current along the eastern flank can be suppressed by southerly (or SW) winds, i.e. the most common wind direction over this area. Against a background of all the sediment transport activity, the sandbanks do not appear to migrate. This pattern might be related to: (a) a long-term equilibrium of sand transport, due to currents and low waves along the eastern flank; and (b) sand transport, due to currents and more significant waves, along the more exposed western flank.

For the Baltic Sea, KRAUSE *et al.* (this volume) have provided a contribution on the physical and biological impact of sand extraction, associated with a dredging site in the western Baltic Sea. Oxygen depletion zones were found in the most heavily impacted part of the dredging site. These physical impacts had a significant, but short-lived, effect on the common non-vulnerable benthic species. However, the effects were more severe for the sensitive benthic species, which did not recover within one year after dredging.

CONCLUSIONS

This Special Issue provides a unique interdisciplinary overview of a wide range of scientific methods, used in combination, for the study of former extraction sites in tidal and non-tidal environments. The methods applied include: geophysical and hydrodynamic measurements; sedimentological and biological sampling; and video-imaging, in combination with hydro-, sediment- and morphodynamic modelling. Resource prospecting issues and the environmental impact of extraction are discussed.

It is to be hoped that regulatory bodies, involved directly in aggregate extraction, will use the integrated scientific results and knowledge, gained throughout the project. Moreover, the synthesis provided can serve also as guidance to industry, related mainly to the approaches used for resource prospecting and evaluation.

ACKNOWLEDGEMENTS

The Research Training Network EUMARSAND (European Marine Sand and Gravel Resources: Evaluation and Environmental Impact of Extraction) was funded by the European Commission (Contract N° HPRN-CT-2002-00222) within the 5th Framework Programme, 'Improving the Human Research Potential and the Socio-economic Knowledge Base', and by the Department of Agriculture, Fisheries and Food of the Basque Government, the Marine Research Division of AZTI-Tecnalia and Severn Sands.

The project was classified within the Geo and Environmental Sciences Division; it ran from November 2002, until January 2006. Fieldwork undertaken on the Kwinte Bank was a joint research initiative undertaken within the Belgian Science Policy project Marebasse ('Management, Research and Budgeting of Aggregates in Shelf Seas related to End-users' (contract EV/02/18A). The Management Unit of the Mathematical Model of the North Sea and Schelde Estuary granted ship time on board the Belgian oceanographic vessel *R/V Belgica*. The Flemish Institute of the Sea (VLIZ) provided ship time on the *R/V Zeeleeuw*; likewise, the Marine Biology Section of Ghent University, for the use of additional sampling gear, logistic support and assistance provided during the biological sampling. For the Baltic Sea, the help of the officers and crew of the *R/V Alkor* and *R/V Littorina*, in collecting the data, is gratefully acknowledged.

Bob Breen (Severn Sands Ltd., Newport, Wales, U.K.) is thanked for his continuous support, prior to and during the research undertaken throughout the project.

The same applies to FPS Economy, SMEs, Self-employed and Energy, Quality and Security - Service Continental Shelf (Belgium). Its additional support in the publishing phase is highly appreciated.

Marta Pascual and Amaia López (MER (MSc) Students) are thanked warmly for their very considerable effort in outing the final version of the manuscript together; without their assistance, the Issue could never have been completed.

Finally, we are utmost grateful to Irantzu Zubiaur (AZTI-Tecnalia), for her skilful design of this Special Issue.

LITERATURE CITED

Bellec, V.; Diesing, M. and Schwarzer, K., this volume. Last Quaternary Evolution of Gravel Deposits in Tromper Wiek, Southwestern Baltic Sea. *Journal of Coastal Research.*

Bellec, V.; Van Lancker, V.R.M.; Degrendele, K.; Roche, M. and Le Bot, S., this volume. Geo-environmental Characterization of the Kwinte Bank. *Journal of Coastal Research.*

Bonne, W.M.I., this volume. Macrobenthos characteristics and distribution following intensive sand extraction on a subtidal sandbank. *Journal of Coastal Research.*

Brière, C.; Roos, P.C.; Garel, E. and Hulscher, S.J.M.H., this volume. Modelling the Morphodynamics of the Kwinte Bank, Subject to Sand Extraction. *Journal of Coastal Research.*

Degrendele, K.; Roche, M.; Schotte, P.; Van Lancker, V.R.M.; Bellec, V. and Bonne, W.M.I., this volume. Morphological Evolution of the Kwinte Bank Central Depression Before and After Cessation of Aggregate Extraction. *Journal of Coastal Research.*

Gao, S. and Collins, M.B., 1991. A critique of the "McLaren Method" for defining sediment transport paths. Journal of Sedimentary Petrology 61, 143-146.

Garel, E., this volume. Tidally-averaged Currents and Bedload Transport over the Kwinte Bank, Southern North Sea. *Journal of Coastal Research.*

Garel, E. and Lefebvre, A., this volume. Wave-Induced Sand Re-suspension At Dredged Gravel Pits Based Upon Hydrodynamic Measurements (Tromper Wiek, Baltic Sea). *Journal of Coastal Research.*

Giardino., A.; Van den Eynde, D. and Monbaliu, J., this volume. Wave effects on the morphodynamic evolution of an offshore sand bank. *Journal of Coastal Research*

Humphreys, B.; Coates, T.; Watkiss, M. and Harrison, D., 1996*, Beach Recharge Materials, Demand and Resources,* Construction Industry Research and Information Association (CIRIA) Report 154, London, 173pp.

Idier, D.; Hommes, S.; Brière, C,; Roos, P.R.; Walstra, D.-J. R.; Knaapen, M.A.F. and Hulscher, S.J.M.H., this volume. Morphodynamic models used for studying the impacts of offshore aggregate extraction: a review. *Journal of Coastal Research*

Kortekaas, S.; Bagdanaviciute, I.; Gyssels, P.; Alonso Huerta, J.M. and Héquette, A., this volume. Assessment of the Effects of Marine Aggregate Extraction on the Coastline: an Example from the German Baltic Sea coast. *Journal of Coastal Research*

Krause, J.C.; Diesing, M. and Arlt, G., this volume. The Physical and Biological Impact of Sand Extraction: a Case Study in the Western Baltic Sea. *Journal of Coastal Research.*

Manso, F.; Radzevicius, R.; Blažauskas, N.; Balay, A. and Schwarzer, K., this volume. Nearshore dredging in the Baltic Sea: Condition after cessation of activities and assessment of regeneration. *Journal of Coastal Research.*

McLaren, P.A. and Bowles, D., 1985. The effects of sediment transport on grain-size distributions. *Journal of Sedimentary Petrology*, 55(4), 457-470.

Poulos, S.E. and Ballay, A., this volume. Grain-Size Trend Analysis for the Determination of Non-Biogenic Sediment Transport Pathways on the Kwinte Bank (southern North Sea), in Relation to Sand Dredging. *Journal of Coastal Research.*

Radzevičius, R.; Velegrakis, A.F.; Bonne, W.M.I.; Kortekaas, S.; Garel, E.; Blažauskas, N. and Asariotis, R., this volume. Marine Aggregate Extraction Regulation in EU Member States. *Journal of Coastal Research.*

Selby, A. and Ooms, D.F., 1996. Assessment of offshore sand and gravel for dredging. *Terra et Aqua*, 64, 18-28.

Schwarzer, K., this volume. Aggregate Resources And Extraction In The Baltic Sea – An Introduction. *Journal of Coastal Research.*

Van den Eynde, D.; Giardino, A.; Portilla, J.; Fettweis, M.; Francken, F. and Monbaliu, J., this volume. Modelling the Effects of Sand Extraction on Sediment Transport due to Tides on the Kwinte Bank. *Journal of Coastal Research.*

Van Lancker, V.R.M.; Bonne, W.M.I.; Velegrakis, A.F. and Collins, M.B., this volume. Aggregate extraction from tidal sandbanks: is dredging with nature an option ? Introduction. *Journal of Coastal Research.*

Van Lancker, V.R.M.; Bonne, W.M.I.; Garel, E.; Degrendele, K.; Roche, M.; Van den Eynde, D.; Bellec, V.; Brière, C.; Collins, M.B. and Velegrakis, A.F., this volume. Recommendations for the sustainable exploitation of tidal sandbanks. *Journal of Coastal Research.*

Velegrakis, A.F.; Ballay, A.; Poulos, S.; Radzevičius, R.; Bellec, V. and Manso, F., this volume. European marine aggregates resources: Origins, usage, prospecting and dredging techniques. *Journal of Coastal Research.*

Journal of Coastal Research	SI	51	1-14	West Palm Beach, Florida	Summer 2010

European marine aggregates resources: Origins, usage, prospecting and dredging techniques

Adonis F.Velegrakis[1*], Arnaud Ballay[2], Serafim Poulos[2], Rolandas Radzevičius[1,], Valerie Bellec[1,3***] and Faustino Manso[4****]**

[1] University of the Aegean,
School of Environment,
Department of Marine Sciences,
University Hill, Mytilene 81100, Greece
afv@aegean.gr

[2] Department of Geography and Climatology
Faculty of Geology and Geoenvironment
National and Kapodistrian University of Athens
Panepistimioupolis, Zografou
15784 Athens, Greece

[3] Ghent University
Renard Centre of Marine Geology,
Krijgslaan 281, s. 8, 9000 Gent, Belgium

[4] Christian-Albrechts-University Kiel,
Institute of Geosciences,
Olshausenstrasse 40, 24118 Kiel, Germany

[*] corresponding author afv@aegean.gr

[**] Present address: Department of Marine Research,
Institute of Geology and Geography,
Ševčenkos str. 13,
03223 Vilnius, Lithuania

[***] Present address: Geological Survey of Norway
Leiv Eirikssons vei 39
7040 Trondheim, Norway

[****] Present address: Fugro-Geoteam AS
Address Hoffsveien 1C
Zip N-0213
(Norway)00126 Rome (Italy)

ABSTRACT

Marine aggregates (sand and gravel) are important mineral resources and traded commodities. Their significance is bound to increase further, due to increasing coastal zone development, stricter environmental regulation concerning land-won aggregates and increasing demand for beach replenishment material. Marine aggregate (MA) deposits can be differentiated into relict and modern deposits. The former consist of sedimentary material deposited in the past and under different environmental and sedimentary regimes than those existing presently (e.g. the gravel/sand deposits of the Pleistocene buried river valleys of the northwestern European shelves). The latter are deposits, which have been formed and controlled by the modern hydro-and sediment dynamic conditions (e.g. the linear sand banks of the southern North Sea). The present contribution reviews the current state of affairs in 9 representative European Member States concerning the prospecting and extraction (dredging) techniques as well as the levels of production and usage. The review has shown a mixed record as, in some of the studied States, marine aggregate production is an important and streamlined activity, whereas other States have not yet developed efficient marine aggregate policies and industries. It has also shown that although attempts have been lately made to coordinate the field, the industry still faces problems, which hinder its sustainable development. These include (amongst others): lack of standardisation of the relevant information, difficulties in the access to information, non-coherent regulatory regimes and limited collaboration/coordination between the marine scientific research establishments and the marine aggregate industry. These issues should be addressed as quickly as possible in order to exploit effectively this important mineral resource.

ADDITIONAL INDEX WORDS: *Marine aggregates, dredging, offshore mineral resources, relict sediments, buried palaeovalleys, mineral resource prospecting.*

INTRODUCTION

In recent years, the importance of marine aggregates (sand and gravel) as a mineral resource has increased in the EU, due both to increasing demand and stricter regulations concerning land-won aggregates in the Member States (e.g. Jewell, 1996; Phua *et al.*, 2004). In the last 20 years, more than 50 million m^3 of sand and gravel have been extracted annually (on average) from the northern European continental shelf alone and the production may increase further to supply the material needed for the construction of the planned projects of coastal infrastructure (Phua *et al.*, 2004; Seaman, 2006; http://www.dredging-in-germany.de) and the replenishment of the eroding European beaches (Eurosion, 2003; Humphreys *et al.*, 1996; Ices, 2006; Selby and Ooms, 1996). Marine aggregates are of particular importance in the coastal states of northwestern Europe, with the UK, the Netherlands and Denmark collectively producing more than 80% of the European marine aggregate production (e.g. Ices, 2005; Ices, 2006).

Marine aggregates (MA) are non-metallic sediment deposits, consisting of sands, gravels and shells/shell debris, which have been formed as a result of either contemporary (modern) or past sedimentary/hydrodynamic processes (relict deposits). Two different classification schemes are in place concerning the size of marine sand and gravels. Geologists use the Folk (1980)

DOI: 10.2112 / SI51-002.1 received 23 February 2007; accepted in revision 5 October 2007.

grain-size classification, according to which sediments consisting of particles with sizes ranging between 0.063 and 2 mm are classified as sands and with sizes greater than 2 mm as gravels. In comparison, the MA industry classifies sediments consisting of particles with diameters ranging between 0.063 and 4 (or 5) mm as sands, and sediments with particle-sizes greater than 4 (or 5) mm as gravels. In the present contribution, the second classification is used, as most of the available data on supply and demand follow the MA industry's classification.

The nature/texture of marine aggregates is generally similar to land-won aggregates (Gubbay, 2005; Harrison, 2003). However, there are also differences, as marine aggregates are generally less 'contaminated' by fine-grained material (silts and clays) and have higher concentrations of undesirable salts (NaCl) and biogenic material (shells/shell debris). In addition, siliciclastic marine aggregates consist generally of "harder" material than land-won aggregates, as they have been subjected to rigorous abrasion in the energetic coastal and inner shelf marine environments (e.g. Pettijohn, Potter, and Siever, 1972).

The composition of the MA deposits varies, depending on the original sediment source. For example, flint forms the greater part of the gravel deposits of the eastern English Channel and those offshore of the Riugen Island (Germany), being the product of erosion of the flint bands of the extensive Cretaceous Chalk outcrops found in these areas (Kennedy and Garrison, 1975). In comparison, marine aggregates found offshore of the Humber Estuary (UK sector of the North Sea) have more variable composition, reflecting their glacial origin (Gubbay, 2005).

The aim of this contribution is to review the MA uses, origin, demand/supply and exploitation (prospecting/dredging) techniques in (9) coastal EU Member States (Belgium, France, Germany, the UK, the Netherlands, Poland, Spain, Denmark and Greece), representing the different European coastal areas (i.e. the Atlantic, Baltic and Mediterranean coasts).

USE OF THE MARINE AGGREGATES

Marine aggregates are used (Bmapa, 2004, 2005; Ceda, 1993): in concrete and mortar manufacture; as ingredients of asphalt and coated products; for block making; as drainage and capping material and in other fill-related uses; and as beach replenishment material. In sandy beach replenishment schemes (Dean, 2002), material specifications (apart from project-specific grain-size requirements) are relatively simple, as the mineralogy of the material is not, generally, a significant concern. Nevertheless, replenishment material must be clean and not containing fresh biogenic material and/or contaminants such as chemical pollutants; for example, sediments from some areas of the Bristol Channel (UK) cannot be used as beach replenishment material, as they are characterised by large concentrations (exceeding in some cases 40% of the sediment weight) of waste coal (Hamilton *et al.*, 1979; Velegrakis *et al.*, 1996). Sand used in construction must comply with certain standards (De Vree, 2003) regarding, for instance, its chloride content (Table 1.).

Table 1. *Chloride content limits (according to BS 882, App. C, Table 7.) in marine aggregates.*

Concrete Type	Chloride Content (% weight)
Pre-stressed concrete, heat-cured concrete with embedded metal	0.01
Concrete with embedded metal made with cement BS4027	0.03
Concrete with embedded metal made with cement BS12, BS146,DS1370, BS4246, BS 6588, BS6610, or combinations with ground granulated blastfurnace slag or pulverised-fuel ash	0.05
Other concrete	no requirement

Marine gravels are also used for beach replenishment and in the construction industry. With regard to their use in the construction industry, although gravel-sized aggregates form an essential ingredient of certain concretes (see Table 2. for shell content requirements) and asphalt products, they can be replaced by good quality crushed-rock aggregates. In contrast, marine gravels are vital resources for certain beach replenishment schemes, due to their grain-size and (generally) rounded shape (e.g. Arthurton, 1997; Bates *et al.*, 1997).

Table 2. *Shell content limits (according to BS 882 1992, Table 1.)*

Grain Size/Type	**Shell content (% weight)**
Material with size less than 5 mm (sand)	no requirement
Shingle size up to 10 mm, graded or all-in aggregate (> 5 mm and < 10 mm)	20
Shingle sizes, graded and all-in aggregate (> 10 mm)	8

in marine aggregates.

ORIGINS OF THE MA DEPOSITS

Exploitable MA deposits have been mostly formed in the Quaternary. On the basis of their formation period, they may be differentiated into relict and modern sedimentary bodies (e.g. McManus, 1975). Relict deposits are those formed in the past and under different environmental conditions i.e. in environments controlled by sedimentrary regimes different than those existing presently. Typical examples are the gravel/sand deposits found within the Pleistocene buried river valleys of the northwestern European shelf (Antoine *et al.*, 2003; Gibbard, 1988; Velegrakis, Dix, and Collins, 1999), the moribund banks found at the outer shelf (at 60-140 m water depths) of the Celtic Sea (e.g. Kenyon *et al.*, 1981; Reynaud *et al.*, 1999) and the glacial (e.g. Herrmann *et al.*, 1999) and transgressive (Bellec, Diesing, and Schwarzer, this volume) deposits of the southern Baltic Sea. Such deposits are not normally involved in the modern sedimentary processes, although some movement of their superficial layers may take place under particular conditions,

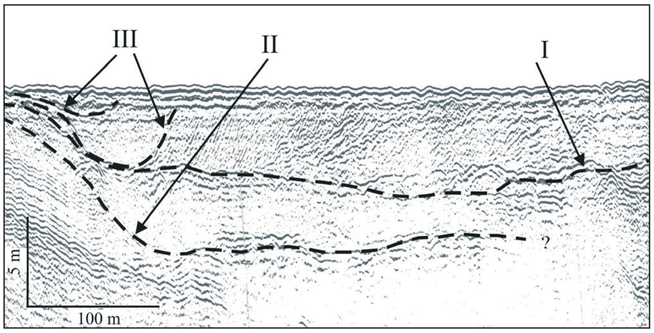


Figure 1. Seismic (boomer) section and its interpretation from a tributary paleovalley of the 'English Channel River' (Gibbard, 1988; Hamblin et al., 1992) in the central English Channel. The infilling sediments form different seismostratigraphic units, with coarse-grained sediment topping the sequence (shown from the acoustic character of the deposit, e.g. from the presence of numerous diffractions, and ground truth data). Key: I, lower bounding unconformity of the coarse-grained deposit; II, upper bedrock erosional surface; III, late channels.

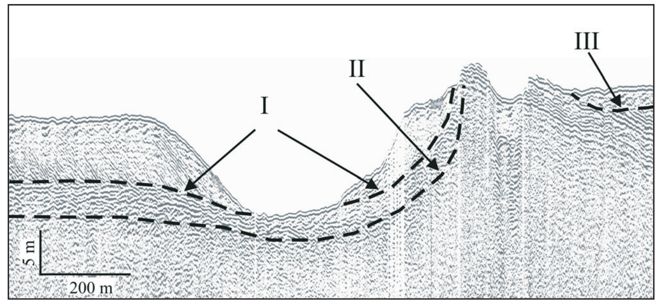


Figure 2. Seismic (boomer) section and its interpretation showing drowned river terraces in the Eastern English Channel (water depth ~30 m at the upper part of the deposit). These terraces are found along a submerged tributary of the Northern Paleaovalley (the large submerged valley of the English Channel, see Hamblin et al. (1992)), which, in many areas, is devoid of sediment infilling, possibly due to an extreme flooding event during the last (Flandrian) transgression (e.g. Smith, 1985; 1989). The terrace material consists mainly of flint gravel and/or sandy gravel, indicated by the presence of acoustic diffractions on the echogram and verified by ground-truth data. Key: I, lower bounding unconformity of the coarse-grained terrace deposit; II, upper bedrock erosional surface at the terrace area; III, upper bedrock erosional surface at the interfluve.

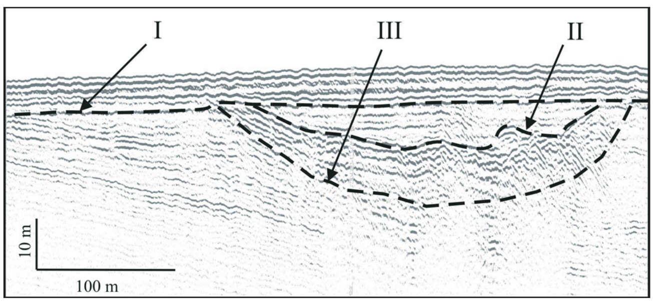


Figure 3. Seismic (boomer) section and its interpretation from a buried valley of the eastern English Channel. The infilling sediments form different seismostratigraphic units, with (mostly) fine-grained deposits topping the infilling sequence. Key: I, upper bounding unconformity of the transgressive deposit (transgressive system tract (TST)); II, upper bounding unconformity of the coarse-grained deposit of the lowstand system tract (LST) see Posamentier and Vail (1988); and III, upper bedrock erosional surface.

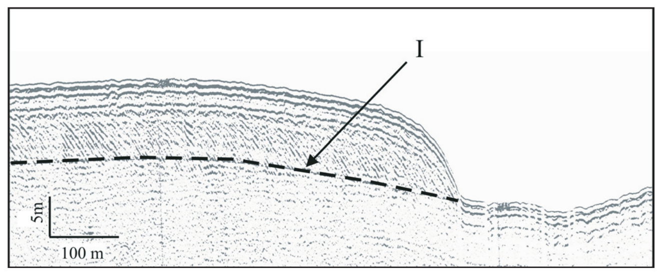


Figure 4. Seismic (boomer) section and its interpretation showing a coarse-grained drowned beach in the Eastern English Channel (water depth ~35 m at the upper part of the deposit). The material consists probably of flint gravel and/or sandy gravel, shown by the plethora of sound wave diffractions present on the image and ground truth data (core sampling). Key: I, upper bedrock erosional surface.

such as storm waves (e.g. Dalrymple *et al.*, 1992). Modern deposits are those, which have been formed and controlled by the modern hydro-and sediment dynamic conditions. In areas associated with high tidal and/or wave energy, as it is the case in most shallow Atlantic continental shelves, modern deposits can be characterized by significant mobility (e.g. Velegrakis *et al.*, 2007; Vincent, Stolk, and Porter, 1998), which may result in considerable material exchanges between them and the adjacent areas.

Relict MA deposits

These deposits have been mostly formed during the Pleistocene climatic changes and sea level oscillations. During the Pleistocene sea level falls (lowstands), continental shelves around northern Europe were repeatedly exposed to subaerial erosion and drained by large periglacial river systems (e.g. Antoine *et al.*, 2003; Gibbard, 1988); deposition of unconsolidated (and relatively well-sorted) coarse-grained material was taking place at the riverine thalwegs, terraces, point bars and fans (Leeder, 1999). These deposits are of particular interest for the MA industry, since they contain large quantities of gravel and sandy gravel (Figure 1.). Although, such coarse-grained deposits are usually buried under transgressive/highstand finer-grained deposits (see below), in some cases they can also be found exposed on the present seafloor (Figure 2.).

During the early stages of the subsequent marine transgression, the lowstand fluvial environments were transformed first into estuarine and then marine environments (e.g. Allen and Posamentier, 1993). Therefore, the last (Flandrian) transgression caused fine-grained sedimentation (i.e. muddy sands and muds) over large sections of the river palaeovalleys, which were previously characterised by coarse-grained sedimentation (e.g. Fletcher , Knebel, and Kraft, 1992). Such sedimentary sequences (Figure 3.) are difficult to exploit, as fine-grained sediment deposits must be excavated before reaching the coarse-grained resource (but see Loman (2006) for new technological developments which may address this problem).

Other relict sedimentary bodies with a good resource potential are associated with drowned beaches and barrier islands (Leeder, 1999). These are coastal sedimentary bodies left behind during the last marine transgression, as a result of their protected position (e.g. perched in front of coastal cliffs) and/or the fast rate of the transgression (Figure 4.). These deposits are of particular interest, as they are characterised by relatively good sorting and consist of material resistant to abrasion, which makes them ideal for beach replenishment. Their texture depends on the particulars of the drowned sedimentary environment and their exploitability is controlled by the depth of their present position (Bates *et al.*, 1997).

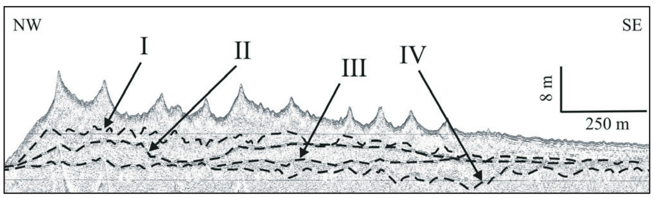


Figure 5. Seismic section and its interpretation across the Kwinte Bank (Flemish Banks, southern North Sea). Key: I, base of the modern sand bank; II, base of the transgressive coastal bar preceding the modern bank; III, base of the tidal flat deposits; and IV, base of the estuarine channels.

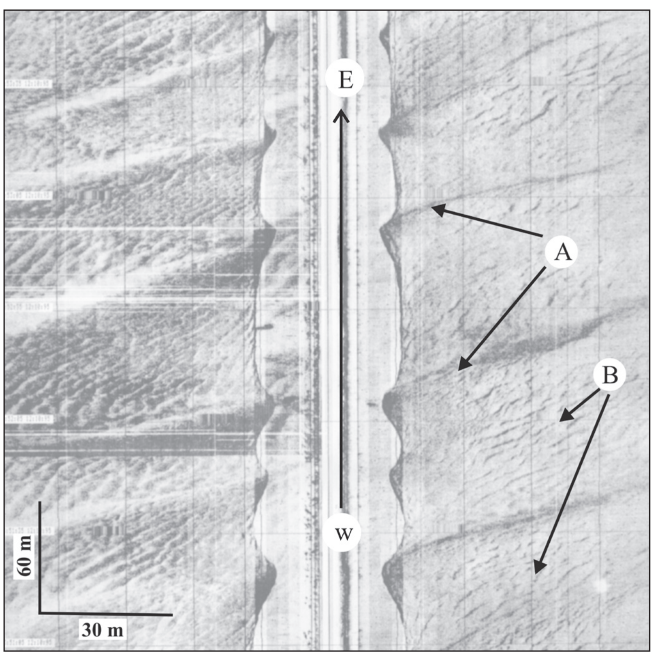


Figure 6. Side-scan sonar sonograph from the Bristol Channel (UK), showing a field of sand subaqueous dunes (Velegrakis *et al.*, 1996). Key: A, large subaqueous dunes; B, medium subaqueous dunes superimposed on the larger bedforms.

In some areas during the Pleistocene glacial episodes, ice-sheets originating from the land masses spread and extended to the shelves, depositing extensive mantles of sub-glacial till consisting of clays, sands, gravels and boulders. Although these deposits can attain substantial thicknesses (e.g. Jackson *et al.*, 1995; James, Harrison, and Ciavola, 1992), they may only rarely be of economic interest due to (a) their consolidation and 'contamination' by both fine and oversize material and (b) regulatory restrictions put in place for some areas (e.g. in the Baltic Sea, see Helcom (1998)). In some areas, however, pro-glacial till deposits, deposited by melt ice rivers from the ice front and consisting of sandy gravels and coarse gravelly sands can be of interest to the MA industry (e.g. the Cleaver Bank in the Dutch sector and the areas east of Norfolk and the Humber in the UK sector of the North Sea).

Finally, some areas of the northern European shelves are characterised by veneers of lag gravel. These deposits have been substantially reworked by the present hydrodynamic regime; they usually form thin sedimentary bodies, as it is the case in the Baltic Sea (e.g. Blazhchishin, 1976) and the English Channel (Hamblin *et al.*, 1992) and, thus, they have only limited economic potential.

Modern MA deposits

In terms of their dynamics, modern deposits may be broadly differentiated into: (i) sediment sinks, i.e. depositional centres that do not supply sediments to the surrounding areas and (ii) sediment stores, i.e. deposits characterised by considerable sediment exchanges with the adjacent areas. In energetic marine environments, superficial sediment deposits are likely to be mobile and, thus, can be generally classified as 'stores'. Sand stores in the continental shelf include sand sheets, sandbanks (Figure 5.), sand patches, sand ribbons and subaqueous dune fields (Figure 6.).

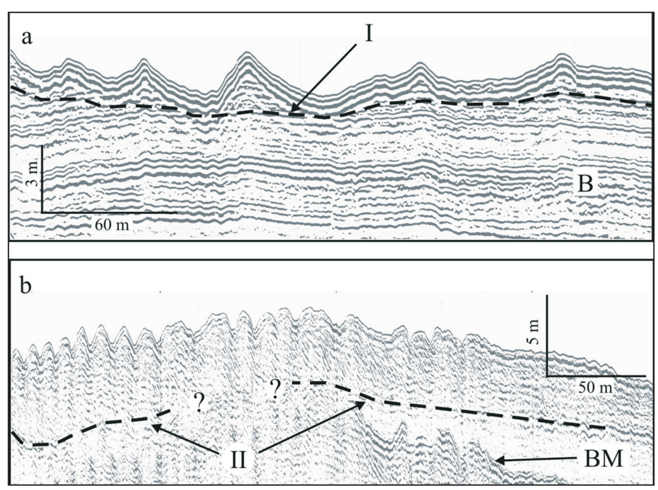


Figure 7. (a) Seismic (boomer) section showing subaqueous sand dunes in the English Channel and (b) Seismic (boomer) section showing subaqueous gravel dunes in Christchurch Bay, (southern UK). Key: I, basal unconformity of the sand bedforms; II, basal unconformity of the gravel sediments; BM, bottom multiple; B, Tertiary bedrock.

Table 3. *Official MA information holders in the investigated EU Member States.*

Country	Organisation/Data sets
Belgium	Fund for Sand Extraction, FPS Economy, SMEs, and Energy (www.mineco.fgov.be) (resource maps and databases of multibeam data/dredging activity) Management Unit of the North Sea Mathematical Models - MUMM, Department VI of the Royal Belgian Institute of Natural Sciences (www.mumm.ac.be/) (resource maps, lisenced areas, dredging activity data, including EMS "black-box" data) Geological Survey of Belgium (www.naturalsciences.be/geology/) (geological maps and primary data sets)
France	BRGM-Bureau de Recherches Géologiques et Minières (Office of Geological and Mine Research) (www.brgm.fr) (geological maps, primary geological data) IFREMER (French Research Institute for Exploitation of the Sea) (www.ifremer.fr) (MA licenses, MA reserve maps, oceanographic databases (SISMER), subsurface data (CORIOLIS), satellite data (CERSAT)) SHOM-Service Hydrographique et Oceanographique de la Marine (Hydrographic and Oceanographic Service) (www.shom.fr) (marine data/information, including hydrographic, multibeam and geophysical data)
Poland	PGI (Polish Geological Institute) (http://www.pgi.gov.pl/) (MA licensed areas, geological maps, natural resource maps, central geological archives) and MIDAS Register (Management and Protecting of Polish Mineral Raw Materials) DGiKG (Department of Geology and Geological Concessions, Ministry of the Environment) (http://www.mos.gov.pl/dgikg/) (national proven, probable and possible mineral reserves)
Germany	BSH (Federal Maritime and Hydrographic Agency) - (http://www.bsh.de/de/index.jsp) (MA licenses, resource maps, marine environmental data and CONTIS database BGR Federal Institution for Geosciences and Natural Resources in Hanover (http://www.bgr.bund.de/cln_029/DE/Home/homepage__node.html__nnn=true) (central authority advising the German Federal Government) State (Lander) Geological Surveys (e.g. http://www.uni-mainz.de/FB/Geo/Geologie/GeoSurv.html): Landesamt für Umwelt, Naturschutz und Geologie Mecklenburg-Vorpommern (Office for Environment, Nature Protection and Geology) http://www.lung.mv-regierung.de/ in Mecklenburg-Vorpommern (Geological and natural resource maps, Baltic Sea Territorial Water environmental data, GIS-based geological data) Landesamt für Bergbau, Energie und Geologie (LBEG) (Office for Mining Industry, Energy and Geology (est. in 1-1-2006) in Lower Saxony (http://www.lbeg.niedersachsen.de/) (geological/natural resource maps and North Sea Territorial Water environmental data) Landesamt für Natur und Umwelt (Office for Nature and Environment) - http://www.umwelt.schleswig-holstein.de/servlet/is/155/ - in Schleswig-Holstein (geological and mineral resource data/maps, environmental databases) Behörde für Stadtentwicklung und Umwelt Geologie (Agency for Town Development and Environmental Geology) in Hamburg http://fhh.hamburg.de/stadt/Aktuell/behoerden/stadtentwicklung-umwelt/umwelt/geologie/start.html
Denmark	GEUS (Geological Survey of Denmark and Greenland) (http://www.geus.dk/) (MA extraction licenses, geological/mineral resource data and maps)
The Netherlands	TNO (Netherlands Institute of Applied Geosciences - Geological Survey) (http://www.nitg.tno.nl/eng/) (MA extraction licenses, geological/mineral resource maps and databases) Ministry of Transport, Public Works and Water management (http://www.verkeerenwaterstaat.nl/?lc=nl) and North Sea Directorate (http://www.rijkswaterstaat.nl/
The UK	British Geological Survey http://www.bgs.ac.uk/ (geological and mineral resource maps and data bases) The Crown Estate (http://www.crownestate.co.uk/) and BMAPA (www.bmapa.org/) (information on MA extraction licenses, extraction activity database)
Spain	Instituto Español de Oceanografía (Spanish Institute of Oceanography) - IEO - http://www.ieo.es/version_eng/indexingles.htm Del Ministerio de Agricultura, Pesca y Alimentación en España (Ministry of Agriculture, Food and Fisheries) - http://www.mapa.es/ Instituto Geológico y Minero de España (Geological and Mining Institute of Spain) - http://www.igme.es/internet/default.htm Dirección General de Costas, Ministerio de Medio Ambiente (General Directorate of Coasts, Ministry of Environment) - http://www.mma.es/costas/htm/actua/infor/
Greece	IGMR Greek Geological Survey (marine geological data/maps) and HCMR (Hellenic Centre for Marine Research) (marine environmental data) Public Estates Company (MA licenses) YYN (Naval Hydrographic Office) (Hydrographic data and maps)

Sand sheets are extensive, continuous veneers of sand of variable thickness. Such deposits are commonly found over the western European shelf, mostly at relatively large (> 40-60 m) water depths (Kenyon and Stride, 1970). Therefore, even though they may form substantial marine aggregate resources, they are probably beyond the operational capability of the majority of the vessels of the dredging industry fleet (e.g. Bates *et al.*, 1997; Visser, 2007). Sandbanks are elongated sedimentary bodies, which may reach lengths well in excess of 30 km (Collins *et al.*, 1995; Dyer and Huntley, 1999; Pattiaratchi and Collins, 1987). These sedimentary structures form huge resources of good quality, relatively well-sorted sand-sized sediments and are one of the primary targets of the MA industry (e.g. Ices, 2005; Velegrakis *et al.*, 2001). Sand ribbons are flow parallel bedforms (e.g. Kenyon, 1970; McLean, 1981) consisting of elongated patches of sand resting on coarser-grained sediments and/or bedrock substrates; they form good quality MA deposits which, however, are characterised by a limited thickness and rigorous hydrodynamic regime that makes their mining difficult. Subaqueous dunes (Ashley *et al.*, 1990) are flow-transverse repetitive sediment structures developing on a sedimentary bed under the influence of current- and/or wave-induced flows (Belderson, Johnson, and Kenyon, 1982; Dalrymple *et al.*, 1992). They have dune-like shapes with their crests aligned (almost) perpendicular to the prevailing flow direction and are characterised by variable sediment texture and dimensions (Figures 6. and 7.), reflecting the sediment and flow diversity of the shallow marine environments. Subaqueous dune fields can be of large economic interest, although they present certain practical problems in their exploitation (Bates *et al.*, 1997).

EUROPEAN MARINE AGGREGATE RESOURCE INFORMATION

In all investigated European Member States, MA resource information has been found to be dispersed among various organisations (Table 3.). The available information consists of both analogue and digital data sets and includes marine aggregate reserve maps and maps of areas licensed for extraction, shallow seismic and side-scan sonar records, borehole logs and vibro-core, gravity core and grab sample records. The data quantity and quality vary widely, with the most modern and uniform data bases found in the UK, the Netherlands and Denmark, where most of the information is held electronically (Ices, 2005; Meakins *et al.*, 1999; Nielsen and Jensen, 2003). Although the recent years substantial research has been undertaken to access the MA resource potential of the European shelves, there are still information gaps in all investigated EU Member States; this is true even for those states where modern surveys have been carried out. Thus, accurate estimations of the overall reserves are not available (Ices, 2006), particularly over areas exceeding 40 m water depths (e.g. Bates *et al.,* 1997).

Resource information is also not always standardised (Ices, 2005; Meakins *et al.*, 1999). Not only is there a wide disparity in the type/quality of data sets held by individual states, but there are discrepancies in the resource classification schemes and descriptions, in spite of the obvious benefits of data standardisation. Marine aggregate classifications appear to depend on the area, type of material and end-user. For example, the lowest grain-size limit for in the UK varies from 2 mm to 4 mm to 5 mm, whereas in France variations occur even between regions. Classification discrepancies are of significant concern when quantitative data, such as demand or reserve estimates, are compared between different areas and/or EU Member States. Some efforts towards a consistent format/standards have been made (e.g. De Vree, 2003), particularly by organisations in the UK, the Netherlands and Denmark; however, satisfactory standardisation has not been yet achieved. In the Mediterranean region, MA reserve information is not available in a comprehensive way, although it appears that substantial relict and modern deposits are available (e.g. Velegrakis *et al.*, 2001).

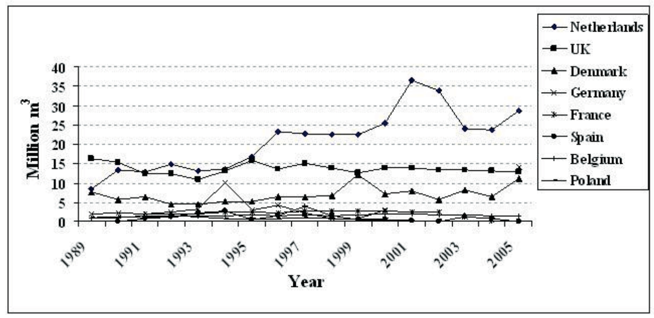


Figure 8. Marine aggregate production in 8 EU Member States in the period 1989-2005 (see also Table 4.). Data from Ices, (1995, 2000-2006) and Meakins *et al.* (1999).

Table 4. *National marine aggregate extraction for the period 1989-2005. (Data from Ices, 1995; 2000-2006; Meakins et al. (1999) and the Belgian Fund for Sand Extraction). Note that the UK data have been estimated on the basis of a volume/weight coefficient 1/1.66 (Ices, 2005, 2006). The first value for Germany and Denmark refers to the total production volume, whereas the values in parentheses refer to production volumes from the North Sea. Key: nd, no data available.*

Year	Extraction volumes (in million m³)								
	Germany	Poland	UK	France	Netherlands	Spain	Denmark	Greece	Belgium
1989	1.97 (1.97)	0.96	16.27	nd	8.43		7.68	nd	0.96
1990	2.27 (2.27)	1.35	15.24	nd	13.36	0.08	5.74	nd	0.95
1991	2.02 (2.02)	0.99	12.23	2.00	12.77	0.66	6.40	nd	1.75
1992	2.49 (2.08)	1.58	12.41	1.90	14.80	1.32	4.38	nd	1.22
1993	3.26 (2.21)	1.35	10.78	1.90	13.02	2.19	4.32	nd	1.45
1994	10.12 (8.81)	0.74	13.13	2.50	13.55	2.75	5.17	nd	1.60
1995	2.91 (1.54)	0.81	15.72	2.50	16.83	0.42	5.31	nd	1.66
1996	4.26 (1.38)	0.85	13.61	2.30	23.15	1.48	6.32	nd	1.44
1997	2.22 (0.00)	0.96	15.00	2.60	22.75	1.67	6.40	nd	3.86
1998	0.70 (0.70)	0.69	13.80	2.60	22.51	1.41	6.66	nd	1.40
1999	0.71 (0.71)	0.74	12.60	2.60	22.40	0.49	12.04	nd	1.69
2000	2.97 (1.67)	0.82	13.89	2.60	25.42	0.41	7.12	nd	1.90
2001	nd	nd	13.71	2.43	36.45	0.30	7.86	nd	1.92
2002	nd	0.53	13.22	2.43	33.84	0.08	5.57 (3.50)	nd	1.62
2003	1.14 (0.70)	nd	13.39	nd	23.97	1.19	8.13 (6.18)	nd	1.65
2004	nd	0.85	12.98	0.34	23.59	0.79	6.46 (4.18)	nd	1.50
2005	14.00 (13.61)	nd	12.78	nd	28.76	0.05	11.05 (9.28)	nd	1.36
Average	3.64 (2.00)	0.94	13.57	2.21	20.92	0.96	6.86	nd	1.64

In view of the information gaps and classification discrepancies, the proven recoverable European MA reserves are difficult to be established with accuracy. However, such estimates exist for some of the investigated states, on the basis of detailed reconnaissance mapping (Ices, 2006). For example, Danish marine sand reserves have been estimated to be very substantial (in the order of several billions m^3), but coarse sand/gravel resources are rather limited in the North Sea (Birklund and Wijsman, 2005). The German recoverable MA reserves of the Baltic Sea are confined (of the order of 40-50 million m^3), whereas the Polish reserves have been estimated to be close to a 100 million m^3 (Herrmann *et al.*, 1999). Estimations for the UK have shown that the proven and potential workable marine sand reserves found within the present operational capability of dredging vessels amount to several billion m^3 (Humphreys *et al.*, 1996). In contrast, coarse-grained deposits are finite, as they mostly form a thin (less than 1m thick) veneer over the seabed; only over certain areas the thickness of the gravel deposits becomes significant (Figures 1., 2. and 4.) and, thus, economically viable (e.g. Arthurton, 1997; Bates *et al.*, 1997).

MA PRODUCTION AND USAGE

Reliable statistics on marine aggregate production in the EU Member States are difficult to collate (e.g. Ices, 2006), due to non-standardised archiving, varying material classification, commercial confidentiality issues (Meakins *et al.*, 1999) and regulation discrepancies (Radzevičius *et al.*, this volume). In general, information is more complete in those countries that have increased dependence on marine aggregates and a mature MA industry; hence, limited/sparse information can be found for the Mediterranean EU States, which rely predominantly on land aggregates. Continuous production (extraction) figures (for the last 30 years) are available for the UK, the Netherlands and Belgium (Ceda, 1993; Ices reports 2000-2006), whereas France and Germany show significant information gaps (Ices, 2006; Ifremer, 2007).

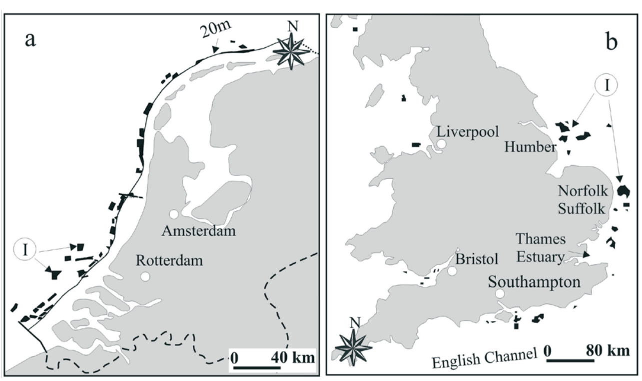


Figure 9. Licenced areas for marine aggregate extraction in (a) the Netherlands and (b) the UK. Adapted from Phua *et al.* (2004), Ices (2005) and Bmapa (2005). Key: 20 m, contour line of the 20 m water depths; and I, major dredging areas.

MA Production

In the late 1980s, MA production increased significantly in several states. The level of production has since been, more or less, stabilised (with the exception of the Netherlands), although significant interannual variations may occur in response to project-led demand (Figure 8. and Table 4.). The three main MA production countries in the EU are the Netherlands, the UK and Denmark, which collectively yield over 80% of the marine aggregates produced by the 9 studied countries (Harrison, 2003; Ices, 2006; Uscinowicz *et al.*, 2003).

The Netherlands

MA production (extraction) has been increasing more or less steadily since 1989 (Figure 8). The production from the North Sea licensed areas (Figure 9a.) peaked in 2001 at 36.5 million m^3, in response to increased demand for fill and beach replenishment material during that year; in 2005, total marine sand production was ~29 million m^3 (Ices, 2006). In the Dutch sector of the North Sea, there are no exploitable gravel resources and, thus, the gravel needs of the country are covered through imports (around 2 million m^3 per year) mainly from the UK. The increased MA production is compounded by the construction of modern facilities (wharves) in the port of Rotterdam for the landing and processing of marine aggregates. This large investment shows that the Netherlands plans to shift further the production from land- to marine-based sources.

The UK

MA production has increased steadily in the past four decades (~5.7 million m^3/year in the 60s, ~9 million m^3/year in the 70s, ~11 million m^3/year in the 80s and ~13 million m^3/year in the 90s). The production peaked in 1989 at 16.9 million m^3 (to supply the large infrastructure/building projects in the London metropolitan area), to decline subsequently to 10.8 million m^3 in 1993 (Gubbay, 2005); since then, the annual production has again been increasing to an annual average of ~13 million m^3 (Table 4.) to provide the additional material required for beach replenishment schemes and increasing exports. It is expected that the marine aggregate demand will be further increased in the near future, in order to supply the large development projects associated with the 2012 London Olympics (Seaman, 2006).

The highest demand for marine aggregates is in SE England; thus, MA production is concentrated in the southern North Sea and the English Channel (Bmapa, 2004). Aggregates are supplied from licensed areas offshore of the Thames Estuary, the Norfolk and Suffolk coasts and the Central and Eastern English Channel (Figure 9b.). The 3 other main MA production areas are located in the Bristol Channel, offshore of the Humber Estuary and in Liverpool Bay; these production sites supply local markets. Very limited MA extraction takes place to the north of these areas. With regard to the type of material produced (gravel or sand), there is also a differentiation according to location, with the southern coast, the Thames and the Humber licensed areas producing most of the gravel (Seaman, 2006).

Denmark

There has been a considerable production of marine sand (mostly for fill purposes) over the last decade (Table 4. and Figure 8.), to meet demands from the large infrastructure projects undertaken along the Danish coastal zone (e.g. HERRMANN *et al.*, 1999). With the exception of the peaks of 1999 and 2005, production volumes have remained stable at around 6-7 million m^3 during the last 10 years (CEDA, 1993; ICES, 2005; 2006).

France

Marine aggregate production has remained stable (at around 2- 2.6 million m^3 per year, see Table 4.) in France for several years (IFREMER, 2007). There is a significant aggregate demand in the northern Seine and Loire regions but, little MA extraction takes place despite the occurrence of substantial MA resources. At the same time, some 47 million tonnes of aggregates have been abstracted from the channel and fluvial terraces of the Rhone River alone since 1949 (ARNAUD-FASSETTA, 2003). Therefore, even though the annual aggregate demand is ~300 million tonnes, less than 1% of that is supplied from marine sources. Approximately 1 million tonnes of marine aggregates are imported annually from the UK and to much lesser extent from Belgium (IFREMER, 2007).

Germany

Marine sands and gravels are produced in several areas of the German sectors of the Baltic and (particularly) the North Seas (see SCHWARZER, DIESING, and MANSO, this volume). The produced volumes have not been great (Figure 8. and Table 4.), but they make an important contribution to regional aggregate supply. Significant quantities of the extracted material are utilised in beach replenishment schemes, whereas the remainder (approximately half of the annual production) is used in the construction industry (ICES, 2002). In 1994 and 2005, the production increased sharply due to project-led demand (ICES, 2006).

Belgium

Although the seabed of the Belgian sector of the southern North Sea contains large quantities of sand, production is concentrated mainly on the Kwinte Bank (DEGRENDELE *et al.*, this volume; HARRISON, 2003); however, sand extraction from this site has stopped in 2003 in order to study its potentially detrimental effects on the stability and biodiversity of the bank (see VAN LANCKER *et al.*, this volume). MA production has increased since the 1980s. In the recent years, with the exception of a peak during 1997 (Figure 8. and Table 4.), the annual production has remained relatively stable at 1.5-2 million m^3. Most of the produced sand is used in the construction industry, whereas some small quantities are exported to France (ICES, 2006; SCHOTTE, 2003). Belgium imports yearly about 1.5 million m^3 of marine sand/gravel from the UK.

Poland

Production in Poland is limited, having an average of less than 1 million m^3 per year (Table 4. and Figure 8.). In 2004, the fine- and medium-grained sand extracted from the Polish sector of the Baltic Sea (~0.8 million m^3) was used mostly in beach replenishment and coastal defence schemes (ICES, 2005); limited quantities were used in the construction industry. Some material (e.g. ~0.3 million m^3 in 2000), extracted from the Slupsk Bank, has been exported to Germany (USCINOWICZ *et al.,* 2003).

Spain

MA production in Spain is allowed only for beach replenishment (see RADZEVIČIUS *et al*., this volume). The average annual production is about 1 million m^3, but there are significant interannual fluctuations in response to beach replenishment needs (Table 4. and Figure 8.). Extraction takes place both in the Atlantic and in the Mediterranean inner continental shelves, but presently is concentrated offshore of the southern Spanish coastline (ICES, 2006).

Mediterranean European coast

There is not an accurate registry of MA production for Italy, the southern French coast and the other EU Mediterranean countries (e.g. Greece). In these areas, most aggregate material is still produced from land open-quarries, river channels and terraces. Published information suggests that about 690 million m^3 of aggregates have been extracted in the period 1958-1981 from the Po River valley (DAL CIN, 1983; MARCHETTI, 2002), ~93 million m^3 (1950-1992) from the Emilia-Romagna rivers (IDROSER, 1994), 12.7 million m^3 (1966-1975) from the rivers of the Marche Region and more than 26 million m^3 (1966-1981) from the Abruzzo rivers (AQUATER, 1982). Lately, MA production has attracted more attention, due to the discovery of significant reserves offshore of the coasts of Lazio (S. Capucci, pers. comm.) and Emilia Romagna (A. Lamberti, pers. comm.). With regard to Greece, MA extraction has been taking place since the 1960s, mainly from the inner continental shelf of the Greek islands (e.g. Andros, Mykonos); most of the material produced was used in the construction industry. Since the 1990s, stricter environmental regulations have resulted in the termination of most inshore MA extraction and production has since been concentrated offshore of the coasts of Trikeri (N. Evoikos Gulf) and Southern Evia. Although, there is no readily available information on annual extraction volumes, it is thought that these are of the order of hundreds of thousands of m^3 rather than millions.

MA Usage

With the exception of the UK and to a lesser extent Poland and the Netherlands, marine aggregates are used in the country of production (Table 5.). Annual exports of aggregates extracted from the UK waters vary but, in some years, can be more than 20% of the UK production with the main foreign markets being the Netherlands, Belgium and France (BMAPA, 2004; ICES, 2005). Relatively small quantities of Danish marine aggregates are exported in some years to Sweden and Germany, whereas there are also intermittent Dutch and Polish MA exports to Belgium and Germany, respectively (ICES, 2005).

In the Netherlands, most of the MA production is used for fill and beach replenishment, whereas in Spain the whole production is reserved for beach replenishment (Table 5.). This is not the case in the UK, where more than 60% of the MA production can be used in the construction industry (GUBBAY, 2003, 2005; MEAKINS *et al.*, 1999). In Denmark, almost 40% of marine sand is used in beach replenishment schemes, mainly along the west Jutland coast, whereas almost 80% of the Polish production is used for beach replenishment (Ices, 2005).

With regard to beach replenishment, most of the southern UK coast beaches consist of flint/chert gravel (shingle), whereas the remainder of the UK coastline is characterised by sandy beaches. Therefore, there will be an increasing demand for (flint) marine gravels in the southern UK to supply the beach replenishment schemes. As gravel deposits are limited (found mainly in the buried valleys/drowned beaches of the English Channel and the southern North Sea), extreme care should be taken to use them in a sustainable manner i.e. to reserve them for beach replenishment and not to use them in the construction industry, for which material of lesser quality is sufficient (e.g. Arthurton, 1997; Bates *et al.*, 1997).

Table 5. *Different usage of marine aggregates during the last years (as a percentage of the overall production). Data extracted from Ices, 2002-2006.*
Note: Data for Spain have been extracted from Ices (2006) and data for Belgium are based on an estimation and can be used only as an approximation.

Country	MA extracted (million m^3)	Construction Industry (%)	Beach replenishment (%)	Exports (%)
Belgium	1.63	93.8	6.2	0
Denmark	7.01	59.9	38.8	1.4
France	2.77	nd	nd	0
Germany	7.57	nd	nd	0
Netherlands	29.07	49.2	43.4	7.4
Poland	0.64	2.9	79.6	17.5
Spain	0.48	0	100	0
UK	13.13	66.6	4.8	28.8

Future MA demand

Prediction of the future MA demand is not an easy exercise, as it depends on forecasts of economic growth, the cyclical nature of the construction industry, national and European policies and regulation, the ability of the MA industry to penetrate markets long held by land-won aggregates and related investment (e.g. construction of dredging vessels and wharves). In addition, future demand/supply is dependent on the availability of suitable marine aggregate resources. In the Bristol Channel (UK) for example, certain MA deposits which have been dredged for over 60 years are coming to the end of their exploitation life (Harrison, 2003); likewise, extraction from old Outer Thames Estuary licenses is in decline. However, the UK industry has found significant new reserves in the Eastern English Channel, the Irish Sea and the Bristol Channel (e.g. Seaman, 2006), which could last for some decades at the present rates of extraction, even though special care should be given on the availability of gravelly material which appears to be limited (Arthurton, 1997; Bates *et al.*, 1997; Harrison, 2003).

Future demand figures can be distorted by large "one-off" capital development projects. For example, the UK Lincshore beach replenishment project used 8 million tonnes of marine aggregates (Meakins *et al.*, 1999). In the Netherlands, plans exist to use marine aggregates in major future developments, which will require large quantities of material (Phua *et al.*, 2004).

Within northwestern Europe, only the UK and the Netherlands have produced official estimates of the future demand for marine sand and gravel. For the English part of the UK, the Department of Environment (DOE) (now DEFRA) has estimated that the total aggregate demand in the period 1995-2015 will be up to 7000 million tonnes (Humphreys *et al.*, 1996; Meakins *et al.*, 1999). This demand is not spread evenly; in southeastern England, where outcrops of hard rock suitable for use (after mining and crushing) in the construction industry are not available, land-won and marine sand and gravel are vital for the construction industry (Bates *et al.*, 1997; Gubbay, 2005). Future annual total aggregate demand for the Netherlands (until 2020) has been estimated as 20 million tonnes of gravel, 23 million tonnes of sand for concrete and 53 million m^3 of fill sand (Meakins *et al.,* 1999); 7 out of the 20 million tonnes of gravel will be derived from Dutch land-based sources, whereas it is thought that the remainder will be supplied from recycling and imports. In 1997, the Ministry of Transport, Public Works and Water Management updated their future demand figures for MA extraction from Dutch waters. These updates suggest that for the period 1996-2030 the average annual extraction should be in the order of 30-33 mil-

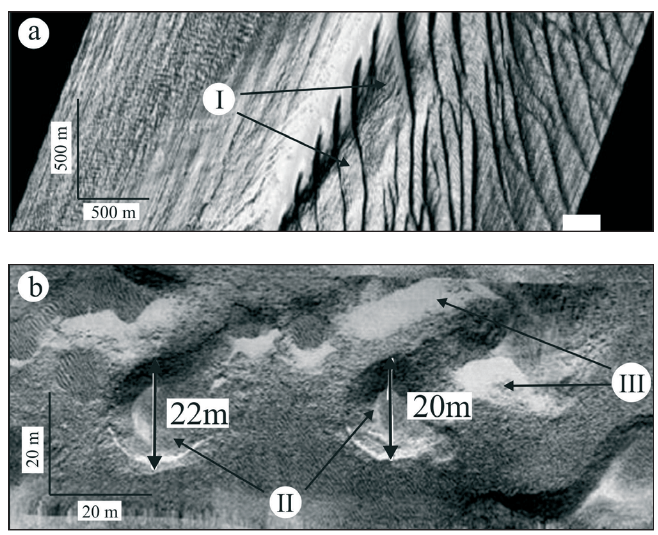


Figure 10. (a) Multibeam image of trailing suction dredging marks from the Kwinte Bank, (Flemish Banks, southern North Sea), adapted from data of The Fund for Sand Extraction, Belgium; and (b) side scan sonar image from the dredging area of Tromper Wiek (German Sector of the Baltic Sea), showing the presence of several anchor dredging pits on the gravelly seabed. Key: I, dredging marks from trailing suction dredger (Figure 10a); II, anchor dredging pits (Figure 10b); III, surficial sand deposits (light areas) on the gravelly (dark) background, formed from the spillage of the sand-size fraction of the dredged material after its screening on the dredging vessel (Figure 10b).

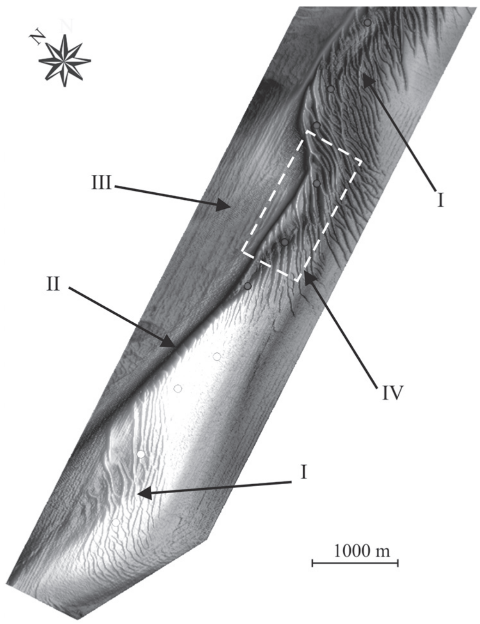


Figure 11. Multibeam image of the Kwinte Bank (Flemish Banks, southern North Sea), adapted from data of The Fund for Sand Extraction, Belgium. Key: I, large subaqueous dunes; II, bank crest; III, poorly-sorted swale sediments; and IV, dredged area.

Table 6. *Main differences between multibeam echosounders and side scan sonars (After Van Lancker, 2003).*

Very-high resolution multibeam system	**Very-high resolution digital side-scan sonar system**
• Highly accurate water depth measurements • Integrated sensors for motion correction or positioning • Provision of (depth- and angle-corrected) backscatter data, expressed in numerical values (dB), allowing quantitative evaluations • Transducers rigidly mounted onto the survey vessel hull or poles, eliminating most casting shadows • Better in deeper waters as swath width depends on water depth • Very-high resolution imagery, but extensive processing time • Sound velocity measurements over the vertical are needed • Expensive system/need for additional sensors • Various corrections required (e.g. systematic errors, tidal effects, heave, vessel lift/squat, antenna motion and internal time delays), particularly in shallow water. Sensor calibration needed.	• Very-high resolution, multi-parameter image obtained in real time • Most systems have no additional sensors for water depth, motion correction or positioning • Backscatter is function of the relief and intrinsic nature of the seafloor and depends on gain settings; thus, only qualitative evaluations are possible • Superior for target detection due to the low grazing angle which produces distinctive shadows behind objects • More efficient bandwidth sampling • Better in shallow waters due to the low grazing angle and swath widths which are independent of water depth • Generally, higher resolution images • Quick processing, but thorough interpretation requires skilled personnel • No calibration required • Cost-friendly system that can easily be deployed from vessels of opportunity

lion m^3 of sand (Meakins *et al.*, 1999). These figures do not take into account additional demand for one-off projects.

It has been estimated that large quantities of marine aggregates (between 6 and 14 million m^3 of sand) will be required for beach replenishment to compensate for sand loss in eroding areas of the Dutch coastline, particularly if the effects of sea level rise are considered (Ron2, 2004; Harte *et al.*, 2003; Van Dalfsen and Essink, 1997). Future annual marine aggregate demand for construction (excluding large infrastructure projects) has been estimated as between 9.3 and 29 million m^3 (Phua *et al.*, 2004). As, however, large land reclamation projects have been planned for the near future, Dutch MA extraction may increase very substantially. The most important of these projects are: the enlargement of the Rotterdam Harbour, which will require up to 300 million m^3 of sand and the Westerschelde (Western Scheldt) Container Terminal (WCT), which will require up to 20 million m^3 (Dhv Milieu & Infrastructuur, 2003).

MA PRODUCTION TECHNIQUES

MA production incorporates 3 main phases: (i) identification of the potential deposit; (ii) evaluation (prospecting) of the deposit and (iii) aggregate mining (extraction). The first phase (identification of a potential deposit, Phase 1) is often linked to other marine research projects such as general geological mapping of the seabed (e.g. Hamblin *et al.*, 1992; Jackson *et al.*, 1995) and/or habitat mapping. If an area appears promising, a prospecting license will be obtained according to the procedures in place in each state (see also Radzevičius *et al.*, this volume) to prospect/evaluate the potential of the deposit in detail (Phase 2). Finally, if the deposit is found to be economically viable, an extraction license is obtained and mining (dredging) commences (Phase 3).

Prospecting techniques

The evaluation of sand and gravel deposits (Phase 2) requires the use of specialized equipment, such as: (a) acoustic (seismic) sources, powerful enough to penetrate the medium- and coarse grained sediments and, at the same time, having sufficient resolution to map accurately the internal architecture of the sedimentary deposit and (b) coring equipment able to penetrate at least 2 to 3 m into a medium- and/or coarse-grained sedimentary sequence. Reviews of seabed mapping techniques already exist (e.g. Kenny *et al.*, 2003). Nevertheless, it is useful to summarise particular techniques used in the marine aggregate prospecting and which are based on the:

- collection of indirect (remotely-sensed) information on the geomorphology/geology of the seabed, using acoustic sources (e.g. single and/or multibeam echosounders, side-scan sonar, continuous seismic profiling equipment) and
- collection of (direct) ground-truth data, using superficial (grab) and sub-bottom (gravity and vibro-core) sediment samplers.

Information from both the direct and indirect methods is combined, as the scope of the prospecting is not only to identify the spatial (horizontal and vertical) extent of the MA deposit, but also to evaluate its quality (i.e. its texture, mineralogy, shell and salt content etc).

Acoustic sources

The acoustic devices used in MA prospecting are differentiated into those that provide information on the seabed geomorphology (bathymetry) and superficial sedimentology of the resource and those that provide information on its thickness and internal architecture (sub-bottom profilers). Depending on the research vessel used and the logistics of the prospecting survey, such equipment can be used either concurrently or sequentially.

Superficial mapping of the MA deposits

The 'work horse' of seabed geomorphological mapping is the side-scan sonar. It provides information (sonographs) on the distribution of the acoustic characteristics of the seabed, on the basis of the intensity of the seabed backscatter of the transmitted acoustic energy front. As the backscatter intensity is controlled by the acoustic reflection coefficient (C_R), which is different for each particular sedimentary material, sedimentary facies (and/or areas of exposed bedrock) can be demarcated on the seabed (Figures 6. and 10b.), provided that the backscatter intensity patterns will be calibrated by sufficient ground truth data (superficial sediment samples). In addition, as bedrock outcrops, sedimentary bedforms and other morphological features produce "acoustic shadows" behind them (Figure 6.), the position, dimensions and symmetry (in the case of sedimentary bedforms) of these features can be estimated from the dimensions of the acoustic shadow and its position relative to the side-scan sonar "fish". However, corrections should be made on the different distortions apparent on the sonographs (e.g. Voulgaris and Collins, 1991), which are nowadays performed by algorithms incorporated within the data acquisition systems of the digital side-scan sonars. The resolution of the sonographs depends on the frequency of the transmitted pulse being commonly between 100 and 500 kHz in the new dual frequency high resolution systems used for the mapping of the marine aggregate deposits.

Multibeam echo-sounders provide both bathymetric and backscatter data of the seabed (Davies *et al.*, 2001). Accurate water depth information concerning the MA deposit is essential for its efficient exploitation, whereas the acoustic backscatter of the transmitted pulses can provide information on the nature of the seabed. Although the multibeam echo-sounders are extremely powerful water depth measuring and imaging devices (Figures 10a. and 11.), they have both advantages and disadvantages concerning the mapping of the acoustic character of the seabed in relation to the side-scan sonar systems (Table 6.).

Thickness and internal architecture of the MA deposit

The MA deposit thickness and architecture are studied using continuous reflection profiling and seismostratigraphic techniques (e.g. McQuillin and Ardus, 1977; Posamentier and Vail, 1988). MA deposit surveying requires high resolution acoustic sources (e.g. sparkers, boomers, chirp and 3.5-2.5 kHz systems), which produce sequences of relatively high frequency acoustic pulses that after their reflection from the seabed and sub-bottom reflectors return to hydrophone strings towed behind the survey vessel to be recorded and provide images of the internal architecture of the deposit (see Figures 1., 2., 3., 4., 5. and 7.). As the frequency and energy of the transmitted acoustic waves control the resolution and penetration, it is important to use the right acoustic source for optimal results. As a general rule, medium- and coarse-grained deposit surveying requires acoustic sources with frequencies equal and/or less than 2.5 kHz, commonly at 500-2000 Hz depending on the texture of the deposit. It should be noted that, as the exploitable MA deposits are located at relatively shallow areas (10-40 m water depths) there are certain difficulties in the interpretation of the acoustic (seismic) records, related to the masking of primary reflections by multiples (see for example Figure 7b.).

Ground-truth data

The remotely-sensed acoustic information requires 'calibration/validation' from ground truth data. These data are either superficial sediment samples collected using Van Veen, Hammon and/or large hydraulic grabs (for the calibration of the side-scan sonar and multibeam images) or sediment cores (for the calibration of sub-bottom profiling data). The preferred coring equipment is the vibro-core, as it can achieve satisfactory penetration into the medium- and coarse-grained sediments of the MA deposits. The ground truth data not only calibrate/validate the acoustic data allowing volume estimations but, they provide also information on the quality of the MA deposit (e.g. on its grain-size, mineralogy and carbonate, organic matter and chloride content) through the analysis of the recovered sediment samples.

The prospecting data can also be used to provide essential information on the mobility/morphodynamics of the MA deposit (Brampton *et al.*, 1998) and to map its habitats, which are essential components of the required environmental impact assessment of the exploitation of the deposit (Radzevičius *et al.*, this volume; Vivian, 2003). It must be noted, however, that both the collection and the interpretation of the relevant information require careful analysis and skilled personnel, otherwise serious errors may arise in the evaluation and subsequent exploitation of the deposits (Velegrakis, Gao, and Collins, 1994).

Extraction

The type of dredging vessel is usually determined by the existing regulatory regime, economic considerations, contactor requirements and site conditions. Nowadays, dredging vessels operate around the clock, 365 days a year. In the UK, the construction cost of a modern tailing suction vessel is around £15-20 million (22-30 million €). A modern large dredger can extract and load some 5,000 tonnes of marine sand and gravel from 40-60 m water depths in 3 hours, with overall operational cycles usually between 12 and 36 hours, depending upon the port of discharge (Bates *et al.*, 1997).

Two main types of dredging vessels are used for marine sand and gravel extraction: (i) trailer suction dredgers and (ii) anchor suction dredgers (see for example IHC, 2007). The former can operate under relatively rough sea conditions, extracting sediments through their suction 'pipes' while steaming over the deposit; they operate very much like moving 'vacuum cleaners', resulting in the development of suction furrows (up to 1 m deep) on the sedimentary bed (see Figure 10a.). The aggregates are emptied by opening bottom hatches or by pumps. Because of their high production rates, these dredgers carry out most land reclamation projects and are also suitable for harbour maintenance dredging and pipe trenching. The latter extract sediments while anchored and the suction method employed results in the development of suction pits (Figure 10b.). These vessels can operate in relatively deep waters, but they are sensitive to strong currents and rough weather conditions; moreover, they are not suitable for channel/harbour construction projects, as they produce confined excavations. This method is now prohibited in some EU Member States (e.g. Belgium), as it is considered to have large environmental impacts.

Dredging activities are subject to environmental impact assessments and should be controlled by the competent regulatory authorities (see RADZEVIČIUS *et al.*, this volume). In several (but not all as it should) EU Member States, dredging vessels are required to be equipped with Electronic Monitoring Systems ("black boxes"), which allow the monitoring of their activities and their compliance with the licensing terms.

SUMMARY AND CONCLUSIONS

Marine aggregates are a mineral resource of increasing importance for the EU Member States. Additional resources are needed to meet future demand, which is bound to increase substantially due to both increasing coastal zone development and the need to battle accelerating coastal erosion effectively. However, in order to develop an effective and sustainable European strategy, several problems facing the industry should be addressed. These include (amongst others): lack of standardisation of the relevant information, difficulties related to the access to information and the presence of barriers between the scientific research establishments and the marine aggregate industry.

This review has shown that there are serious standardization issues as well as important information gaps that hinder the sustainable development of the industry. With the exception of few Member States, the situation is rather discouraging, particularly in the Mediterranean countries. In some cases, it has shown to be very difficult to access the relevant information (e.g. production volumes, resource estimates), as this is scattered between several organizations. It is important that these issues should be addressed as quickly as possible, possibly through European-wide initiatives.

Although the technology and 'know-how' are available, it appears that these are seldom employed in the discovering and evaluation of new marine aggregate resources. Hence, multibeam echosounding techniques are used rarely and the same is true for the modern techniques in the acquisition and interpretation of the remainder of the acoustic data. These problems appear to be related to an apparent lack of coordination between the scientific research establishments and the MA industry, which is endemic in most EU Member States. A closer collaboration between them would not only have substantial benefits for both, but it would also prove to be cost-effective.

Finally, it should be kept in mind that marine aggregates are finite, being a non-renewable resource. Therefore, they should be used in a sustainable manner and effective policies/administrative frameworks should be developed to address future shortages, particularly with regard to certain types of material (e.g. gravel).

ACKNOWLEDGEMENTS

The authors acknowledge the support of European Commission through the EU-RTN FP5 Project EUMARSAND (Contract HPRN-CT-2002-00222). Dr A. Brampton and two other anonymous reviewers are thanked for their constructive comments which improved the manuscript.

LITERATURE CITED

ALLEN, G.P. and POSAMENTIER, H.W., 1993. Sequence stratigraphy and facies model of an incised valley fill: the Gironde Estuary, France. *Journal of Sedimentary Petrology*, 63, 378-391.

ANTOINE, P.; COUTARD, J.-P.; GIBBARD, P.L.; HALLEGOUET, B.; LAUTRIDOU, J.-P., and OZOUF, J.-C., 2003. The Pleistocene rivers of the English Channel region. *Journal of Quaternary Science*, 18(3-4), 227-243.

AQUATER, 1982. Studio generale per la difesa della costa. *Prima Fase*, Vol. 2, 90-196.

ARNAUD-FASSETTA, G., 2003. River channel changes in the Rhone Delta (France) since the end of the Little Ice Age: Geomorphological adjustement to hydroclimatic change and natural resource management. *Catena*, 51, 141-172.

ARTHURTON, R., 1997. Offshore sand and gravel resources and the need for careful management. *In*: EARLL, R. (ed.), *Marine Environmental Management: A Review of past and Future Trends* No. 4, pp.19-22.

ASHLEY, G.M.; BOOTHROYD, J.C.; BRIDGE, J.S.; CLIFTON, H.E.; DALRYMPLE, R.W.; ELLIOT, T.; FLEMMING B.W.; HARMS, J.C.; HARRIS, P.T.; HUNTER, R.E.; KRIESA, R.D.; LANCASTER, N.; MIDDLETON, G.V.; PAOLA, C.; RUBIN, D.M.; SMITH, J.D.; SOUTHARD, J.B.; TERWINDT, J.H.J., and TWITCHELL, D.C. Jr., 1990. Classification of large scale subaqueous bedforms: a new look at an old problem. *Journal of Sedimentary Petrology*, 60, 160-172.

BATES, R.; VELEGRAKIS, A.F.; BRAND, C.; COLLINS, M.B., and NUNN, A., 1997. Deep Water and Inshore Aggregates Exploitation. *Research Report for the Countryside Council of Wales*. 91 p.

BELDERSON, R.H.; JOHNSON, M.A., and KENYON, N.H., 1982. Bedforms. *In*: STRIDE, A.H. (ed.), *Offshore Tidal Sands: Processes and Deposits*. London: Chapman and Hall, pp. 27-57.

BELLEC, V.; DIESING, M., and SCHWARZER, K., this volume. Last Quaternary evolution of a gravel area located on the Tromper Wiek. *Journal of Coastal Research*.

BIRKLUND, J. and WIJSMAN, J.W.M., 2005. Aggregate Extraction: A Review of the Effect on Ecological Functions. DHI Water and Environment and WL/Delft Hydraulics (SANDPIT Project), *Technical Report Z3297.10*

Blazhchishin, A.I., 1976. Types of bottom sediments. *In*: Gudelis, V. and Emelyanov, E. (eds.), *Geology of the Baltic Sea*. Vilnius, Mokslas, pp. 187-212. (In Russian).

Bmapa, 2004. Marine Aggregate Dredging 2004: The Area Involved. *The Crown Estate/British Marine Aggregate Producer Association*, 7th annual Report, 4 p.

Bmapa, 2005. Aggregates from the Sea: Drawing Strength from the Depths. *British Marine Aggregate Producer Association*. 6 p. www.bmapa.org.

Brampton, A.; Evans, C.D.R., and Velegrakis, A.F., 1998. South Coast Mobility Study. London, UK: *CIRIA PR65*, 201 p.

Collins, M.B.; Shimwell, S.; Gao, S.; Powell, H.; Hewitson, C., and Taylor, J. A., 1995. Water and sediment movement in the vicinity of linear sandbanks: The Norfolk Banks, southern North Sea. *Marine Geology*, 123, 125-142.

Ceda, 1993. Marine sand and gravel in the EC seas, *CEDA Report 93/01*, 46 p.

Dal Cin, R., 1983. I litorali del delta del Po e alle foci dell'Adige e del Brenta: Caratteri tessiturali e dispersione dei sedimenti, cause dell'arretramento e previsioni sull'evoluzione futura. Boll. Soc. Geol. It., 102, 9-56.

Dalrymple, R.W.; LeGresley, E.M.; Fader, G.B.J., and Petrie, B.D., 1992. The western Grand Banks of Newfoundland: Transgressive Holocene sedimentation under the combined influence of waves and currents. *Marine Geology*, 105, 95-118.

Davies, J.; Baxter, J.; Bradley, M.; Connor, D.; Khan, J.; Murray, E.; Sanderson, W.; Turnbull, C., and Vincent, M., 2001. Marine Monitoring Handbook, *Joint Nature Conservation Committee, UK, ISBN 1-86107-524-3*, 405 p.

Dean, R.G., 2002. *Beach Nourishment: Theory and Practice*. Advanced series on Ocean Engineering, Vol. 18, New Jersey: World Scientific Publishing, 399 p.

Degrendele, K.; Roche, M.; Schotte, P.; Van Lancker, V.; Bellec, V., and Bonne, W., this volume. Morphological evolution of the Kwinte Bank central depression before and after cessation of aggregate extraction. *Journal of Coastal Research*.

De Vree, 2003. Quality demands on aggregates-European standards. *EMSAGG Bulletin, Special Edition April 2003*, 2 p.

Dhv Milieu & Infrastructuur, 2003. Zeeland Seaports- MER(EIA) Zandwinning WCT, Amersfoort.

Dyer, K.R. and Huntley, D.A., 1999. The origin, classification and modelling of sand banks and ridges. *Continental Shelf Research*, 19, 1285-1330.

Eurosion, 2003. Trends in Coastal Erosion in Europe. Final Report of the Project Coastal Erosion – Evaluation of the Need for Action. Directorate General Environment, European Commission, 72 p.

Fletcher III, C.H.; Knebel, H.J., and Kraft, J.C., 1992. Holocene depocenter migration and sediment accumulation in Delaware Bay: a submerging marginal marine sedimentary basin. *Marine Geology*, 103, 165-183.

Folk, R.L., 1980. *Petrology of the Sedimentary Rocks* (2nd Edition). Austin, Texas: Hemphill Publishing Company, 182 p.

Gibbard, P.L., 1988. The history of the great northwest European rivers during the past three million years. *Philosophical Transactions of Royal Society of London*, B 318, 559-602.

Gubbay, S., 2003. Marine Aggregate Extraction and Biodiversity. *Joint Marine Program of the Wildlife Trusts and WWF-UK,* 24 p.

Gubbay S., 2005 A Review of Marine Aggregate Extraction in England and Wales, 1970-2005. 36 p. www.crownestate.co.uk (accessed 10.2006)

Hamblin, R.J.O.; Crosby, A.; Balson, P.S.; Jones, S.M.; Chadwick, R.A.; Penn, I.E., and Arthur, M.J., 1992. The Geology of the English Channel. London: *British Geological Survey Report, HMSO*.

Hamilton, E.I.; Watson, P.G.; Cleary, J.J., and Clifton, R.J., 1979. The geochemistry of recent sediments of the Bristol Channel-Severn Estuary system. *Marine Geology*, 31, 139-182.

Harrison, D.J., 2003. European overview of marine sand and gravel. European Marine Sand and Gravel – Shaping the Future. *EMSAGG Conference* (Delft University, Netherlands), 3 p.

Harte, M.; Huntjens, P.M.J.M.; Mulder, S., and Raadschelders, E.W., 2003. Zandsuppleties en Europese Richtlijnen. Ecologische effecten boven water gehaald. Maart. *Ministerie van Verkeer en Waterstaat. Rijksinstituut voor Kust en Zee*.

Helcom, 1998. HELCOM Recommendations 19/1 on Marine Sediment Extraction in the Baltic Sea Area. http://www.helcom.fi/Recommendations/en_GB/rec19_1/.

Herrmann, C.; Krause, J.C.; Tsoupikova, N., and Hansen, K., 1999. Marine Sediment Extraction in the Baltic Sea: Status Report. *Baltic Sea Environment Proceedings No.76* (Helsinki Commission (HELCOM), Baltic Marine Environment Protection Commission), 50 p.

Humphreys, B.; Coates, T.; Watkiss, M., and Harrison, D., 1996. Beach Recharge Materials: Demand and Resources. *CIRIA Technical Report No. 154*, Construction Industry Research and Information Association, London. 176 p

Ices, 1995. Report of the Working Group on the Effects of Extraction of Marine Sediments on the Marine Ecosystem (WGEXT). Dublin, Ireland 25-28 April 1995. *ICES C.M. 1995/E:5,* 44 p.

Ices, 2000. Report of the Working Group on the Effects of Extraction of Marine Sediments on the Marine Ecosystem (WGEXT), 11–14 April 2000, Gdansk, Poland. *ICES CM 2000/E:07,* 172 p.

Ices, 2001. Report of the Working Group on the Effects of Extraction of Marine Sediments on the Marine Ecosystem (WGEXT). Stromness, Orkney, Scotland 3–6 April 2001. *ICES CM 2001/E:06,* 84 p.

Ices, 2002. Report of the Working Group on the Effects of Extraction of Marine Sediments on the Marine Ecosystem (WGEXT). Boulogne-sur-Mer, France 9–13 April 2002. *ICES CM 2002/E:06*, 124 p.

Ices, 2003. Report of the Working Group on the Effects of Extraction of Marine Sediments on the Marine Ecosystem (WGEXT), 1–5 April 2003, Ostend, Belgium. ICES *CM 2003/E:07*, 104 p.

Ices, 2004. Report of the Working Group on the Effects of Extraction of Marine Sediments on the Marine Ecosystem (WGEXT), 30 March–2 April 2004, Isle of Vilm, Germany, *ICES CM 2004/E:07*, 102 p.

Ices, 2005. Report of the Working Group on the Effects of Extraction of Marine Sediments on the Marine Ecosystem (WGEXT). San Sebastián, Spain 5–8 April, *ICES CM 2005/E:06*, 102 p.

Ices, 2006. Report of the Working Group on the Effects of Extraction of Marine Sediments on the Marine Ecosystem (WGEXT). 4-7 April 2006, Cork, Ireland, *ICES CM 2006/E:06,* 91p.

Idroser, U., 1994. *Aggiornamento ed Integrazione del Piano Progettuale per la Difesa della Costa Adriatica Emiliano-Romagnola, Relazione Generale*. Regione Emilia-Romagna, Bologna: ED, 276 p.

Ifremer, 2007. http://www.ifremer.fr/drogm_uk/Realisation/Miner/Sable/presentation.htm.

Ihc, 2007. http://www.ihcholland.com/topleft-menu/news-and-events/newspages/products-and-services/dredging-equipment/

Jackson, D.I.; Jackson, A.A.; Evans, D.; Wingfield, R.T.R.; Barnes, R.P., and Arthur, J., 1995. The Geology of the Irish Sea. UK, *United Kingdom Offshore Regional Report, British Geological Survey, HMSO.*

James, J.W.S.; Harrison, D.J., and Ciavola, P., 1992. Marine Aggregate Survey, Phase 4: Irish Sea. Nottingham, UK, *British Geological Survey Marine Report WB/92/10.*

Jewell, T., 1996. Mineral Extraction. *In*: Hughes, D. (ed.), *Environmental Law* (3rd Ed.). Butterworths, London Bell, pp.333-362.

Kennedy, W.J. and Garrison, R.E., 1975. Morphology and genesis of nodular chalks and hardgrounds in the Upper Cretaceous of Southern England. *Sedimentology*, 22, 311-386.

Kenny, A.J.; Cato, I.; Desprez, M.; Fader, G.; Schuttenhelm, R.T.E., and Side, J., 2003. An overview of seabed-mapping technologies in the context of marine-habitat classification. *ICES Journal of Marine Science*, 60, 411-418.

Kenyon, N.H., 1970. Sand ribbons of European tidal seas. *Marine Geology*, 9, 25-39.

Kenyon, N.H. and Stride, A.H., 1970. The tide-swept continental shelf sediments between the Shetland Isles and France. *Sedimentology*, 14, 159-173.

Kenyon, N.H.; Belderson, R.H.; Stride, A.H., and Johnson, M.A., 1981. Offshore tidal sandbanks as indicators of net sand transport and as potential deposits. International Association of Sedimentologists Special Publication No. 5, pp. 257-268.

Leeder, M.R., 1999. *Sedimentology and Sedimentary Basins: from Turbulence to Tectonics*. Oxford: Blackwell Science, 591 p.

Loman, G., 2006. BeauDredge, a new environmental friendly dredging technique developed by Boskalis for lowering various ground surfaces. *EMSAGG Bulletin No. 12*, pp. 3-4.

Marchetti, M., 2002. Environmental changes in the central Po plain (northern Italy) due to fluvial modifications and anthropogenic activities. *Geomorphology*, 44, 361-373.

McLean, S.R., 1981. The role of non-uniform roughness in the formation of sand ribbons. *Marine Geology*, 42, 49-74.

McManus, D.A., 1975. Modern versus relict sediments on continental shelf. *Geological Society America Bulletin*, 86, 1154-1160.

McQuillin, M. and Ardus, C., 1977. *Exploring the Geology of the Shelf Seas*. Graham and Trotman Ltd. 234 p.

Meakins, S.C.; Leggett, D.J.; Arthurton, R.A.; Harrison, D., and Humphreys, B., 1999. The Development of Marine Sand and Gravel in Northwestern Europe - Identifying the Issues over the next 25 years, *CIRIA Report PR 68.*

Nielsen, P. and Jensen, J.B., 2003. Marine resources in Danish waters – Exploitation potential and sustainable management. European marine sand and gravel – shaping the future. *EMSAGG Conference,*(Delft University, Netherlands), 4 p.

Pattiaratchi, C. and Collins, M.B., 1987. Mechanisms for linear sandbank formation and maintenance in relation to dynamical oceanographic observations. *Progress in Oceanography*, 19, 117-176.

Pettijohn, F.G.; Potter, P.D., and Siever, R., 1972. Sand and Sandstone. New York: Springer-Verlag, 618 p.

Phua, C.; Van Den Akker, S.; Baretta, J., and Van Dalfsen, M., 2004. Ecological Effects of Sand Extraction in the North Sea. *Report*, 22 p.

Posamentier, H.W. and Vail, P.R., 1988. Eustatic controls on clastic deposition II- sequence and systems tract models. *In*: Wilgus, C.K.; Hastings, B.S.; Kendall, C.G.; Posamentier, H.W.; Ross, C.A., and Van Wagoner, J.C. (eds.), *Sea Level Change- An Integrated Approach.* Society of Economic Palaeontologists and Mineralogists, Special Publications, 42, pp. 125-154.

Radzevičius, R.; Velegrakis, A.F.; Bonne, W.; Kortekaas, S.; Garel, E.; Blažauskas, N., and Asariotis, R., this volume. Marine aggregate extraction: regulation and management in EU Member States. *Journal of Coastal Research.*

Reynaud, J.Y.; Tessier, B.; Berne, S.; Chamley, H., and Debatist, M., 1999. Tide and wave dynamics on a sand bank from the deep shelf of the Western Channel approaches. *Marine Geology*, 161(2-4), 339-359.

Ron2, 2004. Regionale Ontgrondingenplan Noordzee 2. Ministerie van Veerker en Waterstaat, Rijkswaterstaat 83 p. http://nzl-www.sentia.nl/Images/RON2_tcm14-2777.pdf.

Seaman, K., 2006. Turning gravel into gold- the growing role of the Bristish marine aggregate industry. Paper submitted *to 2nd EMSAGG Conference*, London, 21st February 2006.

Selby, A. and Ooms, D.F., 1996. Assessment of offshore sand and gravel for dredging. *Terra et Aqua*, 64, 18-28.

Schotte, P.A.J., 2003. Belgian governmental control on the extraction of marine sand and gravel. European marine sand and gravel – shaping the future. *EMSAGG Conference(Delft University, The Netherlands)*, 4 p.

Schwarzer, K.; Diesing, M., and Manso, T., this volume. Review of marine aggregate deposits and exploitation in the non tidal Baltic Sea. *Journal of Coastal Research.*

Smith, A.J., 1985. A catastrophic origin for the palaeovalley system of the eastern English Channel. *Marine Geology*, 64, 65-75.

Smith, A.J., 1989. The English Channel-by geological design or catastrophic accident? *Proceedings of the Geologists' Association*, 100, 325-337.

Uscinowicz, S.; Kramarska, R.; Maslowska, M., and Zachowicz J., 2003. Exploration and extraction of sand and gravel resources in the Polish Exclusive Economic Zone of the Baltic Sea. European marine sand and gravel – shaping the future. *EMSAGG Conference (*Delft University, the Netherlands), 4 p.

Van Dalfsen, J.A. and Essink, K., 1997. Risk analysis of coastal nourishment techniques in the Netherlands (RIACON). *National Institute for Coastal and Marine Management/RIKZ.*

Van Lancker, V. 2003. *Tools in Oceanography*. Marine and Lacustrine Sciences Course Lecture Notes. Ghent University.

Van Lancker, V.; Bonne, W.; Velegrakis, A.F., and Collins, M.B., this volume. Aggregate extraction from tidal sandbanks: is dredging with nature an option? An introductory perspective. *Journal of Coastal Research.*

Velegrakis, A.F., Gao, S., and Collins, M.B., 1994. Independent Assessment of the Marine Aggregate Extraction from Hastings Shingles Bank. Southampton, UK: University of Southampton, Department of Oceanography, *Technical Report SUDO/TEC/94/15/C,* 70 p.

Velegrakis, A.F.; Lee, M.W.E.; Dix, J.K., and Collins, M.B., 1996. Evaluation of waste coal deposits offshore Lavernock Point, Bristol Channel. Southampton, UK: University of Southampton, Department of Oceanography, *Technical Report SUDO/TEC/96/1/C,* 85 p.

Velegrakis, A. F.; Dix, J.K., and Collins, M.B., 1999. Late Quaternary evolution of the upper reaches of the Solent River, southern England, based upon marine geophysical evidence. *Journal of Geological Society of London*, 156, 73-87.

Velegrakis, A.F.; Collins, M.B.; Owrid, G., and Houghton, A., 2001. Sandbanks of the European shelf. Southampton, UK: University of Southampton, School of Ocean and Earth Science to WWF, *Technical Report SOES/TEC/00/3/C,* 401 p.

Velegrakis, A.F.; Collins, M.B.; Bastos, A.C.; Paphitis, D., and Brampton, A., 2007. Seabed sediment transport pathway investigations: review of scientific approach and methodologies. *In*: Balson, P.S. and Collins, M.B. (eds.), *Coastal and Shelf Sediment Transport.* Geological Society of London Special Publication No. 274, pp. 127-146.

Vincent, C.E.; Stolk, A., and Porter, C.F.C., 1998. Sand suspension and transport on the Middelkerke Bank (southern North Sea) by storms and tidal currents. *Marine Geology*, 150, 113-129.

Visser, 2007. Bert Visser's Directory of Dredgers. http://www.dredgers.nl

Vivian, C., 2003. UK Approach to Environmental Assessment of Sand and Gravel Dredging Proposals. European marine sand and gravel – shaping the future, *EMSAGG Conference*,(Delft University, The Netherlands), 6 p.

Voulgaris, G. and Collins, M.B., 1991. Linear features on side-scan sonar images: an algorithm for the correction of angular distortion. *Marine Geology*, 96, 187-190.

Journal of Coastal Research	SI	51	15-38	West Palm Beach, Florida	Summer 2010

Marine Aggregate Extraction Regulation in EU Member States

Rolandas Radzevičius[1,*], Adonis F. Velegrakis[1], Wendy Bonne[2***], Stella Kortekaas[3****], Erwan Garel[4*****], Nerijus Blažauskas[5******] and Regina Asariotis[6+]**

[1] Department of Marine Sciences
School of Environment
University of the Aegean. University Hill
Mytilene 81100, Greece

[*] Present address: Department of Marine Research
Institute of Geology and Geography
Vilnius 03223, Lithuania

[**] corresponding author afv@aegean.gr

[2] AZTI Foundation
Marine Research Division
Herrera Kaia - Portualdea z/g
20110 Pasaia (Gipuzkoa), Spain

[***] Present address: Federal Public Service
DG General Environment, Marine Environment Service
Victor Hortaplein 40 box 10
B-1060 Brussels, Belgium

[3] Coastal Geomorphology and Shoreline Management Unit
Université du Littoral-Côte d'Opale
189a Avenue Maurice Schumann
59140 Dunkerque, France

[****] Present address: Fugro Engineers B.V.
Veurse Achterweg 10
P.O. Box 250
2260 AG Leidschendam, The Netherlands

[4] School of Ocean and Earth Science
National Oceanography Centre, Southampton
University of Southampton
European Way, Southampton, UK

[*****] Present address: CIACOMAR
University of Algarve
Avenida 16 de Junho
8700-311 Olhão, Portugal

[5] Maritime Institute in Gdansk
Dlugi Targ 41-44
PL 80-830 Gdansk, Poland

[******] Present address: Coastal Research and Planning Institute
Klaipėda University
H. Manto 84, 92294 Klaipėda, Lithuania

[6] Policy and Legislation Section
UNCTAD
Palais des Nations
1211 Geneva, Switzerland

+ Any views expressed here are those of the author and do not reflect the views of the UNCTAD secretariat.

ABSTRACT

This paper provides a brief review of regulations and procedures relevant to the authorization of marine aggregate (MA) operations in eight EU Member States. MA operations are affected by a multi-level legislative/regulatory regime, consisting of international conventions (e.g. the UNCLOS 1982, OSPAR, Helsinki, ICES, Barcelona and Espoo Conventions), secondary EC legislation (e.g. the Environmental Impact Assessment Directives (85/337/EEC and 97/11 EC) and the Freedom of Access to Environmental Information Directive (2003/4/EC)) and national legislation or regulation.
It appears that rules and procedures relevant to MA extraction vary considerably between the considered Member States. In general, relevant information is not easily available in accurate, comprehensive and up-to date form. As a result, it is difficult to assess whether and to which extent national practice in relation to MA extraction authorization is in substantive compliance with the requirements of existing international and European rules and regulations aimed at sustainable development and protection of the marine and coastal environment.

ADDITIONAL INDEX WORDS: *Marine aggregates, aggregate mining licensing, environmental law and regulation, marine sand and gravel, environmental impact assessment.*

INTRODUCTION

In the past three decades, marine aggregates (MA)[1] have emerged as an important mineral resource in a number of European Member States, particularly in the Netherlands, the UK[2] and Denmark (Velegrakis *et al.*, this volume) and, to a lesser extent, in Belgium, Germany, France and Poland (ICES 2001; 2003a; 2004; 2005; 2006, 2007). MA exploitation/extraction[3] has become an increasingly important activity due to (a) stricter mining regulations (Jewell, 1996; Pring, 1999) and growing social resistance against land aggregate extraction (Phua *et al.*, 2004) and (b) increasing general demand (Birklund and Wijsman, 2005; and Meakins *et al.*, 1999).

In the near future, extraction is bound to increase from the current levels in order to provide the marine aggregates needed for the realisation of large-scale infrastructure projects planned for the European coastal areas[4]. At the same time, since Eu-

[1] Non-metallic marine sediment deposits (sands and gravels), used in the construction industry (e.g. in the construction of highways and buildings), as fill material and in beach replenishment, dune restoration, and foreshore nourishment (http://www.walesenvtrust.org.uk/content.asp?id=548). The marine aggregate industry classifies granular sedimentary material consisting of particles with diameters ranging between 0.063 and 4 (or 5) mm as sand, and material with particle-sizes greater than 4 (or 5) mm as gravel.

[2] Mostly in England and Wales (http://www.crownestate.co.uk/).

[3] MA extraction is a mining activity carried out in shallow marine areas (usually up to 45-50 m water depth) with the sole purpose of collecting granular sedimentary material to be used as aggregates. Bottom sediment removal and disposal related to the excavation/deepening of navigation channels and berths or other marine construction works (see, for example http://en.wikipedia.org/wiki/Dredging; http://www.iadc-dredging.com/index2.html; http://www.mceu.gov.uk/mceu_local/FEPA/MENU-IE.HTM) are beyond the scope of this contribution and will not be considered.

[4] For example, the construction of the deep-water port of Jade Weser Port (Wilhelmshaven) for large container vessels and the airport facilities for the new mega-airliner A 380 in Hamburg-Finkenwerder in Germany require 50 and 12.5 x 10^6 m^3 sand respectively (http://www.dredging-in-germany.de). In the Netherlands, the enlargement of the Rotterdam harbour (MV2) and the construction of the Westerschelde Container Terminal (WCT) require 250-300 x 10^6 m^3 and 20 x 10^6 m^3 sand, respectively (Van Dalfsen *et al.*, 2004), which are planned to be extracted from the

DOI: 10.2112 / SI51-003.1 received 23 January 2007; accepted in revision 12 February 2008.

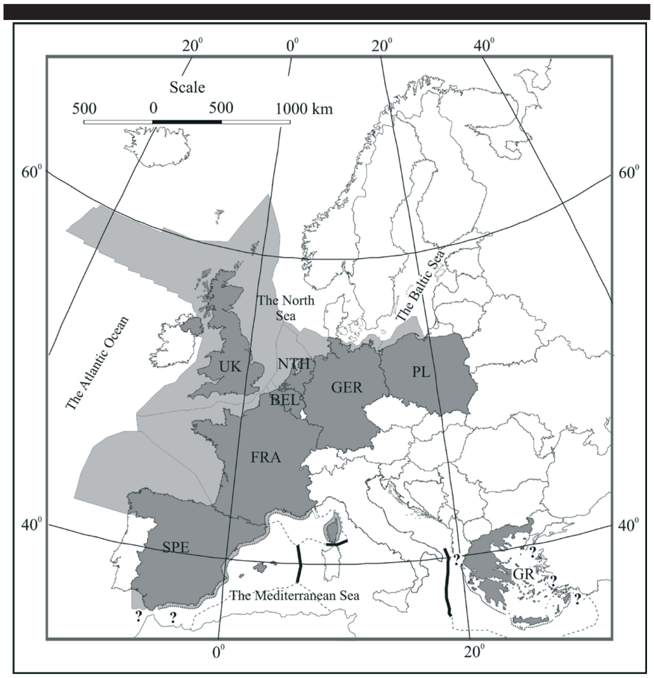


Figure 1. Overview map of 8 EU Member States which were considered and involved in the EUMARSAND Project. (Note: The map does not give the exact boundaries of maritime areas of the coastal states). Key: BEL, Belgium; FRA, France; GER, Germany; PL, Poland; NTH, The Netherlands; SPE, Spain; GR, Greece; and UK, The United Kingdom. The Atlantic and Baltic waters under the jurisdiction (including the Territorial Waters (TW) and the Exlusive Economic Zones (EEZ)) of 7 EU Member States and the Mediterranean waters (only the TW)under the jurisdiction of 2 EU Member States are shown in light grey. In the Mediterranean Sea, the bold line shows the agreed boundaries between two coastal states, whereas the dash line shows the median line between coastal states and the question-marks the interrogation points between two coastal states. Adapted from the WWF/S.Christiansen (see Unger, 2004), Alsied, 2006, Polish Geological Institute (see http://www.pgi.gov.pl/), http://www.offshore-sea.org.uk/site/scripts/sea_archive.php, and BSH maps (see http://www.bsh.de/en/).

ropean coasts are under increasing coastal erosion (Eurosion, 2003; 2004a and 2004b), coastal protection schemes (e.g. Dean, 2002) requiring large quantities of marine aggregates[5] are necessary in order to facilitate and manage coastal zone development (Humphreys *et al.*, 1996; Phua *et al.*, 2004; and Van Dalfsen *et al.*, 2004). New resources must be found and, at the same time, diverse environmental and economic concerns must be addressed.

Mineral resource exploitation affects all environmental media. Pring (1999) states that "*mining inherently implies environmental degradation...[it] is not an environmentally-friendly activity*". MA extraction, in particular, may have significant effects on the coastal water quality, the seabed and the associated flora and fauna and influence significantly the coastal zone morphodynamics (Birklund and Wijsman, 2005; Brampton, Evans, and Velegrakis, 1998; De Groot, 1996; Ellis and MacDonald, 1998; Gubbay, 2003; and Kenny and Rees, 1994; 1996); it must be noted that, as the operating costs of dredging are generally high and increase with the distance from the landing ports and the depth of the deposits, marine aggregate extraction takes place at water depths less than 45-50 m[6]. There are also potential conflicts of interest between the MA industry and other shallow marine water users, such as the fishing, shipping and the oil industries, due to competing demands for space, access and usage (Barry, Elema, and Van Der Molen, 2003; BMAPA, 1995; and Netherlands Ministry of Housing, 2001).

Gradual depletion of the easily accessible resources, coastal ecosystem conservation and diverse stakeholder interests require that resource sustainability, environmental prudence and careful management should be crucial components of the practice and regulation of MA operations; moreover, they demand the development of coherent policies/regulations on the licensing and practice of offshore mining operations. However, it is not clear whether the current regulatory framework governing MA operations in EU Member States adequately reflects the above considerations, as no comprehensive review of MA regulation appears to have been carried out so far.

The present contribution attempts to provide an overview of the regulation of MA operations[7] in a number of European Member States (Figure 1) to help identify existing discrepancies and weaknesses and provide some necessary background for potential areas for improvement. The specific objectives of this contribution are to:

(i) describe the current regulatory regimes governing MA extraction/exploitation activity in several EU Member States and their relation to the relevant international and supra-national environmental legislation; and

(ii) provide some tentative comment on whether the identified existing regulatory regime succeeds in effectively addressing concerns regarding the environmental impact of marine aggregate extraction.

THE RELEVANT REGULATORY REGIME

Marine resource exploitation is commonly regulated according to two different regimes, both of which are designed to prevent overexploitation and ensure nature conservation. The first of these regimes, which is the subject matter of this contribution, governs mainly the activity-based management. The second regime, which is beyond the scope of this contribution, applies to marine areas, which enjoy special protection status (e.g. Marine Protected Areas, MPAs) and are subject to particular protection regulations[8].

Activity-based management measures are predominantly sector-based regulations which, in the case of the MA industry, are dealing with the different stages of exploitation i.e.

North Sea. Moreover, huge quantities of marine aggregates will be needed for the construction of the new London Olympic facilities.

5 For example the future need of sand for beach nourishment in the Netherlands is predicted to be between 9.8 and 14 x 10^6 m^3 per year (Van Dalfsen *et al.*, 2004) and in Germany at least 1.3 x 10^6 m^3 per year (in Schleswig-Holstein and Mecklenburg-Western Pomerania) (http://www.dredging-in-germany.de).

6 See http://www.ihcholland.com/t/ihcholland_com/; http://www.ukdredging.com/our_services/dredging.htm and http://www.dredging.com/).

7 Every effort has been made to identify primary sources of legislation/regulation using information available electronically in the public domain (information accurate as in February 2008). However, in some cases reliance had to be placed on secondary sources, which are identified as appropriate.

8 For details and analysis of these regulatory regimes, see, for example, Gubbay (2004); (2005a); (2005b); Richartz and Sporrong (2003) and Schmidt and Christiansen (2004).

resource exploration (prospecting) and its licensing and mining operations and their licensing[9]. The legal and institutional framework which controls these operations will be considered with regard to: (i) seabed ownership/private property rights and their transfer to another public or private entity for the purpose of MA extraction and the relevant administrative regulation (e.g. prospecting regulation, data management and exploitation licensing); and (ii) the environmental impact assessment (EIA) of MA operations, so as to help consider how effective the existing regulations are in terms of environmental protection/ conservation (e.g. environmental impact assessment of MA extraction, operation monitoring, liability and sanctions).

As the relevant regulation consists of several layers or levels (i.e. international, European and national), these need to be taken into account and presented in context. The international dimension will be presented by way of an overview of the most relevant Conventions, in particular the UN Convention on the Law of the Sea (UNCLOS) 1982, the OSPAR Convention 1992, the HELSINKI Convention 1992, the Barcelona Convention 1995, the ICES Convention 1964 and the ESPOO Convention 1991 together with its 2003 SEA Protocol. The European dimension will be considered by reviewing relevant EC Directives, in particular the Environmental Impact Assessment Directives (85/337/EEC and 97/11 EC), the Strategic Environmental Assessment Directive (2001/42/EC), the Freedom of Access to Environmental Information Directive (2003/4/EC) and the Habitats (92/43/EEC) and Wild Birds (79/409/EEC) Directives. Finally, the national dimension will be presented by considering the national legislation/regulation in eight EU Member States, namely the United Kingdom, Germany, Spain, France, the Netherlands, Poland, Belgium and Greece. Information available as of the end of November 2007 has been taken into account.

INTERNATIONAL CONVENTIONS

Marine environmental policy development takes place within a framework of over 70 international and regional conventions and agreements; however, only a few of these directly affect MA operations.

The United Nation Convention on the Law of the Sea 1982 (UNCLOS)

The 1982 UNCLOS[10], which has been adopted by all of the EU Member States under consideration here[11], provides for the delimitation of maritime zones[12] and prescribes a detailed overarching international legal framework of rights and obligations in respect of usage, development and preservation for these zones, including resource mining. According to the 1982 UNCLOS, the starting point for the delimitation of the different maritime zones is the baseline[13]. Coastal States are entitled to claim territorial seas[14] up to 12 nautical miles wide (starting from the baseline) and, in relation to these, enjoy full sovereignty.

Relevant to MA operations is also the Exclusive Economic Zone (EEZ), which can extend up to 200 nautical miles from the baseline[15]. Within the EEZ, the Coastal States exercise sovereign rights to explore and exploit the natural resources, whether living or non-living, of the waters superjacent to the sea-bed and of the sea-bed and its subsoil; they also have jurisdiction over artificial structures, marine scientific research and marine environment protection[16]. A similar (though not identical) regime deals with the Continental Shelf (CS) of Coastal States[17]. It must be noted that for some Coastal States (for example the UK) national claims of CS (reflected in their national legislation) were originally based on the 1958 Geneva Convention on the Continental Shelf (CSC)[18] and have not yet been changed according to the 1982 UNCLOS[19].

Contracting Parties to the 1982 UNCLOS are under wide-ranging obligations to protect and preserve the marine environment[20] and take all necessary measures to prevent, reduce and control pollution[21]. Thus, the Contracting Parties are under the obligation to monitor and assess whether potential harmful effects of marine mining activities may occur[22] and communicate/publish reports on this monitoring and assessment[23]; moreover, the Contracting Parties are required to: (a) adopt effective laws and regulations to "*prevent, reduce and control pollution of the marine environment arising from or in connection with seabed activities* …" and (b) ensure the enforcement of such laws and regulations[24].

[9] The management/regulation of associated activities, such as the sea transportation to land-based treatment facilities of the extracted marine aggregates, their treatment and transport to placement sites, which are also related to this regime, are not going to be dealt with here.

[10] Final draft presented and signed in Montego Bay on the 10/12/1982 and entered into force on 16/11/1994. For further details, as well as the text and latest status of ratification of the Convention and related agreements, see: http://www.un.org/Depts/los/index.htm. Attention should also be drawn to the "Agreement relating to the Implementation of Part XI of the Convention", which deals with deep-sea mining in "*The Area*". The term is defined, in Art. 1(1)(a) of the Convention, as "*the seabed and ocean floor and subsoil thereof, beyond the limits of national jurisdiction*". The Agreement, which entered into force on 28/7/1996, has had important implications on the ratification of the Convention by most developed States, having also been adopted by all of the EU Member States under consideration here.

[11] For the ratification status of the Convention for the 8 EU Member States considered, see http://www.un.org/Depts/los/LEGISLATIONANDTREATIES/ and http://www.oceanlaw.net/texts/index.htm.

[12] The maritime zones are the Territorial Sea, the Contiguous Zone, the Continental Shelf, the Exclusive Economic Zone and the High Seas.

[13] The baseline is a line along the Coastal State's coastline (at or close to it) from which the breadth of each of the maritime zones is estimated. For details on the different methods used for the determination of the baselines, see Articles 5-14 of the 1982 UNCLOS.

[14] See UNCLOS Articles 2 and 3.

[15] See UNCLOS Article 57.

[16] See UNCLOS Article 56.

[17] See Part VI of the Convention, in particular Articles 76 and 77. It must be noted, that there are some differences between the EEZ and CS regimes. A Coastal State's rights in relation to the Continental Shelf may extend beyond 200 nm (Article 76). However, the rights do not extend to superjacent waters. Art. 77(4) defines natural resources for the purposes of the Continental Shelf regime as "*mineral and other non-living resources of the seabed and subsoil together with living organisms belonging to sedentary species* …".

[18] Adopted in Geneva on 29/4/1958; entered into force in 10/6/1958.

[19] Gibson, 2004; see also UNCLOS Webpage: http://www.un.org/Depts/los/LEGISLATIONANDTREATIES/, where an up to date table of maritime claims can be found.

[20] Art. 192. This is regulated in great detail in Part XII of the Convention which is devoted to "Protection and Preservation of the Marine Environment".

[21] See in particular UNCLOS Art. 194 (3)(b) and (c), which provides for an obligation to take measures to "*minimize to the fullest possible extent*" pollution from "*vessels*" and from "*installations and devices used in exploration and exploitation of the natural resources of the seabed and subsoil* …". .

[22] See UNCLOS Articles 204 and 206.

[23] See UNCLOS Article 205.

[24] See UNCLOS Articles 208 and 214, which are specifically relevant in relation to exploration and exploitation of the seabed and, thus, to marine aggregate operations.

Table 1. *Participation in the Conventions referred to in the text, of the EU Member states considered in the paper. (http://www.un.org/Depts/los/LEGISLATIONANDTREATIES/, http://www.oceanlaw.net/texts/index.htm, www.ices.dk/indexfla.asp, www.ospar.org, www.helcom.fi, www.unepmap.org/home.asp and http://www.unece.org/env/eia/).*

COASTAL STATE	CONVENTIONS					
	UNCLOS	ICES	OSPAR	Helsinki	Barcelona	Espoo
Belgium	X	X	X			X
France	X	X	X		X	X
Germany	X	X	X	X		X
Greece	X				X	X
The Netherlands	X	X	X			X
Poland	X	X		X		X
Spain	X	X	X		X	X
The United Kingdom	X	X	X			X
European Community	X	X	X	X		X

The Convention for the Protection of the Marine Environment of the North East Atlantic 1992 (OSPAR Convention)

The OSPAR Convention[25] provides a legal framework for agreements and cooperation in the North-East Atlantic region (Table 1), with the objective of taking all possible steps to prevent and eliminate pollution and protect the marine environment from the adverse effects of human activities. The Convention includes specific rules in its Annexes I to IV to deal with pollution from land-based sources, dumping, and offshore sources, as well as with monitoring and assessment of the marine environment. Annex V, adopted in 1998, had the aim to extend the cooperation of the Contracting Parties to cover all human activities that might adversely affect the marine environment of the North East Atlantic. It deals with the protection and conservation of marine ecosystems and, when practicable, with their restoration. Criteria for identifying potentially harmful human activities for the purposes of Annex V are set out in Appendix 3[26]; these clearly cover MA operations. In 2003, a specific "Agreement on Sand and Gravel Extraction" was adopted[27]. The Agreement requires Contracting Coastal States to take into account the "ICES Guidelines for the Management of Marine Sediment Extraction" (ICES, 2003b) within their procedures for authorising marine sediment extraction. National procedures should also take into account "*the ecosystem-based approach to management of human activities*"; where appropriate, strategic plans should be developed and subjected to strategic environmental assessment (SEA). Finally, the Agreement provides that authorisations for extraction of marine sediments from any ecologically sensitive site should only be granted after consideration of an environmental impact assessment (EIA)[28] and, "*where a site is subject to protective measure, but over-riding public interests require the extraction of marine sediments with a consequential significant adverse effect on the site, all necessary steps are taken to avoid adverse impacts on the functioning of the ecosystem of which it forms part …*".

The Convention on the Protection of the Marine Environment of the Baltic Sea Area, 1992 (Helsinki Convention)

The Helsinki Convention[29] requires its Contracting Parties *inter alia*, to take "*all appropriate legislative, administrative or other relevant measures*", individually or by means of regional co-operation, "*to prevent and eliminate pollution in order to promote the ecological restoration of the Baltic Sea area and the preservation of its ecological balance*"[30]. The Contracting Parties (Table 1) are under the obligation to exercise control over their dredging operations (HELCOM, 2002). In addition, the HELCOM Recommendation 19/1 on "Marine Sediment Extraction in the Baltic Sea Area"[31] should be taken into consideration when issuing extraction permits. According to these recommendations, all sediment extractions should be carried out in accordance with the detailed guidelines set out in Recommendation 19/1. These require environmental impact assessments to be carried out, in accordance with specified minimum criteria, as part of all extraction permission procedures. The guidelines also require that in extraction practice, "*all measures shall be taken in order to minimize the ecological impacts caused by sediment extraction and transport of the extracted material*" and that environmental monitoring is to be a component of every kind of extraction activities. Importantly, the guidelines also require that "*monitoring data*", as well as

[25] The OSPAR Convention opened for signature in Paris on the 22/9/1992 and entered into force on the 25/3/1998. For further details, as well as the text and status of ratification of the Convention, see www.ospar.org.

[26] Annex V on the protection and conservation of the ecosystems and biological diversity of the maritime area. Note that Annex V and Appendix 3 entered into force on 30/8/2000. Annex V has been ratified by six of the eight EU Member States here considered, namely Spain, the United Kingdom, the Netherlands, Belgium, Germany and France; it has also been ratified by the EC.

[27] Agreement 2003-15, adopted in Bremen (Germany).

[28] In accordance with the ICES Guidelines or with the EC Habitats Directive, as appropriate. ICES Guidelines and the relevant EC Directives are considered below.

[29] The Helsinki Convention, signed in 1992, entered into force on the 17/1/2000. For details, see www.helcom.fi. Of the EU Member States considered here, only Poland and Germany are Contracting States.

[30] Helsinki Convention Art. 3(1).

[31] Adopted on the 23/3/1998, http://www.helcom.fi/Recommendations/en_GB/rec19_1/.

"*the results of the environmental impact assessement which has formed the basis for the decision on an extraction permit should be made available for scientific evaluation.*" In which way is, however, not specified further.

According to the guidelines, extraction permits for "*Sensitive Areas*", shall only be granted if a "*thorough EIA*" in accordance with the guidelines "*is proving that the extraction is not likely to cause significant negative ecological effects or lead to a deterioration of the area*"[32]. The list of the sensitive areas in the guidelines includes, among others, Baltic Sea Protected Areas (BSPAs), in relation to which special planning and management guidelines and tools have been prepared[33]. However, the list also includes more generally "*marine areas near to the coast with significance for coastal sediment transport or with protective function for the coastline (e.g. sand banks, spits and bars)*". Thus, in respect of MA extraction in relation to such "sensitive areas", a thorough EIA is always required and extraction permits should only be issued if the EIA proves that significant negative ecological effects or deterioration of the area is not likely.

As concerns compliance with HELCOM Recommendation 19/1, Contracting States are required, under Art. 16 (1) of the Convention to report, at regular intervals, on "*legal, regulatory or other measures taken for the implementation of the Convention, its Annexes and of recommendations*", as well as on the effectiveness of such measures and problems encountered. Nevertheless, a report, published by HELCOM in 2003[34], suggests that none of the HELCOM Recommendations in the field of nature conservation and coastal zone management have been fully implemented and that in many cases, reporting is sketchy and does not allow for any reliable conclusions to be drawn. As concerns Recommendation 19/1, the summary table in the report records implementation by only some of the Contracting States, including Poland, but not Germany.

The Convention for the Protection of the Mediterranean Sea against Pollution, 1976 and Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean, 1995 (Barcelona Convention).

The Barcelona Convention[35] sets out a legal framework for regional and sub-regional agreements and cooperation[36] for the protection of the marine environment of the Mediterranean Sea from pollution. It requires the Contracting Parties (Table 1) to take all appropriate measures (individually or jointly) in accordance with the provisions of the Convention and those of its Protocols[37] to which they are a party, to prevent, abate and combat pollution of the Mediterranean Sea area and to protect and enhance the marine environment in that area.

The issue of MA extraction is covered by Art. 7 of the Convention, which requires Contracting Parties to "*take all appropriate measures to prevent, abate, combat and to the fullest possible extent eliminate pollution … resulting from exploration and exploitation of the continental shelf and the seabed and its subsoil*". The corresponding Offshore Protocol to the Convention[38] which, however, has not yet entered into force, contains more specific requirements relevant to authorization of MA operations, such as surveys concerning the effects of the proposed activities on the environment and, in appropriate cases, environmental impact assessment in accordance with Annex IV (Environmental Impact Assessment) to the Protocol[39].

The Convention for the International Council for the Exploration of the Sea (ICES), 1964

The International Council for the Exploration of the Sea (ICES)[40] is an international scientific organization with the objective to study and assist in the safeguarding of the North Atlantic marine ecosystems and their living resources. The ICES Convention 1964 sets out a Constitution for the Council with a view to facilitating implementation of its programme, as well as some substantive obligations for the State Parties, such as the obligation to furnish to the Council any information which will contribute to the purposes of the Convention[41]. A strategic plan was adopted by the State Parties in 2002, further strengthening the mandate and activities of ICES .

The Council promotes marine research and publishes and communicates its results. Furthermore, ICES provides formal advice and data handling services to the OSPAR and Helsinki Commissions. In relation to MA extraction, the ICES and its Working Group on the "Effects of Extraction of Marine Sediments on the Marine Ecosystem (WGEXT)"[42] investigate the

[32] See HELCOM Recommendation 19/1, Attachment 1B. The guidelines also state that extraction permits shall not be granted for (a) nature reserves, (b) national parks or (c) areas included in or proposed for the NATURA 2000 network, except when the procedure of Art. 6 of the EC Habitats Directive is followed.

[33] Baltic Sea Environment Proceedings No. 105, Planning and management of Baltic Sea Protected Areas: Guidelines and tools, HELCOM 2006 http://www.helcom.fi/stc/files/Publications/Proceedings/bsep105.pdf

[34] HELCOM 24/2003, Compliance with the requirements of the Convention and HELCOM Recommendations, Bremen, 25/6/2003. http://www.helcom.fi/stc/files/BremenDocs/HCsuppCphDecl.pdf

[35] The original 1976 Barcelona Convention entered into force on the 12/2/1978; it has been modified/replaced by the amended 1995 Convention adopted in Barcelona on the 10/6/1995, which entered into force on 9/7/2004. For details see http://www.unepmap.org/home.asp

[36] See also one of the main tools for the implementation of the Convention and its Protocols, the "Mediterranean Action Plan for the Protection of the Marine Environment and the Sustainable Development of the Coastal Areas of the Mediterranean" (MAP Phase II), which amends the previous plan, the "Mediterranean Action Plan" (MAP). It has as its main objectives (a) to ensure sustainable management of natural marine and land resources and to integrate the environment in social and economic development, and land-use policies, (b) to protect the marine environment and coastal zones through prevention of pollution, and by reduction and, as far as possible, elimination of pollutant inputs, whether chronic or accidental, (c) to protect nature, and protect and enhance sites and landscapes of ecological or cultural value, (d) to strengthen solidarity among Mediterranean coastal States in managing their common heritage and resources for the benefit of present and future generations and (e) to contribute to improvement of the quality of life. For further information, see www.unepmap.org.

[37] There are a number of Protocols to the Convention, but not all of these have yet entered into force.

[38] The Protocol for the Protection of the Mediterranean Sea against Pollution Resulting from Exploration and Exploitation of the Continental Shelf and the Seabed and its Subsoil was adopted on the 14/10/1994 by the Conference of Plenipotentiaries held in Madrid, but has not yet entered into force and has not been ratified by any of the EU Member States considered here who are Parties to the Convention. According to Art. 3 of the Protocol, the Contracting Parties shall, individually or through bilateral or multilateral cooperation, take all appropriate measures to prevent, abate, combat and control pollution in the Protocol Area resulting from activities, *inter alia*, by ensuring that the best available techniques, environmentally effective and economically appropriate, are used for this purpose.

[39] See Article 5.

[40] The ICES was established in 1902. For details, as well as the Convention and the ICES Strategic Plan, see http://www.ices.dk/indexfla.asp

[41] See Preamble to the ICES Convention. See also Art. 5 of the Convention.

[42] For details see http://www.ices.dk/iceswork/wgdetail.asp?wg=WGEXT

impacts of MA extraction on marine ecosystems and review and report on the status of MA extraction activities and related environmental research, as well as on any reported legislative and regulatory changes. In 2003, a set of detailed "Guidelines for the Management of Marine Sand Extraction" (ICES 2003b) was developed. The guidelines establish general principles for the sustainable management of mineral resources, emphasizing issues such as the need for conservation, efficient use of materials and least adverse methods of extraction, as well as the importance of encouraging an ecosystem approach to the management of extraction activities and the selection of extraction sites, and the need to protection of sensitive areas and important habitats. The guidelines recommend that international and regional initiatives are taken into account when developing national frameworks and guidelines and that appropriate administrative frameworks are set up for the management of sand and gravel extraction. Detailed guidance is provided on the recommended contents of EIAs and their assessment, as well as on the monitoring of compliance with conditions attached to any extraction authorization.

The Convention on Environmental Impact Assessment in a transboundary context, 1991 (ESPOO Convention) and the Protocol on Strategic Environmental Assessment, 2003 (SEA Protocol)

The Convention on Environmental Impact Assessment in a transboundary context was signed in Espoo, Finland, in 1991 and entered into force in 1997[43]. All EU Member States are Contracting States to the Convention (Table 1), although in some cases, such as in the case of Germany, only since 2002. The Convention, adopted under the auspices of the United Nations Economic Commission for Europe (UNECE), sets out obligations of Parties to assess the environmental impact of certain activities at an early stage of planning. The activities covered by the Convention are listed in Annex I, referring, inter alia (at para. 14), to "*major quarries, mining, on-site extraction and processing of metal ores or coal*". It appears that transboundary aggregate dredging activities, such as in the English Channel, are covered by the Convention[44]. The Convention also lays down the general obligation of States to notify and consult each other on all major projects under consideration that are likely to have a significant adverse environmental impact across boundaries. A Protocol to the Convention, adopted in 2003, in Kiev[45], extends the requirements of the Convention to plans and programmes. However, the Protocol has not yet entered into force and, of the eight EU Member States under consideration here, only Germany has so far ratified the Protocol[46]. In the European Union, the requirements of the Convention and of the SEA Protocol are reflected in two Council Directives, namely the EIAA Directive and the SEA Directive.

OTHER RELEVANT INITIATIVES

European Code of Conduct for Coastal Zones

Although not a legally binding instrument, mention should also be made of this policy document, which addresses marine aggregate dredging. The European Code of Conduct for Coastal Zones[47] is an initiative of the Coastal Union (EUCC)[48], launched in 1993. It was included as a priority action in the Pan-European Biological and Landscape Diversity Strategy –PEBLDS (1995)– and drafted in 1996/97 by EUCC staff under the auspices of the Council of Europe and UNEP. It was officially adopted by the Council of Europe Ministers in April 1999. In respect of guidance for "Sand and Gravel Excavation and Dredging", the Code states:

(i) "*Sand or gravel extraction should only take place in coastal water at a depth where coastal processes are not compromised (i.e. below the so-called active profile of the coastal zone), and never in ecologically sensitive areas. However while this depth is generally appropriate in relation to the influence of normal tides and storms, evidence suggests that sediment can be moved at lower levels by long period waves, residual tidal movement and currents. The impact of this on adjacent coastal areas which rely on sea borne sediment for their continued development is an important and often overlooked issue". (ii) "Extraction activities should be timed to avoid conflict with seasonal events such as fish or bird migration." (iii) "Turbidity plumes should be minimised by utilisation of the best available technology and practices. Extraction should be as "dry" as possible, and working and sailing speed should be regulated so as to reduce environmental impacts. When aggregates with a high content of fines are extracted, equipment with the capacity of retaining very fine particles should be used, if appropriate in conjunction with silt curtains." (iv) "The excavation site should be limited in order to facilitate later recolonisation. Complete removal of the bottom sediment should be avoided." (v) "Consideration should be given to make better use of harbour and other dredging. Care should be taken with dredge spoils contaminated with hazardous substances which should not be dumped at sea or used for nourishment."*

It is not clear to which extent the Code of Conduct is being taken into account in relation to MA operations in EU Member States. The review of regulation in different States for the purpose of this paper did not reveal any specific reference being made to the Code of Conduct or its substantive content.

---

43 The Convention was signed on 25/2/1991 and entered into force on 10/9/1997. It counts 41 Contracting States, including the European Community and all EU Member States. The Convention has been amended twice, in February 2001 (to extend participation by non-UNECE Member States) and in June 2004 (to affect some changes to the Convention), but neither of the two amendments has yet entered into force. For the text of the Convention and a full list of Contracting States, see http://www.unece.org/env/eia/.

44 See the case study referred to in a presentation on the Convention by the UNECE Secretariat, "An Introduction to the Convention including Case-Studies", November 2005, http://www.unece.org/env/eia/

45 The SEA Protocol to the Espoo Convention was signed in Kiev, on 21/5/2003 at an Extraordinary Meeting of the Contracting Parties to the ESPOO Convention.

46 The Protocol requires 16 ratifications or accessions. Only seven States have so far ratified or acceded to the Protocol, see http://www.unece.org/env/eia/. A great deal of explanatory material and guidance on aspects of the Convention can be found in http://www.unece.org/env/eia/. Related material, such as the World Bank Environmental Assessment Sourcebook and Updates is also available at www.worldbank.org under "Environmental Assessment". See in particular Chapter 2 of the Sourcebook and Update 7, published in 1994, which deals with "Coastal Zone Management and Environmental Assessment".

47 http://www.coastalguide.org/.

48 http://www.eucc.net/. Please note that the Code of Conduct is also available for purchase from the Council of Europe website at http://book.coe.int/ (Model law on sustainable management of coastal zones and European code of conduct for coastal zones (Nature and Environment No. 101) (2000).

THE EUROPEAN LEGAL FRAMEWORK

The functions and powers of the EU institutions and the matters in relation to which the Community is competent to establish and implement common policies depend upon the Treaties establishing the European Community (EC Treaty) and European Union (EU Treaty)[49]. The Community has the task of preparing and implementing common policies, *inter alia*, in the fields of the environment, transport, agriculture and fisheries and to adopt measures in the spheres of energy, civil protection and tourism[50]. Community policy in relation to the environment aims, *inter alia*, at "*preserving, protecting and improving the quality of the environment*". More particularly, "*community policy on the environment shall aim at a high level of protection taking into account the diversity of situations in the various regions of the Community. It shall be based on the precautionary principle and on the principles that preventive action should be taken, that environmental damage should as a priority be rectified at source and that the polluter should pay*"[51]. In the field of environmental protection, a considerable amount of secondary EC legislation has been enacted, in particular in the form of Directives[52]. In contrast to Regulations, which are directly applicable and effective in all EU Member States, Directives are binding on Member States as to their aims, but require transposition, i.e. implementation at the national level, by way of legislation[53]. If a Member State fails to transpose a Directive into national legislation by the relevant date, or does so incompletely, it is in breach of its obligations under Art. 5 of the EC Treaty. In these cases, citizens may be able to invoke the Directive in question directly before the national courts. Moreover, the European Commisison may institute infringement proceedings against Member States, including in the form of actions before the Court of Justice[54]. Failure to comply with any resulting judgment of the European Court of Justice may lead to the imposition of substantial fines[55]. Annual surveys on "Implementation and Enforcement of Community Environmental Law"[56], and on "Monitoring the Application of Community Law"[57], as well as leading judgments of the European Court of Justice in the field of environmental law[58] are published by the European Commission. It is interesting to note that nature, air, waste, water and impact assessment legislation, which includes the Directives discussed in this paper, are the five areas with the highest number of open cases, accounting jointly for 90% of the total number of complaints and infringement cases in the environmental field[59].

In relation to MA operations, a number of EC Directives are directly relevant[60], in particular the Environmental Impact Assessment Directive (Directive 85/337/EEC (hereafter the EIA Directive) as amended by Directives 97/11/EC (hereafter the EIAA Directive) and 2003/35/EC), as well as Directive 2001/42/EC on the assessement of the effects of certain plans and programmes on the environment (the so called Strategic Environmental Assessment Directive, hereafter the SEA Directive). Also relevant are Council Directive 92/43/EEC on Conservation of Natural Habitats and of Wild Fauna and Flora (hereafter the Habitats Directive) and Council Directive 79/409/EEC on the Conservation of Wild Birds (hereafter the Wild Birds Directive), as well as Council Directive 2003/4/EC on Freedom of Access to Information on the Environment.

The Environmental Impact Assessment Directive

The EIA Directive was introduced in 1985[61] and was amended in 1997[62]. The Directive outlines which categories of projects shall be made subject to an Environmental Impact Assessment (EIA)[63], the procedure to be followed and the content of the assessment. Projects specified in Annex I of the Directive are subject to mandatory EIA, wheras in respect of other projects, set out in Annex II, Member States must determine, whether EIA should apply (so-called "screening"). The EIA procedure set out in the Directive seeks to ensure that environmental consequences of projects are identified and assessed before authorisation is given. The Directive envisages public participation as part of the authorisation procedure and requires the public to be informed about any decisions made.

Directive 97/11/EC widened the scope of EIA by increasing the number of types of projects covered, and the number of projects requiring mandatory EIA (Annex I). It also strengthened the procedural base of the EIA Directive by providing for new screening arrangements, including new criteria for Annex

[49] The present EC Treaty results from amendments made to the Treaty establishing the European Economic Community, which was signed in Rome in 1957 and entered into force on 1/1/1958. That treaty has been amended several times, in particular by the Single European Act, which came into force in 1987, the Treaty on European Union (Maastricht Treaty), which came into force in 1993, the Treaty of Amsterdam, which came into force in 1999 and the Treaty of Nice, which entered into force in 2003. A consolidated version of the EC Treaty and EU Treaty has been published in the Official Journal (*Official Journal C 321E of 29/12/ 2006*) and is available electronically on the EU website at: http://eur-lex.europa.eu.

[50] See Articles 2 and 3 of the EC Treaty. See also Art. 175 (4).

[51] Art. 174 (1) and (2) of the EC Treaty, as amended by the Treaty of Amsterdam. See further Art. 174 (3), which provides that in preparing its policy, the Community shall take into account the available scientific and technical data.

[52] For environmental legislation in force, see http://eur-lex.europa.eu/en/legis/index.htm. See also the website of the Commission's DG Environment, http://ec.europa.eu/environment/index_en.htm.

[53] For a useful brief summary of the effect of primary and secondary Community legislation, as well as legislative procedures and the respective role of different Community institutions, see "About EU Law - Process and Players" on the EU website at: http://eur-lex.europa.eu.

[54] See further http://europa.eu.int/comm/environment/law/index.htm

[55] Art. 228 EC Treaty and Case C-304/02, *Commission v. French Republic*, 12/7/2005. For clarification, see MEMO/05/482, issued by the Commission on 14/12/2005, http://www.europa.eu/rapid/

[56] http://europa.eu.int/comm/environment/law/implementation.htm

[57] Available on the EC website at http://eur-lex.europa.eu/.

[58] http://europa.eu.int/comm/environment/law/cases_judgements.htm

[59] See 23rd Annual Report from the Commission on Monitoring the Application of Community Law (2005), COM(2006) 416 final, dated 24/7/2006. See also the Annex to the Report, covering different sectors, SEC(2006) 999, 24/7/2006. http://eur-lex.europa.eu/LexUriServ/site/en/com/2006/com2006_0416en01.pdf

[60] In relation to protection of the marine environment, note should also be taken of Council Directive 2000/60/EC establishing a framework for Community action in the field of water policy, which applies to coastal waters, as well as the proposed Marine Strategy Directive (COM/2005/505 final), which envisages the creation of national as well as regional strategies for the protection of the wider marine environment. Discussion of these instruments is unfortunately beyond the scope of this contribution. For further information, see http://ec.europa.eu/environment.

[61] Council Directive 85/337/EEC (27/6/1985) on the Assessment of the Effects of Certain Public and Private Projects on the Environment, which was required to be implemented by 3/7/1988.

[62] Council Directive 97/11/EC (3/3/1997) amended Directive 85/337/EEC. The EIAA Directive was required to be fully implemented by the Member States by 14/3/1999. The main purpose of the amendment appears to have been a recognized need to clarify, supplement and improve the rules on the assessment procedure (cf. 4th preamble) and the expansion of projects subject to environmental impact assessment.

[63] For further information and analysis on environmental impact assessment issues, see http://europa.eu.int/comm/environment/eia/home.htm.

II projects and providing minimum information requirements, as well as introduced changes to align the Directive with the requirements of the ESPOO Convention. The EIAA Directive was further amended by Council Directive 2003/35/EC, to align relevant provisions on public participation in accordance with the Aarhus Convention on public participation in decision-making and access to justice in environmental matters, which had been adopted by the Community in 1998[64].

Marine dredging projects, which were already covered in Annex II of the original EIA Directive, are specifically referred to in Annex II 2(c) of the EIAA Directive[65]. In the case of Annex II projects, Member States may determine projects requiring assessment on a case-by-case basis or establish relevant criteria or thresholds to identify such projects (cf. Art. 4(2)). In either case, the decision needs to be made available to the public[66]. Annex III of the EIAA Directive provides detailed screening or selection criteria focusing on the characteristics, location and potential impact of projects which are to be taken into account in this process[67]. The EIAA Directive requires that the "*competent authorities*" responsible for licensing particular (individual) projects[68] make their decisions on the basis of a clear appreciation of any significant environmental impacts[69]. Environmental impact assessment carried out in accordance with the Directives require identification, description and assessment of a project's effects on human beings, animals and plants, soil, water, air, climate and landscape, cultural heritage, material assets, including any impact interactions that may occur. Moreover, public involvement in decision-making must be ensured. The Directive prescribes that (a) the environmental effects of the proposed project should be properly assessed and (b) all relevant information should be made available to the public within a reasonable time and in an easily comprehensible manner in order to enable the public to express its opinion[70].

In exceptional cases, Member States may decide to exempt a specific project from the requirements of the Directive. In these cases, alternative forms of assessment need to be considered and both the public and the European Commission need to be informed of the reasons for any decisions[71]. According to (non-binding) clarification provided by the Commission, the provision is to be construed narrowly, and is restricted to cases where full compliance with the Directive is not possible, but may cover instances where there is a serious threat to, *inter alia*, economic stability or to security[72]. Detailed guidance on "*screening*"[73], i.e. the question of whether an EIA is required in relation to particular project and on "*scoping*"[74], i.e. on environmental information needed for the purposes of an EIA, has also been published by the Commission[75].

Effective implementation of EC Directives requires new legislation or a change to existing legislation; changes to administrative practices are not sufficient, as administrative measures may be altered by the administration at any time[76]. Despite the fact that the EIA Directive was required to be implemented by the 3rd of July 1988 and the EIAA Directive by the 14th of March 1999, in some cases, there has been incomplete transposition through relevant national legislation or regulations[77], or failure to ensure that national measures are in full conformity with the EIA and EEIA Directives[78]. According to the most recent "Annual Survey on the Implementation and Enforcement of Community Environmental Law", published in 2006, problems with the conformity of national measures with the EIAA Directive continue to persist, giving rise to a considerable number of infringement procedures and com-

[64] For further information, see http://ec.europa.eu/environment/aarhus/index.htm. See also Aarhus Clearing House for Environmental Democracy, maintained by the UNECE, which can be accessed through the same website.

[65] MA mining was included in Directive 85/337/EEC, Annex II 2(c) as "*extraction of minerals other than metalliferous and energy-producing minerals, such as […] sand, gravel […]*". The provision has been amended by Directive 97/11/EC to read: "*extraction of minerals by marine or fluvial dredging*".

[66] See Article 4(4).

[67] See Article 4(3).

[68] The projects requiring impact assessment are defined in Art. 4 and listed in the Directive Annexes I and II. It must be noted that projects serving national defence purposes are not covered by the EIA Directive (see Article 1(4)), although projects serving military as well as commercial purposes are covered, provided they mainly serve commercial purposes, *WWF v. Autonome Provinz Bozen and ors.*, C-435/97 (http://www.europa.eu.int/cj/en/index.htm). Projects adopted by specific Acts of national legislation are also not subject to the Directive, since the objectives of the Directive, including that of supplying information, are achieved through the legislative process (Art. 1(5)). According to Lambrechts (1996), this exemption does not serve environmental conservation as, even if it is assumed that the legislative process warrants a measure of democratic information, it is doubtful that this by itself ensures environmental protection. Nevertheless, the European Court of Justice (ECJ) has made it clear that legislation which provides development consent within the meaning of Art. 1(2) can only be considered to fall within the definition of Article 1(5), if the law includes the elements necessary to assess potential environmental impacts of the project (*WWF v. Autonome Provinz Bozen and ors.*, C-435/97, at paras. 58-62). Article 1(5), therefore, cannot be used to circumvent the Directive's aims with regard to specific projects.

[69] Article 1(1) of the EIAA Directive (amended Article 2(1) of the EIA Directive) provides that the competent authority should "*adopt all measures necessary to ensure that, before consent is given, projects likely to have significant effects on the environment by virtue, inter alia, of their nature, size or location are made subject to a requirement for development consent and an assessment with regard to their effects*".

[70] See Article 6(2) and Article 9 of EIA Directive as replaced by Articles 1(8) and 1(11) of the EIAA Directive.

[71] Art. 2(3) of the EIAA Directive. Please note that the text of the provision has undergone some change as a result of amendments effected by Directives 97/11 EC and 2003/35/EC.

[72] See "Clarification of the application of Art. 2(3) of the EIA Directive" published in 2006 (http://ec.europa.eu/environment/eia/eia-support.htm) "*an important criterion for justifying use of Article 2(3) is that full compliance with the Directive is not possible, and not just that the case is exceptional; the exemption might normally be used in a civil emergency, though not all civil emergencies qualify for the exemption; there would need to be a pressing reason to justify the exemption, e.g. serious threat to life, health or human welfare; to the environment; to political, administrative or economic stability; or to security; the exemption is unlikely to be justified if it is intended to meet a situation that could be both anticipated and prevented; when considering the use of Article 2(3), consideration should be given to providing a partial or other form of assessment; Member States need to act quickly (before consent is granted) to provide the Commission with reasons justifying the exemption.*"

[73] "*Screening*" is the process of determining whether or not EIA is required for a particular project. This is particularly relevant in the case of Annex II projects, as Annex I projects are always subject to an EIA.

[74] "*Scoping*" is the process of determining the content and extent of the matters, which should be covered in the environmental information to be submitted to a competent authority for projects, which are subject to EIA.

[75] See http://ec.europa.eu/environment/eia/eia-support.htm.

[76] *Commission v. Belgium*, C-337/89 [1992] ECR I-6103.

[77] For instance, in 2004, the European Court of Justice condemned the UK (Case C-421/02) for incomplete transposition of the amended EIA Directive as regards Scotland and Northern Ireland. Infringement proceedings against the U.K. in relation to the implementation of the EIAA Directive in respect of marine dredging and various other activities were still pending in March 2007, before a new statutory regime was introduced in April 2007; see Explanatory Memorandum to The Environmental Impact Assessment and Natural Habitats (Extraction of Minerals by Marine Dredging (England and Northern Ireland) Regulations 2007.

[78] For further details see a five year report, "How successful are the Member States in implementing the EIA Directive, Report from the Commission to the European Parliament and the Council on the Application and Effectiveness of the EIA Directive (Directive 85/337/EC as amended by Directive 97/11/EC)" COM/2003/334 final, published on 23/6/2003 and available at http://europa.eu.int/comm/environment/eia/news.htm. See also EC Press Release IP/03/876 of 23/6/2003.

plaints to the European Commission[79]. Often, Member States appear to have been satisfied with a minimal transposition of the Directive, or national administrations fail to correctly implement and apply the legal requirements of the Directive. Weaknesses in the operation of the Directive identified by the Commission in the 2003 report on the implementation of the EIAA Directive include lack of evidence of systematic screening of Annex II projects, little real commitment to scoping, few formal measures to control the quality of EIA procedures and little monitoring of EIA in practice. The Commission also noted some key information gaps on significant areas of EIA and a considerable variation of public involvement, with some Member States applying a wide and others a very narrow[80] interpretation of the "*public concerned*".

As concerns MA operations, too, it appears that although the EIA and EIAA Directives may have been implemented in some of the Member States through a variety of Regulations, there have been problems with regard to the universal effective implementation of the Directives' requirements[81].

The SEA Directive

The scope of the EIAA Directive is limited to projects for which the decision making process requires consent or permission, but does not cover plans and programmes. To extend the need for environmental impact assessment to plans and programmes which may have a significant effect on the environment, a further Directive was adopted in 2001. The central objective of the Strategic Environmental Assessment Directive (Directive 2001/42/EC, hereafter the SEA Directive) is "*to contribute to the integration of environmental considerations into the preparation and adoption of plans and programmes with a view to promoting sustainable development, by ensuring that an environmental assessment is carried out for certain plans and programmes which are likely to have significant effects on the environment*"[82].

According to a guidance document on implementation of the Directive, prepared by the European Commission[83], "*the first requirement in order for plans and programmes to be subject to the Directive, is that they […]must be both 'subject to preparation and/or adoption by the prescribed authorities' and 'required by legislative, regulatory or administrative provisions'. […] In identifying whether a document is a plan or programme for the purposes of the Directive, it is necessary to decide whether it has the main characteristics of such a plan or programme. The name alone ('plan', 'programme', 'strategy', 'guidelines', etc) will not be a sufficiently reliable guide: documents having all the characteristics of a plan or programme as defined in the Directive may be found under a variety of names*".

Any plan or programme that has been prepared for one of a number of listed sectors, including, *inter alia*, industry, town and country planning and land use, and which sets the framework for future development consent of projects listed in the EIAA Directive requires an EIA[84].

Minerals planning is, in principle, subject to the SEA Directive[85]. Competent authorities which prepare and/or adopt a plan or programme which falls within the Directive's scope will have to draw up a report on its probable significant environmental effects, consult authorities with environmental responsibilities and the public, and take the findings of both these exercises into account in reaching a decision on how to proceed. In addition, monitoring under the SEA Directive allows, *inter alia*, for the identification of unforeseen environmental effects so that remedial action may be taken[86]. It should be noted that Art. 3(8) of the Directive includes an exemption in the case of plans and programmes the sole purpose of which is to serve civil emergency. According to the latest available annual report on implementation and enforcement of Community environmental law, published in 2006, a number of Member States had failed to transpose the SEA Directive by the deadline of July 2004, including Belgium, Greece, Spain and the Netherlands[87].

There are other Directives, which may affect MA mining operations. Although these Directives are related mainly to the protection of marine areas that enjoy special status and, thus, their analysis is beyond the scope of the present contribution, brief reference will be made here.

The Habitats Directive and the Wild Birds Directive

The main aim of Council Directive 92/43/EEC on Conservation of Natural Habitats and of Wild Fauna and Flora (hereafter the Habitats Directive), is to promote and ensure the preservation of biodiversity; it requires from the Member States to work together in order to maintain or restore to a favour-

[79] Seventh Annual Survey on the implementation and enforcement of Community environmental law 2005, SEC(2006) 1143, 8/9/2006 (http://europa.eu.int/comm/environment/law/implementation.htm). The report also states that a number of Member States had failed to transpose the requirements of Directive 2003/35/EC (public participation) by the deadline of June 2005, including Germany, Spain and France.

[80] This is the case, for instance, in France.

[81] See for instance the situation in the UK, further explained below, and also e.g. Alder (1993) and Sheate (1996) for the previous regulatory framework. The UK had transposed the EIAA and Habitats Directives in respect of most activities, but not in respect of marine minerals dredging projects prior to the adoption of a new statutory regime which entered into force in May 2007.

[82] See Article 1 of the SEA Directive. The SEA Directive's provisions apply to plans and programmes the preparation of which begins formally after the 21/7/2004 or which have not been adopted or submitted to a legislative procedure by the 21/7/2006.

[83] See European Commission Guidance on the Implementation of Directive 2001/42/EC; see also Sheate *et al.* (2005); both documents are available at http://europa.eu.int/comm/environment/eia/home.htm.

[84] See Art. 3(2) of the SEA Directive and n. 83.

[85] For detailed information in relation to minerals planning, see Strategic Environmental Information Service (http://www.sea-info.net/) a website maintained by the Centre for Sustainability and supported by the British Government. Apparently, a free SEA Minerals Newsletter is also available on the website. See also the website of the Mineral Industry Research Organization, MIRO (http:// www.miro.co.uk/) and a most informative report commissioned by the British Geological Survey (British Geological Survey Commissioned Report CR/04/003N, by E.J. Steadman *et al.* 2004) (http://www.mi-st.org.uk/research_projects/final_reports/final_report_ma_1_1_002.pdf). Further reports on EIA in relation to minerals extraction are also available on the Mineral Industry Sustainable Technology (MIST) website, accessible through the MIRO website, above.

[86] Strategic Environmental Assessment (SEA) covers more activities, wider geographic areas and often longer time periods than the project EIAs. SEA might be applied to entire sectors or geographical areas. SEA does not generally replace or reduce the need for project EIA, but it can assist in streamlining the incorporation of environmental concerns (including MA extraction) into decision-making, making project EIA more effective. It can deal with the synergy of small impacts of multiple projects/activities, any of which may be insignificant by themselves, but which together have a significant impact (see Sheate *et al.*, 2005).

[87] Seventh Annual Survey on the implementation and enforcement of Community environmental law 2005, SEC(2006) 1143, 8/9/2006 (http://europa.eu.int/comm/environment/law/implementation.htm).

able conservation status certain rare, threatened, or typical natural habitats and species. These habitats and species are listed in Annex I and II of the Directive respectively. One of the ways in which Member States are expected to achieve this aim is through the designation and protection of sites known as Special Areas of Conservation (SACs). It is interesting to note that sandbanks, which are a very significant source of marine aggregates, are listed in the Annex I of the Habitats Directive (Habitat 11.25). Although the potential implications of this listing for the MA industry have not yet been appreciated, they may be quite significant[88].

Council Directive 79/409/EEC on the Conservation of Wild Birds (hereafter the Wild Birds Directive) complements the Habitats Directive by requiring Member States to protect rare and/or vulnerable bird species through the designation of Special Protection Areas (SPAs). The Habitats and Wild Birds Directives apply both to Member States' territorial waters and the EEZs or equivalents[89]. All marine protected areas designated under both Directives form an ecologically coherent network of protected areas of European importance referred to as Natura 2000. Detailed guidance and information on the implementation of Natura 2000 in the marine environment has recently been published by the European Commission[90].

According to the latest available annual report on implementation and enforcement of Community environmental law, published in 2006, problems with the implementation or adequate transposition of the Wild Birds and Habitats Directives persisted in several Member States, including Greece, France, Spain, Belgium, the Netherlands, the U.K. and Germany[91].

Directive on Freedom of Access to Information on the Environment

Council Directive 2003/4/EC, on Freedom of Access to Information on the Environment, which was required to be implemented by 14th February 2005, imposes a general duty on Member States' public authorities and publicly accountable bodies to make environmental information held by them available to any natural or legal person, upon request[92]. The Directive replaces an earlier Directive[93] on the same subject matter, expanding the existing access granted. However, there are also some narrowly defined exceptions[94]. The information must be supplied within one month[95] and judicial or administrative appeals may be made against a refusal or failure to provide it. In addition, Member States are under an obligation to publish, if possible in electronic form, a wide range of relevant environmental information[96]. This includes international as well as national or local legislation and "*policies, plans and programmes*" relating to the environment; environmental data derived from monitoring activities; periodic reports on the state of the environment, as well as "*authorisations with a significant impact on the environment" and "environmental impact studies and risk assessments"*[97] on elements of the environment set out in the Directive, such as "*coastal and marine areas*". This Directive has changed the approach in the Member States, which previously relied on statutory registers and facilitated access to other sources of information[98]. However, the success of the Directive depends crucially on the ability of the public to exercise their rights, and it is therefore important that sources of information are well publicised, conveniently located, clearly presented and economical to use.

According to the latest available annual report on implementation and enforcement of Community environmental law, a number of Member States, including Greece, Spain and Belgium had failed to transpose Directive 2003/4/EC by the deadline of February 2005 and were referred to the European Court of Justice. At the end of 2005, infringement proceedings remained open against 10 Member States, including Belgium, Germany, Greece, Spain and France for failure to communicate transposition of the Directive to the Commission[99].

At present, it is not clear in how far the Directive has been fully and effectively implemented in all the Member States under consideration here. As far as the dissemination, in easily accessible form, of national rules and regulation relevant to MA operations is concerned, the difficulty in reliably identifying accurate and up-to-date information for the purposes of this paper suggests that even where the Directive may have been transposed into national law[100], adequate implementa-

[88] For more details and discussion on this matter, see Velegrakis *et al.*, 2001; Rogers 2001; Christiansen and Jones, 2001a and 2001b. See also "The Interpretation Manual of European Union Habitats - EUR27", published in July 2007, a scientific reference document based on the version for EUR15, which was adopted by the Habitats Committee on 4/10/1999 and consolidated with the new and amended habitat types for the 10 accession countries (adopted by the Habitats Committee on 14/3/2002) with additional changes for the accession of Bulgaria and Romania (adopted by the Habitats Committee on 13/4/2007). For marine habitats, it follows the descriptions given in "Guidelines for the establishment of the Natura 2000 network in the marine environment. Application of the Habitats and Birds Directives" published in May 2007 by the Commission services. Both documents are available on the Commission website at http://ec.europa.eu/environment/nature/index_en.htm.

[89] Member States exercise full sovereignty over their territorial waters, i.e. the 12 nm maritime zone as measured from the baseline. However, in 1999, the English High Court, in its decision in *Regina v. The Secretary of State for Trade and Industry ex parte Greenpeace Ltd,* Case No CO/1336/1999, 5/11/1999, Kay J. held that "*…the Council (Habitats) Directive 92/43/EEC applies also to the UK Continental Shelf and to superjacent waters up to a limit of 200 nautical miles from the baseline from which the territorial sea is measured*". The Court also confirmed that the Directive "*does have direct effect*" (i.e. may be relied on directly before the courts of Member States). Subsequently the European Commission made it clear that the provisions of the Habitats Directive are applicable to all Member States that exert their sovereign rights to the offshore limit of jurisdiction, e.g. within their EEZ, see only "Guidelines for the establishment of the Natura 2000 network in the marine environment. Application of the Habitats and Birds Directives" published in May 2007 by the Commission services, and Unger (2004).

[90] http://ec.europa.eu/environment/nature/natura2000/marine/index_en.htm.

[91] Seventh Annual Survey on the implementation and enforcement of Community environmental law 2005, SEC(2006) 1143, 8/9/2006 (http://europa.eu.int/comm/environment/law/implementation.htm).

[92] See Articles 2 and 3 of the Directive 2003/4/EC.

[93] The Directive repeals the earlier Directive 90/313 EEC.

[94] See Article 4 of the Directive 2003/4/EC. Exceptions include cases of manifestly unreasonable or overly general requests or requests relating to material in the course of completion, including unfinished documents or data, as well as requests relating to internal communications, taking into account public interest in disclosure.

[95] If this is impossible due to the complexity of the information, the information must be supplied within two months of the request; Art. 3(2) of Directive 2003/4/EC.

[96] Art. 7(2) of Directive 2003/4/EC.

[97] Alternatively, "*a reference to the place where such information can be requested*" should be published.

[98] See Explanatory Memorandum in Proposal for a Directive of the European Parliament and of the council on public access to environmental information. EC Brussels, 29/6/2000, 29p.

[99] Seventh Annual Survey on the implementation and enforcement of Community environmental law 2005, SEC(2006) 1143, 8.9.2006 (http://europa.eu.int/comm/environment/law/implementation.htm).

[100] For instance, in the UK, where the Environmental Information Regulations 2004, S.I. 2004/3391 and the Environmental Information (Scotland) Regulations

tion in accordance with the aims of the Directive has not yet been achieved[101].

By way of context, it should be noted that the Directive seeks to implement, at the Community level, one of the pillars of the UNECE Aarhus Convention on Access to Information, Public Particicpation in Decision-Making and Access to Justice in Environmental Matters 1998, which entered into force in 2001 and was adopted by the Community in 2005. Council Directive 2003/4/EC is complemented by Council Directive 2003/35/EC, which deals with public participation in decision-making in the drawing up of certain plans and programmes, and with access to justice[102]. A new EC Regulation, directly effective in all EU Member States as from 28th June 2007, has also been adopted (Regulation 1367/2006)[103], to extend the application of the Aarhus Convention to Community institutions and bodies, i.e "*any public institution, body, office or agency established by, or on the basis of, the Treaty*"[104].

The Aarhus Convention establishes a number of rights of the public (individuals and their associations) with regard to the environment and the Parties to the Convention are required to make the necessary provisions so that public authorities (at national, regional or local level) will contribute to the realization of these rights. The Convention has three pillars, namely (a) "access to environmental information", i.e. the right of everyone to receive environmental information that is held by public authorities; (b) "public participation in environmental decision-making", i.e. the right to participate in environmental decision-making[105]; and (c) "access to justice", i.e. "*the right to review procedures, to challenge public decisions that have been made without respecting the two aforementioned rights or environmental law in general*"[106]. In respect of the last pillar, it should be noted that an Inventory on all EU Member States' measures on access to justice in environmental matters has been published in September 2007[107]. The relevant country reports, covering all EU Member States suggest that in many cases, there is significant scope for improvement.

NATIONAL LEGISLATION AND REGULATORY FRAMEWORK

This paper does not attempt to comprehensively list every national law and regulation affecting MA extraction, but instead concentrates on the most relevant pieces of national legislation which could be ascertained in the course of this study. All eight EU Member Sates considered here have ratified the UNCLOS 1982 (Table 1). Based on UNCLOS 1982, Contracting States have the right to claim a territorial sea of up to 12 nm from the baseline and an Exclusive Economic Zone (EEZ), where appropriate of up to 200 nm. It should be noted, however, that not all States have used the UNCLOS as a basis for the delimitation of maritime areas. Notably, the UK has not claimed an EEZ, but continues to base its claims to the continental shelf on the Geneva Convention on the Continental Shelf 1958[108] and Greece has not (yet) exercised its rights under the Convention due to political tensions with neighbouring Turkey[109].

States enjoy sovereignty over their territorial sea and are thus able to assert property rights on the mineral resources under those waters. In addition, the UNCLOS and/or the Geneva Convention on the Continental Shelf 1958 provide sovereign rights over the Exclusive Economic Zone and the Continental Shelf outside the territorial sea for the purpose of exploring and exploiting its natural resources. The decision as to how those mineral rights are distributed and may be exercised is, therefore, a matter for national law.

However, Contracting States to the Helsinki, OSPAR and Barcelona Conventions, as well as the ESPOO Convention, are obliged to take the requirements laid down by these conventions into consideration. Germany and Poland are Parties to the Helsinki Convention. The UK, Belgium, Spain, the Netherlands, France and Germany are Parties to the OSPAR Convention and Spain, France and Greece are Parties to the Barcelona Convention (Table 1). All three of the above Conventions have also been ratified by the European Community. All EU Member States are Parties to the ESPOO Convention. In addition, national legislations of EU Member States must be compliant with the requirements of any relevant European legislation.

2004, SSI. 2004/520, which entered into force on 1 January 2005, transpose the Directive, or in Spain, where Ley 27/2006 contains the relevant legislation.

101 In the U.K., information about legislation and policy guidance is available on different websites and it is often difficult to ascertain the latest position or obtain a coherent overview. While correct information on new responsibilities for marine dredging licences is available on the website of the MFA (http://www.mfa.gov.uk/met/default.htm), a sub-site on the website of DEFRA (http://www.mceu.gov.uk/MCEU_LOCAL/FEPA/aggregates.htm), updated on 30/5/2007 and last accessed on 13/11/2007, still contains out-of date information. Various minerals policy guidance documents are only available on the Communities and Local Government website, but not on the MFA website. At the same time, the Communities and Local Government website does not provide any information about the licensing process or responsible Government Departments. The website of the Scottish Executive, on the subsite dealing with "Planning Legislation, Policy and Circulars" provides a circular on the Environmental Assessment of Plans and Programmes (Scotland) Regulations 2004, but makes no reference to the Environmental Assessment (Scotland) Act 2005, which entered into force on 20/2/2006 and repealed the earlier Regulations. Accurate information about the 2005 Act is available elsewhere on the Scottish Executive website, under "sustainable development" (http://www.scotland.gov.uk/Topics/SustainableDevelopment/14587). Although statutory regulations on marine aggregate dredging in England and Northern Ireland entered into force on 1/5/2007, the website of the Crown Estate, last accessed on 13/11/2007 still refers to "*proposed statutory procedures*" and states that the Government View Procedure remains relevant "*pending introduction of the statutory procedures*". The situation is equally, if not more, bewildering in some of the other EU Member States considered in the present contribution, where often numerous pieces of legislation and regulation need to be consulted.

102 See the Commission's Aarhus website at http://ec.europa.eu/environment/aarhus/index.htm

103 Regulation (EC) No. 1376/2006 of the European Parliament and of the Council (6/9/2006) on the application of the provisions of the Aarhus Convention on access to information, Public Participation in decision-making and access to Justice in Environmental Matters to Community institutions and bodies. Available through the Commission's Aarhus website.

104 Art. 2(1)(c) of the Regulation. In respect of Community institutions and bodies acting in a judicial or legislative capacity only, the provisions of Title II, dealing with access to environmental information, are relevant.

105 According to the Commission's Aarhus website "*Arrangements are to be made by public authorities to enable the public affected and environmental non-governmental organisations to comment on, for example, proposals for projects affecting the environment, or plans and programmes relating to the environment, these comments to be taken into due account in decision-making, and information to be provided on the final decisions and the reasons for it*".

106 See the Commission's Aarhus website, http://ec.europa.eu/environment/aarhus/index.htm.

107 Ibid.

108 Continental Shelf Act 1964, see also Continental Shelf (Designation of Areas) (Consolidation) Order 2000, SI 2000/3062 (amended by SI 2001/3670). See also Gibson (2004).

109 The relevant Greek law in relation to the territorial sea continues to be found in Law No. 230/17/9/1936 and Decree 6/18/9/1931. The table of maritime claims, available on the UNCLOS website, records that Greece claims a territorial sea of 6 nm, except for the purposes of aviation, where the limit is 10 nm. Turkey, which is not a Party to UNCLOS is reported as claiming a 6 nm territorial sea in the Aegean. See http://www.un.org/Depts/los/LEGISLATIONANDTREATIES.

The United Kingdom

The regulatory framework concerning MA extraction in the UK is complicated by the different constitutional status of England, Wales, Scotland and Northern Ireland[110]. The central government has exclusive jurisdiction over the UK's continental shelf. In the English territorial sea, the Central Governmental Departments (since April 2007 in particular the Marine and Fisheries Agency (MFA), an executive agency of DEFRA)[111] have responsibility for MA extraction. For the territorial sea of Wales and Scotland, the same responsibility now resides with the Welsh Assembly Government (WAG)[112] and the Scottish Executive (SE)[113] respectively. In Northern Ireland, the Department of the Environment (DoE(NI))[114] is responsible for MA extraction. Each of these departments is also responsible for developing national planning policy guidance, including that for marine mineral development. As concerns England, it should be noted that while the MFA is now responsible for marine aggregate licensing, DEFRA retains the overall policy responsibility.

The ownership of most of the seabed out to the 12 mile territorial limit around the UK[115] and the rights to explore and exploit natural resources of the UK continental shelf are vested in the Crown[116] and are administered by the Crown Estate Commissioners (CEC)[117].

The regulatory regime governing MA activities has recently undergone fundamental change, with the entry into force, on 1 May 2007, of the Environmental Impact Assessment and Natural Habitats (Extraction of Minerals by Marine Dredging) (England and Northern Ireland) Regulations 2007 (S.I. 2007/1067). The decision to enact Regulations at this time, following extended consultations, was at least in part motivated by the threat of the likely imposition of substantive fines by the European Court of Justice for continued non-transposition of the EIAA and Habitats Directive in relation to marine aggregate extraction[118]. Prior to the new legislation, MA extraction regulation was exercised through a non-statutory "interim Government View Procedure" (GVP)[119], which, since 1989, required an Environmental Impact Assessment (EIA) to be undertaken for all MA extraction operations. Subject to a favourable Government View on the environmental acceptability of a proposal, the Crown Estate, as owners, were responsible for the licensing of marine minerals dredging on a commercial basis to dredging companies[120]. The GVP was an informal, voluntary process, incorporating the various elements of the EIA and Habitats Directives, but not in the legally binding form required by EC law[121].

The Environmental Impact Assessment and Natural Habitats (Extraction of Minerals by Marine Dredging) (England and Northern Ireland) Regulations 2007 set up a system of regulation to apply to marine aggregate dredging[122]. They cover English and Northern Ireland territorial waters, the continental shelf around England and Northern Ireland and some outer marine areas around Scotland and Wales[123]. As is pointed out in "Marine Minerals Guidance Note 2" (MMG 2), which provides detailed guidance on the new statutory procedures[124], due to the depth of the waters involved, it is in practice unlikely that any dredging will be proposed beyond the Scottish Zone or towards any of the outer limits of the UK

110 Since 1/7/1999, many statutory responsibilities have been transferred to the National Assembly for Wales through the Government of Wales Act 1998 and the Scottish Parliament through the Scotland Act 1998; others should be assumed in the future by the Northern Ireland Assembly through the Northern Ireland Act 1998 (ATKINS, 2004; BOYES, WARREN, and ELLIOT, 2003; and GIBSON, 1999).

111 Until recently, the Department for Communities and Local Government (www.communities.gov.uk) - formerly Office of the Deputy Prime Minister (ODPM)) - was responsible for the planning and co-ordination of the procedure of licensing MA dredging. The Department for Environment, Food and Rural Affairs (DEFRA - http://www.defra.gov.uk/), among others, was responsible for environmental protection and, with the Centre for Environment Fisheries and Aquaculture Science-CEFAS (http://www.cefas.co.uk/homepage.htm), for environmental monitoring of MA dredging. Recently, as of 1/4/2007, the Marine and Fisheries Agency (MFA), an executive agency of DEFRA has taken on new environmental responsibilities, including the responsibilities previously exercised by the Department for Communities and Local Government with regard to MA. The MFA will be responsible for the implementation of the new statutory regime governing marine aggregate extraction as from 1/5/2007, see http://www.mfa.gov.uk for further information.

112 http://www.wales.gov.uk/index.htm

113 http://www.scotland.gov.uk/Home

114 DoE(NI) – Department of the Environment of Northern Ireland, Planning Service http://www.planningni.gov.uk

115 For a detailed discussion of the legal position regarding ownership of the foreshore and seabed in the UK, see SCOTTISH LAW COMMISSION (2003), where it was also proposed that the extent of the Crown Estate's ownership of the foreshore and seabed adjacent to Scotland be defined by statute. The Crown's property rights are qualified by the public's rights to use the sea and foreshore, which rights the Crown is obliged to respect.

116 Ownership of the foreshore and seabed between low water mark and the limit of territorial sea is *prima facie* vested in the Crown, unless it has passed to other persons by grant or adverse possession. In the Bristol Channel area, for example, the ownership of both the seabed and foreshore is divided between the Crown Estate and a variety of other parties. In Wales, this is due particularly to the historical status of the Marcher Lords. In 1849, the Duke of Beaufort was also judicially declared to be the owner of the entire foreshore of the Gower Peninsular, although some of that land has now been transferred to other proprietors. Elsewhere, there are numerous examples of privately owned foreshore, frequently derived from the historic titles of major landowners. Nevertheless, the Crown Estate owns around 55 % of the foreshore (between mean high and mean low water) and approximately half of the beds of estuaries and tidal rivers in the UK. It also owns the seabed out to the 12 nm territorial limit, as well as the rights to explore and exploit the natural resources of the UK continental shelf, excluding oil, gas and coal, but including renewable energy. The Crown Estate does not own the water column, or govern public rights such as navigation and fishery over tidal waters (GIBSON, 2004; The Crown Estate http://www.thecrownestate.co.uk).

117 Under the Crown Estate Act 1961, all mineral rights (except oil, gas and coal) are administered by the Crown Estate Commissioners (CEC). See also GIBSON (2004).

118 See Explanatory Memorandum to the Environmental Impact Assessment and Habitats (Extraction of Minerals by Marine Dredging) Regulations 2007, Final regulatory impact assessment, at paras. 10, 11 and 32.

119 DETR (1998) "Government View: New Arrangements for the Licensing of Minerals Dredging". The GVP procedure was first introduced in 1968. See also "Offshore Dredging for Sand, Gravel and Other Minerals", dated 1989 and published by the Department of the Environment and the Welsh Office.

120 For further details, see http://www.thecrownestate.co.uk. See also ADNITT, STANILAND, and LEWIS, 2004.

121 The U.K. had failed to transpose the EIAA and Habitats Directives in respect of marine minerals dredging projects and infraction proceedings against the UK were pending prior to the adoption of the new statutory regime. See Explanatory Memorandum to the Environmental Impact Assessment and Habitats (Extraction of Minerals by Marine Dredging) Regulations 2007, at paras. 4.3 and 4.5.

122 A first draft of the Regulations was first published in 1999, but the Regulations were only adopted, after extensive consultations, in April 2007. They entered into force on 1/5/2007 and apply to all new marine mineral dredging proposals, as well as to pending proposals, and to some specified changes to existing operations. The GV procedures will continue to apply to existing MA dredging operations unless either the operators propose to alter them or if the Secretary of State considers that they are likely to have a significant effect on a European site, i.e. a SAC or SPA protected respectively under the Habitats Directive or the Wild Birds Directive or a site proposed for designation as a Special Area of Conservation under the Habitats Directive. See Regulations 2,31, and Schedule 3.

123 Namely the parts of the continental shelf adjacent to Scotland which do not fall within the Scottish zone, as defined in the Scotland Act 1998 and the continental shelf adjacent to Wales, see Explanatory Memorandum to the Environmental Impact Assessment and Habitats (Extraction of Minerals by Marine Dredging) Regulations 2007, at para. 5.1.

124 "The Control of Marine Minerals Dredging from British Seabeds", published by DEFRA in 2007, see www.mfa.gov.uk.

Continental Shelf. In practice, therefore, the regulations will control MA extraction close to the English coastline[125].

The Welsh Assembly[126] has, in relation to Welsh waters, recently enacted similar legislation[127], and the Scottish Parliament is expected to make separate legislation in relation to marine areas[128] covered by its competence under devolved administration[129]. For reasons of economy, the following brief overview provides details only for the new statutory regime applicable in England and Northern Ireland and does not make specific reference to the corresponding Welsh Regulations which, however, appear to be substantially similar.

The new statutory regime for MA extraction introduces some significant changes to the previously existing informal GVP regime, by providing a firm legal framework governing the licensing procedure[130]. The GVP procedure was both lacking in transparency, making the public potentially feel excluded from any real say in decision-making, and lengthy and cumbersome, taking, in some cases, as long as five years; operators were responsible for advertising dredging proposals and carrying out lengthy consultations and had to bear the associated costs[131].

Under the new statutory procedures, these activities will be the responsibilities of the regulator[132]. Statutory and administrative time-scale targets will be established in respect of both handling of applications and monitoring of dredging permissions; there is a target of 17 weeks from receipt of a full and complete application for dredging permission to the issue of a decision[133]. While under the GVP, applications for commercial licences were made by operators to the CEC, the Crown estate will no longer be involved in this process, and will only enter dredging agreements with commercial operators in accordance with the terms of a dredging permission (and the conditions imposed by it) issued by the relevant regulator[134]. Thus, the responsibility for the control of marine minerals extraction now rests fully with the relevant Government Departments. Importantly, marine dredging of minerals without permission or failure to comply with the conditions attached to dredging permissions are criminal offences punishable by the courts[135]. The regulations also envisage the creation of a public register of all dredging applications and other related marine minerals dredging matters that come to the Secretary of State for decision. The register will be maintained by MFA and is envisaged to be made available in electronic form as soon as is practicable.

Marine minerals dredging fees have been determined with effect from 1/5/2007 by the Secretary of State for Environment Food and Rural Affairs under powers conferred on him by the new Regulations[136]. Different fees are assessed for pre-application advice (47000 GBP), processing of dredging permissions (29500 GBP) and variation of existing permissions, as well as the consideration of monitoring reports and the interpretation of Electronic Monitoring System data. As concerns fees for minerals dredging permissions in Welsh national waters, an additional consultation document published in July 2007 by the WAG suggests that the envisaged level of fees are in a similar range[137]. However, it is not clear whether final fees will be published or only notified to parties involved in the consultation.

In England, "Guidance on the Extraction by dredging of Sand, Gravel and Other Minerals from the English Seabed" was published in 2002 in Marine Minerals Guidance Note 1 (MMG1)[138]. The document provides advice on the environmental impacts to be considered and criteria against which applications will be determined, including guidance on the scope and content of environmental statements (ODPM, 2004). The guidance in MMG1 continues to remain relevant under the new statutory procedures for the control of aggregate extraction[139]. The policy objectives in MMG1 are to: (i) minimise the area licensed for dredging at any one time; (ii) carefully locate new dredging areas; (3) consider all new applications in relation to the findings of an Environmental Impact Assessment (EIA); (iv) adopt dredging practices that minimise the impact of dredging; (v) require operators to monitor, as appropriate, the environmental impacts of their activities during, and on completion of, dredging; and (vi) safeguard resources for specific uses.

---

125 Dredging within the coastal waters may also be regulated by other authorities, namely the Coastal Protection Authorities or the MFA under section 18 or section 34 (Safety of Navigation) of the Coast Protection Act 1949. In some cases, therefore, a dredging proposal may require consent under more than one regulatory regime.

126 The specific competence of the Welsh Assembly for measures relating to the extraction of minerals by marine dredging within Welsh territorial waters derives from the European Communities (Designation) (No.3) Order 2000, S.I. 2000/2812, Schedule I, Sect. 2 (c).

127 The Environmental Impact Assessment and Natural Habitats (Extraction of Minerals by Marine Dradging) (Wales) Regulations 2007, W.S.I. 2007 No. 2610 (W.221), which entered into force on 28/9/2007. Note also the consultation by the Welsh Assembly, conducted in late 2006, on proposed Marine Minerals Dredging Regulations and Procedures, which were then expected to enter into force in March 2007, see http://new.wales.gov.uk/consultations/closed.

128 No such legislation has been enacted at the time of writing. In Scotland, consultations by the Scottish Executive have recently been conducted on the proposed "Environmental Impact Assessment and Habitats (Extraction of Minerals by Marine Dredging) (Scotland) Regulations 2006". For consultation responses, see http://www.scotland.gov.uk/Publications/2007/10/31101519/0. Earlier in 2007, consultations were also conducted on "Revision of Circular 15/1999". For details, see "The Environmental Impact Assessment (Scotland) Regulations 1999", the Scottish legislative instrument implementing the EIA Directive, (http://www.scotland.gov.uk). Although reference is made, in Schedule 2 of the 1999 Regulations, to "extraction of minerals by marine and fluvial dredging", it appears that the Regulations do not apply to marine dredging activities, but deal only with planning permissions required under the Town and Country Planning (Scotland) Act 1997, i.e. developments on land.

129 The competence of the Scottish Parliament extends to the limits of the Scottish Zone as defined in the Scotland Act 1998. "The 'Scottish zone' means the sea within British fishery limits (that is, the limits set by or under section 1 of the Fishery Limits Act 1976) which is adjacent to Scotland, see Sect 126 of the Scotland Act 1998

130 Detailed explanation of the statutory procedures for the control of marine aggregate dredging activities is provided in Marine Minerals Guidance Note 2: The Control of Marine Minerals Dredging from the British Seabed (MMG2), published by DEFRA and available on the MFA website at www.mfa.gov.uk.

131 See Explanatory Memorandum to the Environmental Impact Assessment and Habitats (Extraction of Minerals by Marine Dredging) Regulations 2007.

132 Relevant regulators are for English territorial waters and the outer marine areas around Northern Ireland, Scotland and Wales the Secretary of State for Environment, Food and Rural Affairs, and for Northern Ireland territorial waters DoE(NI). If a proposal straddles the boundary with Scottish, Welsh or Northern Ireland Waters, the prospective applicant must also seek separate determinations on screening and scoping from the relevant devolved administration.

133 Provided the application does not need to be referred to an Inspector or be the subject of consultation with another EEA state.

134 For a definition of "dredging agreement" and "dredging permission", see the glossary in MMG2, Annex A.

135 Regulations 4, 14 and 27.

136 http://www.mfa.gov.uk/pdf/fees2007.pdf.

137 http://new.wales.gov.uk/consultations/closed/plancloscons/MMD/?lang=en.

138 "Marine Minerals Guidance Note 1 - Guidance on the Extraction by Dredging of Sand, Gravel and Other Minerals from the English Seabed", which is applicable in England and Wales. Available at http://www.communities.gov.uk/publications/planningandbuilding/marinemineralsguidance.

139 According to the guidance document explaining the new statutory procedures (at para. 3.23), issued by DEFRA in 2007 as MMG2, see above.

It should be noted that the SEA Directive has been transposed into UK law, in relation to plans or programmes related to projects listed in Annex I or II of the amended EIA Directive, which would seem to cover marine aggregate extraction[140]. For England, Northern Ireland and Wales respectively, relevant Regulations were adopted in 2004[141]. In the case of Scotland, the relevant rules are those in the Environmental Assessment (Scotland) Act 2005, which came into force on 20/2/2006[142].

For England, the relevant planning policy guidance in respect of marine aggregates was contained in "Minerals Planning Guidance Note 6" (MPG6). MPG6 has been replaced by "Minerals Policy Statement 1" (MPS1), published in November 2006, the MPS1 "Annex on the Supply of Aggregates, and the current National and Regional Guidelines for Aggregate Provision in England 2001-2016", published in 2003. MPS1 needs to be read together with "Planning and Minerals: Practice Guide", published in November 2006[143].

In Wales, the need for a strategy to deal with aggregate extraction in the Bristol Channel, Severn Estuary and river Severn and an "Interim Marine Aggregates Dredging Policy" for these areas has been published by the WAG[144]. In Scotland, there has been very little interest in marine dredging[145], but it has been suggested that this may change in the future[146]. Scottish "Guidance on Minerals Planning" is documented in NPPG4[147], which, at para. 54, refers to marine dredged minerals. However, NPPG4 has recently been superseded by SPP4, which does not specifically refer to marine minerals extraction. Supplementary advice on the environmental effects arising from mineral working operations is set out in PAN 50[148]. In Northern Ireland, there appears to be a surplus of onshore sand and gravel resources and it seems that so far, no licenses have been issued for the extraction of marine aggregates (Boyes, S.; Warren, L., and Elliott, M., 2003)[149].

Finally, it should be noted that consultations have just been completed on a white paper for a Marine Bill, published on 15 March 2007[150]. A summary of responses to the White Paper has been published and is available electronically on the DEFRA website. The White Paper proposes the adoption of new legislation to introduce changes related to: the introduction of a new UK-wide system of marine planning, including a streamlined, transparent and consistent system for licensing marine developments; introduction of a flexible mechanism to protect natural resources, including marine protected zones with clear objectives; improvements to the management of marine fisheries in relation to England, Wales and Northern Ireland and the ability to share the costs of management with commercial and recreational sectors; and a new Marine Management Organization delivering UK, England and Northern Ireland functions. An analysis of the potential impacts of the proposed legislative changes outlined in the White Paper is beyond the scope of this contribution. However, it is clear that further developments are worth careful monitoring. Should legislation based on the wide-ranging proposals in the White Paper be adopted, much of the existing regulatory and administrative framework relevant to marine aggregate extraction in the UK may, in due course, change.

Germany

Germany is a Federal Republic and, therefore, competence is divided between the Federal Republic ("Bund") and the Federal States ("Länder")[151]. Moreover, there is also another administrative layer (local authorities -Selbstverwaltungsköperschaften) for counties, towns and municipalities (Gibson, 1999).

The Federal Republic has sovereign rights over the seawater and the seabed of the Territorial Sea, as well as rights to explore and exploit the natural resources of the Continental Shelf (CS)[152] and the Exclusive Economic Zone (EEZ). However, in some coastal areas, the ownership rights of the Federal Republic are limited by those of the individual Federal States[153].

In the Territorial Sea, administrative competence is divided between the Federal Government and the government

[140] Each of the respective pieces of legislation adopts the relevant text in the SEA Directive, referring to plans and programmes which are prepared for "*agriculture …, energy, industry, … water management, town or country planning or land use*" and set "*the framework for future development consent in respect of projects listed in Annex I or II of the* [EIAA Directive]". Reference is also made to cases where assessment is required under Art. 6 or 7 of the Habitats Directive. The text would seem to cover plans and programmes related to projects for "*extraction of minerals by marine or fluvial dredging*", as these are listed in Annex II of the Directive. However, it is interesting to note that only the Scottish legislation expressly lists relevant projects in a Schedule, whereas the Regulations for England, Northern Ireland and Wales do not.

[141] The Environmental Assessment of Plans and Programmes Regulations 2004, SI 2004/1633. Similar Regulations were enacted, also in 2004, for Northern Ireland (SR 2004/280) and Wales (WSI 2004/1556 (W.170). For further information on the different Regulations applicable in England, Northern Ireland and Wales, as well as the relevant Scottish legislation, see http://www.communities.gov.uk/planningandbuilding/planning/sustainabilityenvironmental/.

[142] The Act repealed secondary legislation (Regulations) enacted in 2004. The legislation is relevant to MA operations, as it applies to plans and programmes, which set the framework for future development consent of projects involving extraction of minerals by marine or fluvial dredging, see Section 5(3) of the Act and para. 24 (3) of Schedule 1.

[143] All documents are available on the website of the Department of Communities and Local Government which took over the responsibilities of the ODPM in May 2006 (see www.communities.gov.uk, under Planning Policy and Guidance, Minerals and Waste).

[144] Welsh Assembly Government (2004) Interim Marine Aggregates Dredging Policy South Wales, available at (http://www.wales.gov.uk/subiplanning/content/guidance/sand-gravel-e.htm.

[145] There are currently only two extant dredging licenses in Scotland, one in the Firth of Forth and the other in the Tay Estuary. Only minor activity has taken place at both locations, see Extraction of Minerals by Marine Dredging Consultation Paper, July 2006, available on the website of the Scottish Executive.

[146] Friends of the Earth Scotland (1999) Foundations for Sustainable Resource Use: A Strategy for Scotland, Edinburgh (see the web page of the Scottish Executive) that in recent years there has been growing interest in the potential of marine dredging for aggregates, particularly in the Firth of Forth, and Tay, Clyde and Moray Firth Areas.

[147] "National Planning Policy Guideline NPPG 4: Land for Mineral Working" was issued in 1994 http://www.scotland.gov.uk/Publications/2005/03/3085211/52124, which provides, in principle, for the development of up to 4 coastal exporting superquarries in Scotland. Scottish Planning Policy 4 (SPP4): Planning for Minerals, published in September 2006, which replaces NPPG 4 makes no reference to marine minerals dredging.

[148] "Planning Advice Note PAN 50: Controlling the environmental effects of surface mineral workings" http://www.scotland.gov.uk/library5/planning/pan50-00.asp This provides a framework within which planning authorities can prepare policies for all types of mineral development likely to arise in their area, taking into account coastal processes, natural heritage issues as well as possible implications for the transport of material by sea.

[149] However, see "Regional Planning Policy – Minerals"on the DoE(NI) website.

[150] See Consultations on a Marine Bill White Paper, A Sea Change, http://www.defra.gov.uk/corporate/consult/marinebill-whitepaper07/

[151] According the Basic Law ("Grundgesetz"), i.e the constitution of the Federal Republic of Germany.

[152] Bekanntmachung der Proklamation der Bundesregierung über die Erforschung und Ausbeutung des deutschen Festlandsockels, 20/1/1964 (The Declaration by the Federal Government of 20/1/1964), BGB1 1964 II S. 104 (amended 2/9/1974). All federal German laws referred to in this paper are available electronically at http://bundesrecht.juris.de/aktuell.html.

[153] For example, the Federal States own the imperial waterways ("Reichswasserstraße"), which may run through the coastal waters.

of the Federal States[154]. For instance, although the Federal Republic has ownership rights over the German mudflats, the Schleswig-Holstein mudflats were, in 1985, declared a national park, the protection and administration of which falls under the Gesetz zum Schutze des Schleswig-Holsteinischen Wattenmeeres[155]. Nevertheless, the Federal Government[156] is responsible for providing national guidelines and co-ordinating planning policy from which the individual coastal States ("Länder") derive their own planning legislation[157].

Regarding MA permits (i.e. exploration/extraction licenses), these must be obtained from the Land[158] or Bezirksregierung responsible for the relevant territorial waters[159]. The principal regulations are similar to those regarding land mining. The Federal Mining Law[160] applies to all solid, liquid and gaseous mineral resources in the German territory as well as to activities pertinent to their development[161]. Moreover, the Environmental Impact Assessment Act (UVPG)[162], which implements the EIA/EIAA and SEA Directives into German law[163], ensures that for projects set out in Appendix 1 to Paragraph 3 (which include mining operations) environmental impact assessments are carried out and taken into consideration in the granting of permits and licences. However, secondary legislation enacted under the statute seems to exclude most mining projects (other than in sensitive areas) which involve extraction areas of less than 25 hectares from the requirement of an environmental impact assessment. Moreover, mining projects appear to be altogether exempt from the requirement for SEA under the UVPG[164].

Although Germany shows notable consideration for nature protection and conservation, information on MA licensing procedures is not easily accessible. Although the Federal Ministry for the Environment ("Bundesumweltministerium") maintains a good website[165], with much information on environmental issues and legislation, including on EIA, the website does not contain any information on mineral extraction, marine or otherwise. Information about relevant legislation and competencies is, therefore, rather difficult to ascertain and it appears that there is no clear national policy on MA extraction[166]. No uniform guidance exists on the required scope or content of environmental statements concerning the environmental impact assessment of MA extraction. However, it appears that the ICES Guidelines (ICES, 2003b[167]) are used in respect of extraction in the North Sea, whereas the HELCOM Recommendation 19/1 is applicable for extraction sites in the Baltic Sea[168]. Finally, it should be noted that the administrative Directives HABAK and HABAB might also be relevant in some cases[169].

Spain

Competence in the management and protection of the marine environment[170] is shared by the different levels of the Spanish administration[171]. The Central (national) Government has exclusive jurisdiction regarding the Territorial Sea, the

154 The Territorial Sea environmental legislation is very complex, encompassing, amongst others, relevant parts of Environmental Law, Water Law and the Law of National Parks and Nature Reserves. Responsibility for the coastal environment is shared between several public institutions such as the Federal State Water Authorities ("Wasserverbände"), the Federal State Land Authorities ("Bodenverbände"), the "Gemeinden", the Federal States and the Federal Republic.

155 http://sh.juris.de/sh/NParkG_SH_1999_rahmen.htm. The Wasserhaushaltsgesetz is a Federal Act designed to regulate the maintenance of the coastal water chemical and ecological balance. Under §19 of the Act, the Federal States are empowered to create nature reserves (water reserves) if in the public interest. §22 provides for liability in case of changes to the chemical, physical or biological condition of water; see also Scottish Law Commission (2003).

156 The Federal Government environmental responsibilities are primarily exercised through the Ministry for the Environment, Nature Conservation and Nuclear Safety ("Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit") http://www.bmu.de/english/. The Ministry for Regional Planning, Building and Urban Development is responsible for preparing national guidelines (in conjunction with the Länder) and for co-ordinating planning policy (See also ICM in Europe - http://www.coastalguide.org/icm/index.html; Bulthuis *et al.*, 2004).

157 Regarding regional planning, nature conservation and water management, the Länder enjoy a high degree of freedom, subject to conformity with the federal legal framework (See Bulthuis *et al.*, 2004; Gibson, 1999; ICM in Europe http://www.coastalguide.org/icm/index.html).

158 There are five coastal Federal States (Länder): Lower Saxony, Hanseatic Bremen and Hanseatic Hamburg (North Sea), Schleswig-Holstein (North and Baltic Seas) and the Mecklenburg-Western Pomerania (Baltic Sea).

159 One of the major implications of divided competence is the fragmented and lengthy procedure of licensing offshore activities, particularly within the 12 nautical mile zone i.e. the Territorial Sea. The combined Federal State and Federal Government bureaucracy as well as the presence of extensive nature protection zones along the German coastline has made exploitation licensing a time consuming process (Knight, 2005).

160 Bundesberggesetz - BbergG (13/8/1980, amended 9/12/2006) http://bundesrecht.juris.de/bundesrecht/bbergg/.

161 Competence for activities on the Continental Shelf rests with the respective Länder. Under Arts. 132 and 133 of the Federal Mining Law, research surveying in the continental shelf which does not relate to mineral resource exploitation (e.g. fiber optics cable routing) is subject to approval by the Bundesamt fuer Seeschiffahrt und Hydrographie. Deep Sea Mining in "The Area" under Part XI of UNCLOS, i.e. the seabed beyond national jurisdiction, is governed by the Gesetz zur Regelung des Meeresbodenbergbaus - MbergG of 6/6/1995, as last amended on 31/10/2006, http://bundesrecht.juris.de/mbergg.

162 Gesetz über die Umweltverträglichkeitsprüfung – UVPG (12/2/1990, fully revised 25/06/2005 and last amended 23/10/2007) http://bundesrecht.juris.de/bundesrecht/uvpg/gesamt.pdf.

163 The requirements of the SEA Directive were incorporated into the UVPG in 2005 on the basis of a separate law, (Gesetz zur Einführung einer Strategischen Umweltprüfung und zur Umsetzung der Richtlinie 2001/42/EG (SUPG) (25/06/2005).

164 See Paragraph 18, as well Annex I (No. 15.1) UVPG and Paragraph 1(1) of Verordnung ueber die Umweltverträglichkeitspruefung bergbaulicher Vorhaben, UVP-V Bergbau, (13/7/1990, last amended 9/12/2006). Note that in 1995 a „Federal General Administrative Guideline on the Execution of the EIA Act of 18/9/1995" (UVPVwV, 1995), was passed, with further details concerning the implementation of the law and the handling of the single categories. It should be noted that any EIA in relation to fluvial dredging is regulated by State Law, see UVPG, Annex I (No. 13.15).

165 http://www.bmu.de.

166 For an overview over Coastal Zone Management issues in Germany, see http://www.coastalguide.org/icm/index.html. Information can be also found in the following web-portal http://www.dredging-in-germany.de/sites/englisch/g_rechtsg/00_start.html

167 http://www.ices.dk/iceswork/wgdetail.asp?wg=WGEXT.

168 www.sandandgravel.com.

169 Although the original purpose of these instruments was to ensure environmentally sound handling/disposal of material dredged for navigational purposes, they might also be relevant for use of dredged material as fill and/or for beach replenishment purposes. HABAK, Handlungsanweisung für den Umgang mit Baggergut im Küstenbereich (Directive for Dredged Material Management in Federal Coastal Waterways) (HABAK-WSV), Second Revised Edition, 1999, Federal Institute of Hydrology (Bundesanstalt für Gewässerkunde), Koblenz, Germany, http://www.bafg.de/servlet/is/11509/HABAK-engl.pdf. HABAB, Handlungsanweisung für den Umgang mit Baggergut im Binnenland (Directive for Dredged Material Management in Federal Inland Waterways) (HABAB-WSV) 2000, Second Revised Edition, Bonn, Koblenz, 2000. http://www.bafg.de/servlet/is/11509/HABAB-08-2000.pdf

170 The Shores Act ("Ley de Costas") sets out the overarching legal framework concerning the marine environment. (Ley 22/1988 (28/7/1988), de Costas http://noticias.juridicas.com/base_datos/Admin/l22-1988.html).

171 Spain is a "Union State", comprising different administration levels: the Central Government, the Autonomous Communities, the Provinces, and the Local Authorities. There 17 Autonomous Communities ("Comunidades Autónomas"), 12 of which are coastal, and 2 autonomous cities ("Ciudades Autónomas"; Ceuta and Melilla) which group 50 Provinces ("Provincias") http://en.wikipedia.org/wiki/Spain. Each of the Autonomous Communities has individual founding statutes and enjoys varying degrees of autonomy. The Provinces have no formal powers as such, as they form groups of local authorities. In fact, Spain functions as a highly decentralized Federation of Autonomous Communities and might be regarded as the most decentralized European State.

EEZ and the Continental Shelf; in comparison, jurisdiction in the internal waters is divided between the Central Government and the Autonomous Communities. Mineral rights are vested in the state, forming part of the public domain ("dominio público marítimo-terrestre")[172]. The state controls and regulates[173] the rational use of the resources ´in agreement with nature´ i.e. with respect to the landscape and the historical patrimony.

MA extraction is referred to in Art. 63 of the Shores Act. An interesting feature of the Act is that it allows MA extraction only for beach creation and/or replenishment purposes; the Act also requires evaluation of the environmental impacts of MA extraction. In addition, Royal Decree 1471/1989[174] approves General Regulations to develop and execute the Shores Act and includes guidelines/specifications on the authorisation procedures of MA extraction (in Articles 124-127). The requirements for the evaluation of the environmental impact of activities affecting the coastal zone and the marine environment were mainly regulated in the Decree 6/2001[175] which modified the Royal Decree 1302/1986[176] so as to make it compatible with the requirements of the the EIA Directive (Directive 1997/11/EC) and the ESPOO Convention, which Spain had ratified in 1997. According to these requirements[177], full EIA studies are mandatory if MA extraction volumes exceed $3x10^6$ m^3 per year; for lower extraction volumes simpler environmental impact statements are sufficient, unless it is decided, on a case by case basis, in accordance with "screening" criteria set out in Annex III of the (amended) Royal Decree 1302/1986, that a full EIA is required[178]. The procedure is regulated by Royal Decree 1131/1988[179]. However, there was little official guidance on the detailed methodology/content of the required EIA contained in Royal Decree 1131/1988[180]. It appears that Spain was in fact facing infringement proceedings for incomplete transposition of the EIAA Directive and new legislation was introduced, in April 2006. The relevant legislation, Decree 9/2006[181], primarily transposes the SEA Directive into Spanish law, so as to make plans and programmes subject to environmental impact assessment. However, Decree 9/2006, also modifies Royal Decree 1302/1986 in several respects, so as to make it fully compatible with the requirements of the EIAA Directive. In particular, the legislation now provides more detailed requirements as to the substantive contents of any EIA which the relevant authorities require in relation to the licensing of projects, including MA operations.

In addition, under the new legislation, mandatory EIA is also now required, irrespective of the extraction volume, in relation to marine dredging activities in specially sensitive environments protected under the Habitats and Wild Bird Directives.

The Directorate for the Coasts[182] of the Ministry of the Environment[183] is responsible for the protection and policing of the marine-terrestrial zone[184] and the authorisation/licensing of MA extraction. As MA extraction is permitted only for beach creation/replenishment, the Ministry for Public Works[185], which carries out and funds beach replenishment projects, is also relevant.

The powers of the Autonomous Communities include, *inter alia*, the demarcation of the shoreline, coastal-terrestrial planning and zone planning[186]. Processing of MA extraction applications in coastal and internal waters also takes place within the coastal Autonomous Communities. However, as MA extraction is permitted only for beach nourishment, the Autonomous Communities have also an interest in MA extraction in the Territorial Waters.

Finally, it should be noted that another relevant piece of legislation, Decree 27/2006[187], was introduced in July 2006 to transpose into Spanish law Council Directive 2003/4/EC, on Freedom of Access to Information on the Environment, and Council Directive 2003/35/EC[188], reflecting the requirements of the Aarhus Convention on public participation in decision-making and access to justice in environmental matters.

172 The article 132.2 of the 1978 Spanish Constitution declares (affirmed also by Art. 3 of the Shores Act ("Ley de Costas") that State public property shall consist of all properties in any event of the marine-terrestrial zone: the foreshores, beaches, Territorial Sea and all natural resources of the Exclusive Economic Zone and the Continental Shelf (http://noticias.juridicas.com/base_datos/Admin/l22-1988.html).

173 The powers of the State Administration are set out in Arts 110-112 of the Shores Act. With regard to State powers and responsibilities, the Act refers to "*la Administración del Estado*" (State Administration). The State Administration´s responsibilities include the management of the public coastal domain including the granting of permits (licenses) and concessions and the overseeing of the fulfillment of the conditions of these permits. The State Administration has also the responsibility to oversee waste discharges, human safety in bathing areas and maritime safety.

174 Real Decreto 1471/1989 (1/12/89), por el que se aprueba el Reglamento General para Desarrollo y Ejecución de la Ley de Costas 22/1988, (28/7/1988). http://www.juridicas.com/base_datos/Admin/rd1471-1989.html.

175 Ley 6/2001 (8/5/2001) de modificación del Real Decreto Legislativo 1302/1986 (28/6/1986), de evaluación de impacto ambiental http://noticias.juridicas.com/base_datos/Admin/l6-2001.html.

176 Real Decreto Legislativo 1302/1986, (28/6/1986), de Evaluación de Impacto Ambiental http://noticias.juridicas.com/base_datos/Admin/rdleg1302-1986.html.

177 These requirements, which are laid down at the Federal level, are observed closely in the planning legislation of the coastal Autonomous Communities. In the OSPAR area, Andalucía has established an extraction threshold of 3 million m^3 over which a regulated EIA procedure is required, whereas a simpler study on the environmental impacts (an environmental statement) is sufficient for smaller projects. However, Galicia and Cantabria have established a mandatory full-blown EIA for all sediment exploitation activities, including MA extraction. In comparison, the EIA Act of the Pais Vasco does not specifically mention marine sediment extraction, but establishes a mandatory and regulated EIA procedure for all conservation and regeneration activities in the coastal public domain; thus, EIA is required in order to authorise marine aggregate extraction for beach nourishment, which is the only marine sediment exploitation allowed in Spain (ICES, 2006).

178 Annex I of Real Decreto Legislativo 1302/1986 (28/6/1986), de evaluación de impacto ambiental, lists the projects which require a full EIA procedure according to the Directive 97/11/EC (as it was transposed to the Spanish legal system by Ley 6/2001). Projects listed in Annex II (including extraction of less than 3 million m^3 of marine aggregates) only require a full EIA if this is considered necessary, on a case by case basis, in accordance with the "screening" criteria in Annex III.

179 Real Decreto 1131/1988 (30/09/1988) por el que se aprueba el Reglamento para la ejecución del Real Decreto legislativo 1302/1986, de 28 de junio, de evaluación de impacto ambiental http://noticias.juridicas.com/base_datos/Admin/rd1131-1988.html

180 Note that an independent guide was published in 2004 (Buceta-Miller, 2004).

181 Ley 9/2006 (28/04/2006) sobre evaluación de los efectos de determinados planes y programas en el medio ambiente http://noticias.juridicas.com/base_datos/Admin/l9-2006.html.

182 Direccion General de Costas - http://www.mma.es/costas/htm/actua/infor/index.htm

183 Ministerio de Medio Ambiente - http://www.mma.es/

184 See also http://www.mma.es/costas/guia_playas/index.htm.

185 Ministerio de Obras Públicas y Urbanismo

186 Relevant also is the Sectorial Conference of Medio Ambiente, an organisation facilitating co-ordination between the Autonomous Communities and the State Administration.

187 Ley 27/2006 (18/07/2007) por la que se regulan los derechos de acceso a la información, de participación pública y de acceso a la justicia en materia de medio ambiente (incorpora las Directivas 2003/4/CE y 2003/35/CE) http://noticias.juridicas.com/base_datos/Admin/l27-2006.t3.html

188 Council Directive 2003/35/EC amends the EIAA Directive to align relevant provisions on public participation in accordance with the Aarhus Convention on public participation in decision-making and access to justice in environmental matters, which had been adopted by the Community in 2005.

France

Property rights in the French foreshore and seabed are vested in the state. As these areas form part of the public domain ("domaine public de l'etat")[189], they are controlled/regulated by the state and are subject to significant restrictions in relation to property rights[190].

The primary responsibility for the management of marine areas lies with the Ministère de l'Equipement, des Transports et du Logement, which is responsible for development planning[191] and administration of navigable waters. Several national government departments have functions relevant to the marine environment (e.g. Ministère de l'Aménagement du Territoire et de l'Environnement, Ministère de l'Agriculture et de la Pêche[192] and Ministère de l'Economie, des Finances et de l'Industrie (MINEFI)[193]). Competence in environmental management is also given to regional authorities (Régions, Départments and Communes), as well as to national agencies such as the Conservatoire du Littoral. The national government appears to have complete jurisdiction over mining on the Continental Shelf, whereas jurisdiction within territorial waters appears to be shared between the national and regional governments.

The French Mining Code ("Code Minier")[194] sets out the legal framework for the exploitation of mineral resources of the French seabed[195], including the Continental Shelf[196]. The provisions of the Mining Code are supplemented by several other pieces of legislation which are relevant to the exploitation of the Continental Shelf[197] and the French territorial waters[198]. Mining (dredging) permits require Environmental Impact Assessments[199]. However, EIA studies are not in all cases mandatory. The content of EIAs is not adapted specifically to MA dredging projects, but is determined on a case-by-case basis. Since there is no clear and uniform guidance on the required content of the EIA concerning MA extraction, the quality of EIAs carried out by independent consultants on behalf of MA companies may vary[200].

Overall it appears that, until recenly, the administration and regulation of MA activities in France was quite fragmented. The administrative authorities responsible for licensing MA prospecting and extraction were the Ministry of Economy, Finance and Industry[201], the DRIRE[202] (responsible for granting "Mining title investigation" concessions), the DDE[203] (responsible for sanctioning the use of public domains) and local authorities[204] (responsible for mining permits). Scientific organisations were also consulted; for example, IFREMER[205] advises on the preliminary and follow-up studies needed to assess the environmental impact of extraction.

However, new legislation was introduced in July 2006 to streamline and simplify the procedure for applications pertaining to MA operations ("prospection, recherche et extraction"). Under the new legislation, Décret 2006-798[206], which entered into force in October 2006, only one application is required[207] for the purposes of obtaining licences and concessions related to MA operations. The full application, containing, among other things an EIA as provided for in R. 122-3 of the "Code de l'environnement"[208], should be submitted to the Minister in charge of mining (Ministry of Economy, Finance and Industry), but is subsequently handled by the local authority ("préfecture") who then consults with all other competent authorities, which appear to remain the same as previously. The internal consultations are followed by a public enquiry and, four months later, by a meeting involving all the competent authorities, commissions, concerned parties and the ap-

[189] Land within the public domain is not in principle capable of alienation, nor can it legally be acquired or abandoned through prescription. Special procedures have to be followed in order to declassify the land as part of the public domain before the State can transfer property rights. However, it is not clear the extent to which this declassification might occur in respect of the foreshore and seabed (See also Scottish Law Commission, 2003).

[190] Article 1 of the Coastal Act 1986 gives support to public interest issues concerning coastal ownership. It provides that "the coastal area in France is a geographical entity that calls for a particular system of development, protection and exploitation".

[191] In 1983, Article 57 of Loi 83-835 introduced the option of development plans for marine areas, called "Schémas de Mise en Valeur de la Mer" (SMVM). The detailed procedure for their preparation was subsequently elaborated in a 1986 Decree. SMVM are plans concerning marine areas and adjacent coasts, adopted by the Ministère de l'Equipement, des Transport et du Logement, following submissions by the Préfet du Département, consultations with local authorities and other interested parties and public inquiries. They are legally superior to local plans, which must be compliant with them, but it appears that their implementation has been difficult in practice. The SMVM complement the Loi Littoral. Together they provide a statutory planning framework for the whole coastal zone (For further discussion, see Gibson (1999)).

[192] http://www.agriculture.gouv.fr/spip/

[193] http://www.finances.gouv.fr/

[194] Code Minier dates back to 21/4/1810. Law 94-588 of 15/7/1994 is the last amendment of the Mining Code. The present Mining Code codifies existing case law, aims at a better protection of the environment and attempts to bring conformity with relevant European legislation (see Betlem *et al.*, 2002) http://www.legifrance.gouv.fr/WAspad/UnCode?code=CMINIER0.rcv.

[195] The seabed forms part of the public domain. See also (http://www.ifremer.fr/).

[196] Article 6 of the Loi du 30/12/1968 («relative à l'exploration du plateau continental et à l'exploitation de ses resources naturelles») states that "*De cette loi qui institue un régime juridique unique sur le plateau continental Français, précise que le code minier est applicable à toutes les substances minerals*". See also Law 68-1181, (consolidated version of 20/12/2003), http://www.legifrance.gouv.fr/texteconsolide/RHEAH.htm.

[197] In particular, Décret 71-360 du 6/5/1971 ("qui traite des procédures et de diverses dispositions spéciales") amended by Décret 85-1289 du 3/121985, Loi 77-485 du 11/5/1977, Décret 71-362 du 6/5/1971 ("relatif aux autorisations de prospections préalables de substances minérales ou fossiles dans le sous-sol du plateau continental"); see also the consolidated version of 28/12/2003, http://www.legifrance.gouv.fr/

[198] Décret 80-470 du 18/6/1980 "portant application de la loi du 16/7/1976 relative à la prospection, à la recherche et à l'exploitation des substances minérales non visées à l'article 2 du code minier et contenues dans les fonds marins du domaine public métropolitain"; see the consolidated version of 31/10/1998, http://www.legifrance.gouv.fr/

[199] Décret 93-245 du 25/2/1993 ("Décret relatif aux études d'impact et au champ d'application des enquêtes publiques et modifiant le Décret n° 77-1141 du 12/10/1977 pris pour l'application de l'article 2 de la Loi n° 76-629 du 10/7/1976 relative à la protection de la nature et l'Annexe du Décret n° 85-453 du 23/4/1985 pris pour l'application de la Loi n° 83-630 du 12/7/1983 relative à la démocratisation des enquêtes publiques et à la protection de l'environnement"). See also the consolidated version of 5/8/2005, http://www.legifrance.gouv.fr/

[200] It has been suggested that this might be due to the small MA quantities extracted in France, which have not prompted the regulatory authorities to invest in the improvement of the procedures (Cayocca and Du Gardin, 2003).

[201] Through the Directorat des Mines and the Directorat des Carburants of the Ministère de l'Economie, des Finances et de l'Industrie (supervised also by the Conseil General des Mines).

[202] Directions Régionales de l'Industrie, de la Recherche et de l'Environnement http://www.drire.gouv.fr/.

[203] Directions Départementales de l'Equipement, (Ministère de l'Equipement, des Transport et du Logement) http://www.equipement.gouv.fr/rubrique.php3?id_rubrique=21.

[204] http://www.interieur.gouv.fr/rubriques/c/c4_les_prefectures/c46_votre_prefecture.

[205] Institut Français de Recherche pour l'Exploitation de la Mer http://www.ifremer.fr/

[206] Décret 2006-798 du 6/7/2006 relatif à la prospection, à la recherche et à l'exploitation de substances minérales ou fossiles contenues dans les fonds marins du domain public et due plateau continental métropolitain.

[207] Commercial operators must be resident in France or in another EU Member State.

[208] The text of the Environmental Code, as well as an English translation, is available on the official governmental website http://www.legifrance.gouv.fr/.

plicant. The responsible "Préfet" finally sends the completed dossier, together with his own views, to the Ministry responsible for matters related to mining, who then consults further with a number of other Ministries (e.g. Finance, Environment, Maritime Affairs, Fisheries, Defence). Any objections can only be raised within two months. The Minister in charge of mining is responsible for the issuing of a prospecting licence or extraction concession; favourable decisions are published in the "Journal officiel" and, subsequently, in any journal in the nearest coastal zone to the proposed site. However, unfavourable decisions are not published, and the law provides that silence on the part of the Ministry for 48 months (in the case of applications for extraction concessions) or 36 months (in the case of applications for prospecting licences) is considered rejection of the application. Thus, while an applicant apparently now deals only with one local authority directly, the administrative procedures remain complex and, the time-frame for a final decision on any application is considerable.

The legislation also provides that prospecting and extraction activities are subject to control ("police des mines en mer") to ensure that any licence or concession conditions are complied with. Further details in this respect are set out in the legislation.

It should be noted that the legislation does not, however, apply to small extraction projects, which are defined as involving an area of less than 3000 m², with extraction not exceeding 100.000 tonnes annually, and to activities for non-commercial purposes, in particular coastal zone management[209]. In respect of small extraction projects, reference is made to Title I of Book V of the "Code de l'environnement" (Environmental Code), which deals with "Classified facilities for the protection of the environment"[210], including mining operations, which are subject to authorisation on the basis, *inter alia*, of an environmental impact assessment. In relation to MA operations for coastal zone management purposes or other non-commercial purposes, the new legislation makes no reference to any regulatory regime that may apply.

The Netherlands

The national government, provincial governments and municipalities form different levels of public administration with regard to the environment[211]. However, the national government has overall jurisdiction in the Territorial Sea, the EEZ and the Continental Shelf[212]. The extraction of sediments from the bed[213] is regulated by the Extraction Act of 1971[214], which applies not only in the Territorial Sea, EEZ[215] and the Continental Shelf[216], but in all Dutch waters ("Rijkswateren")[217].

The Dutch State is the owner of the seabed in the Territorial Sea. Moreover, it has exclusive rights on mineral resources found on and beneath the seabed of the Dutch Continental Shelf (Article 4b of the Extraction Law). Therefore, in addition to the issuing of an extraction license, a contract must be drawn between the operator and the State i.e. the seabed owner.

The state powers relating to the MA extraction are primarily exercised through the Ministry of Transport, Public Works and Water Management[218], which has the responsibility for integrated planning[219] at the national level and is the competent authority for MA extraction licensing, through the North Sea Directorate[220]. The policies relevant to the extraction of marine sediments[221] are found in the Regional Extraction Plan for the North Sea (RON, 1993) and its updated version(RON2)[222] and the Environmental Impact Assessment Decree[223]. The ICES Guidelines (ICES, 2003b) have been chosen to prescribe the content and scope of the assessment of environmental impacts of MA extraction.

When MA extraction is of small scale, then a full-blown EIA is not necessary and an environmental impact statement/report is sufficient; in addition, the application procedure is short (MER, 1994). Shallow and small-scale sediment extractions are defined in the RONs as those involving the extraction of a sediment layer less than 2 m thick and covering a seabed area less than 500 ha (in the Territorial Sea less then 100 ha); however, if the sediment extraction takes place in water depths less than 20 m, an environmental impact study is compulsory. RON2 allows extraction of sediments up to 5 m in thickness and the sediment storage (filling) in extraction pits outside the 7 m water depth line for coastal protection purposes[224]. Extraction of sediments more than 2 m of thickness is allowed (under conditions) from areas deeper than 20 m[225].

It appears, however, that the position has recently undergone some change. According to ICES (2007), "*In 2006 the limits for the requirement of an Environmental Impact Assessment for the extraction of marine sediments are set on an area of more than 500 ha (5 km²) and/or an amount of more than 10 million cubic meters per license. These limits were already valid for the Exclusive Economical Zone (EEZ). They are now also set for the Territorial Zone (less than 12 miles from the coast line), were previously an area of more than 100 ha (1 km²) was the limit*"[226].

[209] See Art. 2 of Décret 2006-798.

[210] The text of the Environmental Code, as well as an English translation, is available on the official governmental website http://www.legifrance.gouv.fr/.

[211] Article 21 of the Dutch Constitution states that public authorities shall endeavour to ensure a good quality of life in the Netherlands, and to protect and enhance the environment. Legislation takes the form of Acts of Parliament, supplemented by ministerial orders, decisions and directives (Gibson, 1999).

[212] The jurisdiction of provincial governments and municipalities ends at the coastline.

[213] Minerals situated at a depth of up to 100 meters below the seabed.

[214] Extraction Law ("Ontgrondingenwet") 1971 (Wet van 27/10/1965, Houdende regelen omtrent de ontgrondingen) http://wetten.overheid.nl

[215] Article 3 (1) of the Extraction Law 1971.

[216] Article 4a of the Extraction Law 1971.

[217] In addition to the marine areas (North Sea and the Wadden Sea), there are other waters ("Rijkswateren") such as lakes, canals, the exposed bed of rivers in summer and all ports. For all these areas, MA extraction is under the national government jurisdiction (Article 5 (1) and Article 8 (1) of the Extraction Law 1971. For details see Baretta (2004) and http://www.noordzee.nl./waterkwaliteit/

[218] Ministerie van Verkeer en Waterstaat http://www.verkeerenwaterstaat.nl

[219] Activities are being coordinated with other competent ministries and government bodies. For details, on the management in the Dutch sector of the North Sea, see Barry, Elema, and Van Der Molen, 2003.

[220] Rijkswaterstaat http://www.rijkswaterstaat.nl

[221] In the Netherlands, several policy documents have been drawn to provide government guidance/interpretation on sediment extraction (For more detailed information, see Barry, Elema, and Van Der Molen, 2003; and Baretta, (2004).

[222] RON (1993) - Regionaal Ontgrondingenplan Noordzee and RON2 (2004)- Regionaal Ontgrondingenplan Noordzee 2.

[223] MER - The Netherlands Commission for Environmental Assessment (1994) http://news.eia.nl/bibliotheek_detail.aspx?id=8404

[224] Pit refilling is permitted only during 2 summer months and 1 winter month (RON2, 2004).

[225] For more details on the Dutch sediment extraction regulation see DGE (2003) and Baretta (2004).

[226] ICES, 2007. The document also states: " *The policy and the regulations of the Second Extraction Plan for the North Sea and the policy on shell extraction*

Finally, it should be noted that since 2006, sand extracted for the dredging of shipping lanes in areas with water depths of less than 20 m, has to be placed back on the seabed within the 20 m depth contour[227].

Poland

Property rights regarding the seabed are vested in the state and form part of the public domain ("Obszarami morskimi Rzeczypospolitej Polskiej")[228]; mineral resources are also the original and exclusive property of the state[229]. The national government has overall jurisdiction in the sea, beyond the mid-tide water mark (including the Inland Waters, the Territorial Sea and the Exclusive Economic Zone). The Act on Polish Marine Areas[230] sets out the range of competence for the management of both the marine areas ("Obszary morskie Rzeczypospolitej Polskiej") and the newly established "coastal strip". The main authorities responsible for these areas are the three regional Maritime Offices[231] (in Gdynia, Stupsk and Szczecin) and the Ministry of Environmental Protection, Natural Resources and Forestry[232], which guide and control activities with environmental implications. Mineral resource initial investigations, prospecting/evaluation and extraction are subject to the regulations relating to geological investigations[233]. The Ministry of Environmental Protection, Natural Resources and Forestry is the competent authority for mining administration[234] with the Department of Geology and Geological Concessions[235], as task leaders.

Regulation related to MA extraction is similar to that governing land mining. The Polish Mining Law[236] sets out the legal framework and applies to minerals contained in the seabed of the Polish maritime zones. The requirements of environmental impact assessment procedures are detailed in the Act on Access to Information on the Environment and its Protection and on Environmental Impact Assessments Act (9/11/2000)[237], which also lays down the principles concerning environmental protection, provision of environmental information and public participation procedures. There are no national guidelines on the content of EIAs for MA extraction[238] or an integrated national policy regarding MA extraction.

Belgium

Belgium is a federal state[239] made up of three communities[240] and three regions[241], which are subdivided into provinces and communes; therefore, competence[242] is shared by these entiries (Gibson, 1999; Van Elburg-Velinova, D.; Valverde, C.P., and Salman, A., 1999). Nonetheless, only the Flemish Region ("Vlaanderen") borders the North Sea.

Sovereign rights in the seabed are vested in the State. The Federal Government has competence in the North sea (i.e. the territorial waters, the continental shelf and the EEZ)[243] beyond the baseline and/or the mean low-water line along the coast[244] (Gibson, 1999; NBR, 2005, and Van Elburg-Velinova, D.; Valverde, C.P., and Salman, A., 1999). An Advisory Committee[245] has been set up[246] to co-ordinate actions concerning the management of

will be incorporated in a new document for extraction from waters under management of the national government".

227 http://www.noordzeeloket.nl.

228 According to the Act on Polish Marine Areas, Ustawa z dnia 21/3/1991 r. o obszarach morskich Rzeczypospolitej Polskiej i administracji morskiej.

229 According to the Polish Mining Law, the state owns the seabed of the Internal Waters, the Territorial Sea and EEZ, and has the rights to explore and exploit mineral resources. In comparison, the rights of onshore mineral resources are dependent on the type of exploitation. The state has exclusive rights of the mineral resources found beneath the surface (and exploited by underground mining), whereas landowners have the rights on superficial mineral resources (exploited by open pits).

230 Op. cit.

231 These offices are under the jurisdiction of the Ministry of Transport and Construction ("Ministerstwo Transportu i Budownictwa") http://www.mi.gov.pl/en/moduly/jednostki/opis.php?id_jednostki=20.

232 Ministerstwo Środowiska http://www.mos.gov.pl/

233 Under the Article 34 of the Act on Polish Marine Areas.

234 Article 33 of the Act on Polish Marine Areas.

235 Departament Geologii i Koncesji Geologicznych - DGiKG http://www.mos.gov.pl/dgikg/

236 The Act Geological and Mining Law, 1994 ("Prawo geologiczne i górnicze z dnia 1/3/1994") regulates the realisation of geological work, mineral exploitation and protection, and other environmental issues related to mineral resources. It applies all over the Polish territory. http://www.mos.gov.pl/1akty_prawne/ustawy/94.27.96.shtml

237 Ustawa o dostępie do informacji o środowisku i jego ochronie oraz o ocenach oddzialywania na środowisko http://www.mos.gov.pl/1akty_prawne/ustawy/dostep.html

238 An EIA is not mandatory for small-scale onshore mineral (sand and gravel) resource exploitation if the extraction volumes are less than 20000 tonnes per year and the affected area is smaller than 2 hectares.

239 The Kingdom of Belgium, a constitutional monarchy and parliamentary democracy, since 1970 has been gradually transformed into a Federal State. The last radical change of the Constitution ("De Belgische Grondwet / La Constitution Belge") was carried out in 1993, after which the Federal Government is backed up by three Regional Governments (Vlaanderen, Wallonie and Bruxelles), and further by Provincial government and local government structures (see OECD, 1997; Wouters and De Smet, 2001 and http://en.wikipedia.org/wiki/Main_Page).

240 According to Article 2 of the Constitution there are the French Community, the Flemish Community and the German-speaking Community. See http://www.ejustice.just.fgov.be/cgi/welcome.pl, http://www.fed-parl.be/constitution_uk.html and http://www.senate.be/doc/const_fr.html.

241 According to Art. 3 of the constitution there are the Walloon Region, Flemish Region and Brussels Regions. See http://www.ejustice.just.fgov.be/cgi/welcome.pl, http://www.fed-parl.be/constitution_uk.html and http://www.senate.be/doc/const_fr.html.

242 Under the Constitution (Art. 35) powers are divided between the Federal Government and the communities and regions, and Art. 6 of the Special Institutional Reform Law of 8/8/1980 ("Moniteur belge", 15/8/1980, as amended) defines their areas of competence. The constitutional reform and the Special Institutional reform Law extended the competencies of the Communities to social affairs, granted competencies to the Regions and established the institutions of the Communities and the Walloon Region. The competencies of the Flemish Region were exercised by the Flemish Community. The institutions of the German-speaking Community were not established until the law of 31/12/1983, defining its competencies for the same matters as those for which the other two Communities were competent - with the exception of the use of languages - and providing for the possibility of the Walloon Region to transfer the exercising of certain competencies to the German-speaking Community (http://www.crisp.be/wallonie/en/pouvoirs/creation.html). See also OECD (1997) and Wouters and De Smet (2001).

243 Art. 1 of the Belgium Continental Shelf Law, 13/6/1969 ("Wet inzake de exploratie en de exploitatie van niet-levende rijkdommen van de territoriale zee en het continentaal plat") http://www.juridat.be/cgi_loi/loi_N.pl?cn=1969061330 as amended by Art. 27 of the "EEZ" act, 22/4/1999 ("Wet betreffende de exclusieve economische zone van België in de Noordzee"). http://www.juridat.be/cgi_loi/loi_N.pl?cn=1999042247

244 Coastal zone management on land falls under the federal and regional jurisdiction, whereas the federal government (barring some exceptions) is competent for the management of the sea. The dividing line between land and sea is formed by the provincial frontier of West Flanders, which is bounded on the seaward side by the baseline (or the mean low-water line) along the coast. However, divergent laws can assign jurisdiction at sea to the Flemish Region. For example, the Law of 8/8/1988 (B.S. 13/8/1988) provides that certain activities/works in the Belgian part of the North Sea (e.g. the management of waterways, harbours, coastal defence, pilot services, rescue and towing services at sea and nowadays fishing and dredging) fall under the regional authority (NBR, 2005). Nevertheless, MA extraction is under the Federal jurisdiction (see NBR, 2005).

245 To ensure integrated planning and implementation of Belgium's *National Policy on Oceans*. See also http://www.un.org/esa/agenda21/natlinfo/countr/belgium/natur.htm#oceans

246 Art. 1 of the Royal Decree of 12/8/2000 installed a Consultative Commission charged with the co-ordination between the different parts of the administration concerned with the management of the exploration and exploitation of the Continental Shelf and the Territorial Sea and the fixation of modalities and working costs ("Koninklijk besluit tot instelling van de raadgevende Commis-

the exploration and eploitation of marine non-living resources between several competent national departments[247].

Article 3 of the Belgian Continental Shelf Law, together with provisions of the EEZ[248] and MMM[249] Acts set out the legal framework for MA exploration/exploitation. Generally, the exploration and the exploitation of the mineral resources of the seabed and subsoil are subject to a concession regime, which requires environmental impact studies. The Royal Decree of 1/9/2004[250] prescribes the content of EIAs and relevant procedures[251] concerning the exploration and exploitation of mineral and other non-living resourses of the territorial sea and continental shelf.

Management of MA extraction from the Belgian wates is primarily exercised through the Federal Public Service for Economy, SMEs, Self-employed and Energy[252], the Federal Public Service for Health, Food Chain Safety and Environment and MUMM[253], which represents the relevant Federal Ministry and is responsible for marine environmental protection from marine activities and resource assessment. The MA activities are monitored both at the operational level[254] in order to assess compliance with the prescribed terms of the licence and at the environmental impact level with physical and ecological monitoring of the immediate area of MA extractions as well as neighbouring areas that could be potentiallly affected[255].

It appears that changes to the Belgian legislation are under consideration, but no further details are, at this stage, available.

Greece

The national government ("Εθνική Κυβέρνηση"), provincial governments ("Περιφέρειες") and counties ("Νομαρχίες") form different levels of public administration with regard to the environment. Property rights with regard to the seabed are vested in the State, forming part of the public domain; marine mineral resources are also the exclusive property of the state.

The national government has overarching jurisdiction in the marine areas, including the coastal strip[256]; however, some of its powers are devolved to the lower levels of administration (counties). Aggregate extraction is regulated both onshore and offshore through a series of aggregate extraction laws[257], which also define the constitution of the county committees, which decide about the granting of MA extraction concessions[258]. In the decision-making, other administrative authorities are also involved, such as the Ministry of Public Works, Planning and Environment ("ΥΠΕΧΩΔΕ"), and the Fisheries Directorate of the Ministry of Agriculture.

An EIA is a necessary prerequisite for the granting of an extraction licence. However, since there are no national guidelines on the content of the EIA concerning MA extraction, the quality of EIAs carried out by independent consultants on behalf of MA companies has been very variable.

SUMMARY AND CONCLUSIONS

All eight EU Member Sates considered here are under wide-ranging obligations to protect and preserve the marine environment based on the relevant provisions of the UNCLOS 1982, to which these States are Contracting Parties. Requirements laid down by the OSPAR, Helsinki, Barcelona and Espoo Conventions need also to be complied with by those States which are Contracting Parties to any of these Conventions (Table 1). Concerning MA extraction and its management, the OSPAR guidelines, drafted by ICES (ICES, 2003b), are of particular significance, as well as the HELCOM Recommendation 19/1 on "Marine Sediment Extraction in the Baltic Sea". Under the Barcelona Convention, there are no specific guidelines for the management of MA extraction; the Offshore Protocol to the Convention, which provides for research/monitoring surveys concerning the effects of any proposed activities on the marine environment, has not yet entered into force.

Although in all the considered States, the central government appears to have the overarching responsibility for MA extraction and licensing, in some States (e.g. the UK, Spain, Germany and Greece) much of this responsibility has been devolved to lower levels of administration. The regulatory framework relevant to MA extraction differs, as in some States there is specific regulation regarding MA exploitation, whereas regulation in other States seems to be applicable to both land-won and marine aggregates (e.g. in Germany).

sie belast met de coördinatie tussen de administraties die betrokken zijn bij het beheer van de exploratie en de exploitatie van het continentaal plat en van de territoriale zee en tot vaststelling van de werkingsmodaliteiten en -kosten ervan"). http://www.juridat.be/cgi_loi/loi_N.pl?cn=2000081283

247 See Art. 3 of the Royal Decree of 12/8/2000.

248 The Law concerning the Exclusive Economic Zone of Belgium in the North Sea – "EEZ" Act, 22/4/1999 ("Wet betreffende de exclusieve economische zone van België in de Noordzee"), http://www.juridat.be/cgi_loi/loi_N.pl?cn=1999042247

249 The Law on the protection of the marine environment in marine areas under Belgian jurisdiction – "MMM" act, 20/1/1999, amended by the Act of 17/9/2005 ("Wet ter bescherming van het mariene milieu in de zeegebieden onder de rechtsbevoegdheid van België"). http://www.juridat.be/cgi_loi/loi_N.pl?cn=1999012033

250 Royal Decree of the 1/9/2004 on the evaluation of the effects on the environment pursuant to the Law of 13/6/1969 on exploration and exploitation of mineral and non-living resources of the territorial sea and the continental shelf ("Koninklijk besluit houdende de regels betreffende de milieu-effectenbeoordeling in toepassing van de wet van 13 juni 1969 inzake de exploratie en de exploitatie van niet-levende rijkdommen van de territoriale zee en het continentaal plat"). http://www.juridat.be/cgi_loi/loi_N.pl?cn=2004090150

251 Due to the fact, that exploitation takes place in three clearly defined areas on the Belgian continental shelf, the procedure includes particular specifications on these zones concerning their accessibility and extraction volumes. http://www.ejustice.just.fgov.be/mopdf/2004/10/07_1.pdf#Page37.

252 It issues permits for exploiting MA on the Belgian continental shelf.

253 Management Unit of the North Sea Mathematical Models and the Scheldt estuary, which is a Department of the Royal Belgian Institute of Natural Sciences (RBINS). http://www.mumm.ac.be/EN/index.php.

254 Belgium, together with the UK, the Netherlands and Germany require the monitoring of MA dredging operations through an Electronic Monitoring System (EMS) or "black-box". Specialised positioning devices are installed on all dredging vessels working within their waters to control location and intensity of dredging. In addition all licensees are audited each year to confirm the quantities of material landed from each license and to ensure that licence conditions have not been breached (see also Velegrakis *et al*., this volume and www.sandandgravel.com).

255 See, for example, Van Lancker *et al*., this volume.

256 According to the Law 2971/2001 ("Νόμος 2971/2001, 19/12/2001").

257 The Laws ("Νόμοι») 1219/1938, 1416/84, 1473/84 and the Presidential Decrees («Προεδρικά Διατάγματα») 636/77, 284/88.

258 MA aggregate extraction is usually administered at the county level. The granting of concessions is the prerogative of particular committees, consisting of representatives of the County Engineering Directorate ("Νομαρχιακή Τεχνική Υπηρεσία»), the County Service of the Ministry of Finance ("Οικονομική Εφορία») and the local Coastguard Service ("Λιμεναρχείο»).

Regulation in the UK differed, until earlier this year, significantly from that in all other States considered here, as MA dredging used to be administered through a non-statutory procedure (interim Government View Procedure). New statutory regulations have now been enacted in respect of MA operations in English, Welsh and Northern Irish waters, as well as on the UK continental shelf; statutory Regulations have not yet been enacted in respect of Scottish waters, but are expected to be adopted soon. If and when legislative changes, based on the proposals in the White Paper for a Marine Bill, are adopted in the U.K., the regulatory landscape for MA operations may change further.

Some States (e.g. the UK, the Netherlands) have laid down particular policies and guidelines concerning marine aggregates. For example, there is a UK policy towards the increased use of recycled material[259], the Dutch government encourages the use of marine dredged material[260] and Spain allows marine aggregate extraction only for the purpose of beach creation/replenishment.

National legislation must be compliant with the requirements of any relevant secondary European legislation, in particular the Environmental Impact Assessment Directive, as amended (Directive 85/337/EEC as amended by Directives 97/11 EC and 2003/35/EC), which is the most significant regarding the administrative decision-making procedures for the approval of MA projects. The Directive has been transposed into national legislative systems in the form of separate statutes (e.g. Poland, Spain, Germany, France and the Netherlands) or incorporated into marine extraction regulation acts (e.g. Belgium and, very recently, the UK). Although all the Member States considered here prescribe environmental impact assessments of the extraction sites as a prerequisite to extraction licence granting[261] as well as physical and ecological monitoring of the extraction sites following the commencement of the dredging activities, only few of the Member States considered (e.g. the UK and the Netherlands) appear to have published national guidelines on the content and scope of MA extraction-related EIAs. In addition, The quantity and quality of MA reserve and operation data held by the considered States varies widely, with the most modern and uniform data sets held by the UK, the Netherlands and Belgium (see also Velegrakis *et al*., this volume).

This paper only provides a relatively general overview over the regulatory regime governing MA operations in some EU Member States. This in itself, however, has not been an easy task. As an incidental finding, this review, relying to a considerable extent on published information and electronically available sources in the public domain, has shown that it is rather difficult to access accurate, up to date and complete information on administrative structures, regulations, procedures and practice pertaining to the authorization of MA extraction. In many instances, information available on the websites of the diverse relevant regulatory bodies is out of date, incomplete or incoherent[262]. As a result, it is rather difficult to properly assess whether and to which extent the various environmental protection requirements and guidelines arising from international conventions as well as the pertinent European legislation have been complied with. Considered analysis of national regulatory frameworks for MA extraction in the light of existing international requirements has not been possible within the scope of this contribution. However, while further research in this area is clearly required, the results of the present review suggest that there are a number of areas for improvement. In particular, it would appear appropriate that rules, regulations and procedures in relation to MA licensing within the EU are more streamlined, transparent, and uniformly consistent with international obligations than seems to be the case at present. Improved transparency of regulation would potentially serve the interests of effective protection of the marine environment, but could also benefit commercial stakeholders in terms of ensuring competitiveness and an equal playing field throughout the EU.

The "Blue Book", recently published by the European Commission in response to its wide-ranging consultations on an integrated maritime policy for the EU[263] appear to be encouraging in this respect, in particular as concerns the proposed streamlining of maritime spatial planning as a tool for the sustainable development of marine areas and the establishement of an appropriate marine data and information infrastructure.

In this context, the potential relevance of Council Directive 2003/4/EC on Freedom of Access to Information of the Environment should also be noted. Under the Directive, EU Member States are, *inter alia*, required to publish, *if possible in electronic form*, a wide range of relevant environmental information, including (a) "*international, national or local legislation*" and "*policies, plans and programmes*" relating to the environment; (b) environmental data derived from monitoring activities; (c) periodic reports on the state of the environment; (d) "*authorisations with a significant impact on the environment*" and (e) "*environmental impact studies and risk assessments*" on elements of the environment set out in the Directive, such as "*coastal and marine areas*". Effective national implementation of these aspects of the Directive would play an important role in providing better access to information on rules, proce-

[259] According to MPG6, there should be a reduced emphasis on the supply of aggregates from traditional onshore and offshore sources. Hence, the contribution from marine sand and gravel to the overall aggregate supply should remain at around 7 % of the total, and future increasing demand should be met from recycled and secondary aggregates. MPG6 has now been replaced by MSP1 Annex on supply of aggregates which, in relation to marine sand and gravel states: "*It is Government policy to encourage the supply of marine-dredged sand and gravel to the extent that environmentally acceptable sources can be identified and exploited, within the principles of sustainable development. 'Environmentally acceptable' in this context is in terms of both the natural and historic environments. Subject to this overriding consideration, it is assumed that marine dredging of sand and gravel is likely to continue to contribute to meeting part of the national and regional demand for aggregates at a proportion no lower than that of the recent past, currently about 8% of total demand for primary aggregates*".

[260] By offering economic incentives.

[261] At least in the case of MA extraction volumes above a particular threshold.

[262] The situation in the UK is a pertinent example in this respect. See for instance fn. 101, above. However, it should be noted that proposals currently considered as part of the consultations on a Marine Bill could provide some improvement in terms of coordination and consistency of marine licensing rules and procedures throughout the UK.

[263] Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, An Integrated Maritime Policy for the EU, COM (2007) 575 final, published on 10/10/2007. Available on the European Commission website at http://ec.europa.eu/maritimeaffairs/

dures and practices governing MA extraction. This, in turn, would assist in monitoring compliance with the requirements of the multi-layered legal framework for the protection of the marine and coastal environment and, ultimately, benefit environmental protection efforts. For the time being, however, the difficulty in identifying, for the purposes of this review, accurate, complete and up-to-date information on national rules, practices and procedures relevant to MA operations suggests that adequate implementation of the Directive, in accordance with its aims, has not yet been achieved.

ACKNOWLEDGEMENTS

This review has been funded through the EC-TMR EUMARSAND Project (EUMARSAND Research Training Network, HPRN-CT-2002-00222). The authors would like to acknowledge the whole EUMARSAND team who provided basic information. Special thanks are due to Adolfo Uriarte, who gave additional material concerning the Spanish regulation, Cristiana Mutiu, who provided additional information on the French regulation and Ms Marien Boers (Rijkswaterstaat), who kindly answered questions and commented on a text concerning The Netherlands.

LITERATURE CITED

Adnitt, C.; Staniland, R., and Lewis, J., 2004. The future of environmental impact assessment for marine aggregate extraction – best practice and emerging issues. *Journal of Marine Science and Environment,* C1, 36-44.

Alder, J., 1993. Environmental impact assessment – the inadequacies of English law. *Journal of Environmental Law*, 5, 203-220.

Atkins, 2004. ICZM in the UK: A Stocktake Final Report, March 2004, 96p.

Baretta, M.M., 2004. Schatgraven in zee Analyse van de juridische situatie ten aanzien van zandwinning op de Noordzee. Deelrapport binnen het project Natuur in de Zandbak Stichting De Noordzee. September 2004. 23p. (http://www.noordzee.nl./waterkwaliteit/)

Barry, M.; Elema, I., and Van Der Molen, P., 2003. Ocean Governance in the Netherlands North Sea. TS20 New Professional Tasks – Marine Cadastres and Coastal Management TS20.2 FIG Working Week 2003. Paris, France, April 13-17, 2003, 17p.

Betlem, G.; Brans, E.; Getliffe, K., and Groen, F., 2002. Environmental Liability & Mining Law in Europe. 23rd September 2002, School of Law, University of Exeter, UK, 119p.

BfN, 2001. Application of NATURA 2000 in the marine environment. Workshop at the International Academy for Nature Conservation, Vilm from 27 June to 1 July 2001. http://www.bfn.de

Birklund, J. and Wijsman, J.W.M., 2005. Aggregate extraction: A review on the effect on ecological functions. SANDPIT, *Report Z3297.10*, February 2005. Prepared for EC Fifth Framework Programme Project No. EVK3CT200100056, 56p.

Bmapa, 1995. Aggregates from the Sea, Why Dredge? (2nd Edition), British Marine Aggregate Association Producers Association, London, 23p.

Boyes, S.; Warren, L., and Elliott, M., 2003. Regulatory Responsibilities & Enforcement Mechanisms Relevant to Marine Nature Conservation in the United Kingdom. Report to Report to Joint Nature Conservation Committee (JNCC), Institute of Estuarine and Coastal Studies, University of Hull, 52p.

Brampton, A.; Evans, C.D.R., and Velegrakis, A.F., 1998. South Coast Mobility Study: West of the Isle of Wight. Construction Industry Research and Information Association CIRIA, *Report PR 65*, 201p.

Buceta-Miller, J.L., 2004. Diccionario Guía de Reconocimientos Geológicos para Ingeniería Civil. -MONOGRAFIAS. CEDEX, ISBN 84-7790 CX283, 52p.

Bulthuis, J.; Boschman, S.; Kloosterman, J.; Pijlman, E., and Stutterheim, S., 2004. Windrichting op de Noordzee, Faculty of Spatial Sciences, University of Groningen.

Cayocca, F. and Du Gardin, B., 2003. Assessing the impact of sand extraction on the shore stability: project for a methodological framework. European marine sand and gravel – shaping the future, EMSAGG Conference, Delft University, The Netherlands, 5p.

Christiansen, S. and Jones, S., 2001a. Implementation of the EU Habitats Directive Offshore: Natura 2000 sites for reefs and submerged sandbanks, Volume II: Northeast Atlantic and North Sea. A report by WWF UK, 87p.

Christiansen, S. and Jones, S., 2001b. Implementation of the EU Habitats Directive Offshore: Natura 2000 sites for reefs and submerged sandbanks Volume I: Introduction and Rational. A report by WWF, 25p.

De Groot, S.J., 1996. The physical impact of marine aggregate extraction in the North Sea. *ICES Journal of Marine Science*, 53, 1051-1053.

Dean, R.G., 2002. *Beach Nourishment: Theory and Practice*. Advanced series on Ocean Engineering, Vol. 18, New Jersey: World Scientific Publishing, 399p.

Dge, 2003. Dredged Material and Legislation. Part 1. Dutch-German Exchange on Dredged Material. April 2003. 97p.

Ellis, D.V. and McDonald, V.I., 1998. Rapid preliminary assessment of seabed biodiversity for the marine and coastal mining industries. *Marine Georesources and Geotechnology*, 16, 307-319.

Eurosion, 2003. Trends in Coastal Erosion in Europe. Final Report of the Project “Coastal erosion – Evaluation of the need for action” Directorate General Environment, European Commission, 72p.

Eurosion, 2004a. Living with coastal erosion in Europe: Sediment and Space for Sustainability. Part I - Major findings and Policy Recommendations of the EUROSION project. “Coastal erosion – Evaluation of the need for action”. Directorate General Environment European Commission, 54p.

Eurosion, 2004b. Living with coastal erosion in Europe: Sediment and Space for Sustainability. Part II – Maps and statistics. “Coastal erosion – Evaluation of the need for action”. Directorate General Environment European Commission, 25p.

Gibson, J., 1999. Legal and Regulatory Bodies: Appropriateness to Integrated Coastal Zone management. Final Report, MacAlister Elliott and Partners Ltd, 98p.

Gibson, J., 2004. UK Coastal Zone Law Notes. Institute of Marine and Environmental Law, University of Cape Town http://web.uct.ac.za/depts/pbl/jgibson/iczm/notes/index.htm

Gubbay, S., 2003. Marine aggregate extraction and biodiversity. Information, issues and gaps in understanding. Report to the Joint Marine Programme of The Wildlife Trusts and WWF-UK.

Gubbay, S., 2004. Marine Protected Areas in the context of Marine Spatial Planning – discussing the links. A report for WWF-UK, November 2004, 22p.

Gubbay, S., 2005a. Marine protected areas and zoning in a system of marine spatial planning. A discussion paper for WWF-UK, July 2005, 14p.

GUBBAY, S., 2005b. A review of marine aggregate extraction in England and Wales 1970 - 2005. Crown Estate, 37p. At: www.crownestate.co.uk/1401_sue_gubbay_report.pdf

HELCOM, 2002: Environment of the Baltic Sea Area 1994–1998. – Baltic Sea Environment Proceedings No 82B, 216p.

HUMPHREYS, B.; COATES, T.; WATKISS, M., and HARRISON, D., 1996. Beach Recharge Materials: Demand and Resources. *CIRIA Technical Report No. 154*, Construction Industry Research and Information Association, London. 176p.

Construction Industry Research and Information Association (CIRIA) *Report 154*, London, 176p.

ICES, 2001. Effects of extraction of marine sediments on the marine ecosystem. *Cooperative Research Report*, No 247, 84p.

ICES, 2003a. Report of the Working Group on the Effects of Extraction of Marine Sediments on the Marine Ecosystem. *Draft Report*. Ostend, Belgium, 108p.

ICES, 2003b. Guidelines for the Management of Marine Sand Extraction, In: Report of the Working Group on the Effects of Extraction of Marine Sediments on the Marine Ecosystem. *Draft Report*, Ostend, Belgium, 72-79.

ICES, 2004. Report of the Working Group on the Effects of Extraction of Marine Sediments on the Marine Ecosystem (WGEXT). *Draft Report*, Germany, 102p.

ICES, 2005. Report of the Working Group on the Effects of Extraction of Marine Sediments on the Marine Ecosystem (WGEXT). San Sebastian, Spain, 104p.

ICES, 2006. Report of the Working Group on the Effects of Extraction of Marine Sediments on the Marine Ecosystem (WGEXT). Cork, Ireland, 91p.

ICES, 2007. Report of the Working Group on the Effects of Extraction of Marine Sediments on the Marine Ecosystem (WGEXT). Helsinki, Finland 92p.

JEWELL, T., 1996. Mineral Extraction. *In*: HUGHES, D. (ed.), *Environmental Law* (3rdEdition), Butterworths, London Bell, 333-362.

KENNY, A.J. and REES, H.L., 1996. The effects of the marine gravel extraction on the macrobenthos: results 2 years post dredging. *Marine Pollution Bulletin*, 32, 615-622.

KENNY, A.J. and REES, H.L., 1994. The effects of the marine gravel extraction on the macrobenthos: early post-dredging recolonisation. *Marine Pollution Bulletin*, 28, 442-447.

KNIGHT, S., 2005. First permit granted for full cable route, Windpower Monthly, May 2005.

LAMBRECHTS, C., 1996, Environmental Impact Assessment. *In*: WINTER, G. (ed.), *European Environmental Law*, Dartmouth, Aldershot, 63-79.

MEAKINS, S.C.; LEGGETT, D.J.; ARTHURTON, R A.; HARRISON, D., and HUMPHRIES, B, 1999. The development of marine sand and gravel in north-west Europe – Identifying the issues over the next 25 years. *CIRIA Report*, BMPA, 17p.

NBR, 2005. National Belgian report on the implementation of Recommendation 2002/413/EC Integrated Coastal Zone Management, 32p. (http://www.safecoast.org/national/)

NETHERLANDS MINISTRY OF HOUSING, 2001. Making space, sharing space. Fifth National Policy Document on Spatial Planning 2000/2020. Eds.: Ministry of Housing, Spatial Planning and the Environment, National Spatial Planning Agency Communications Directorate June 2001. A publication of Ministry of Housing, Spatial Planning and the Environment Communications Directorate P.O. Box 20951 2500 EZ The Hague The Netherlands, 71p.

ODPM, 2004. A Development Plan for Marine Aggregate Extraction in England. A Scoping Study. June 2004. Posford Haskoning Ltd, David Tyldesley Associates, The Centre for Environment, Fisheries and Aquatic Sciences, H R Wallingford Ltd. Office of the Deputy Prime Minister, London, 192p.

OECD, 1997. Managing Across Levels of Government - Belgium. 15p. (http://www.oecd.org/dataoecd/10/43/1902434.pdf)

PHUA, C.; VAN DEN AKKER, S.; BARETTA, J., and VAN DALFSEN, M., 2004. Ecological effects of sand extraction in the North Sea. *Report*, 22p.

PRING, G. W., 1999. International law and mineral resources. In: Mining, Environment and Development. A series of papers prepared for the United Nations Conference on Trade and Development (UNCTAD). University of Denver, College of Law. Published by UNCTAD, 55p.

RICHARTZ, S. and SPORRONG, N., 2003. North-East Atlantic and Baltic Sea Health Check: Assessing the status of wildlife and habitats. WWF Germany, Frankfurt am Main, 76p.

ROGERS, A. D., 2001. Habitats Directive Implementation in Europe Offshore SACs for reefs. . *In*: JONES, S. (ed.), *Implementation of the EU HABITATS Directive Offshore: Natura 2000 sites for reefs and submerged sandbanks*. Volume II: Northeast Atlantic and North Sea, *WWF Report*, 4-43.

RON2, 2004. Regionale Ontgrondingenplan Noordzee 2. Ministerie van Veerker en Waterstaat, Rijkswaterstaat 83p. http://nzl-www.sentia.nl/Images/RON2_tcm14-2777.pdf.

SCHMIDT, S. and CHRISTIANSEN, S., 2004. The Offshore MPA Toolbox: Implementing Marine Protected Areas in the North-East Atlantic Offshore: Seamounts – A Case Study. OASIS, Hamburg & WWF Germany, Frankfurt am Main, 56p.

SCOTTISH LAW COMMISSION, 2003. Report on Law of the Foreshore and Sea Bed. ScotLawCom No. 190, 68p. www.scotlawcom.gov.uk/downloads/rep190.pdf.,

SHEATE, W.; BYRON, H.; DAGG, S., and COOPER, L., 2005. The Relationship between the EIA and SEA Directives. Final Report to Europian Commision. Imperial College, London, 113p.

SHEATE, W., 1996. Environmental Impact Assessment: Law and Policy - Making an Impact II, Cameron May, London, 300p.

UNGER, S., 2004. Managing Across Boundaries. The Dogger Bank – a future international marine protected area. September 2004. WWF Germany, Frankfurt am Main, 38p.

VAN DALFSEN, J.A.; PHUA, C.; BARETTA, M., and VAN DEN AKKER, S., 2004. Ecological perspectives of marine sand extraction in the Netherlands. WODCON XVII 2004. Hamburg, Germany, 11p.

VAN ELBURG-VELINOVA, D.; VALVERDE, C.P., and SALMAN, A., 1999. Progress of ICZM development in European countries: A pilot study. Working Document 1999 (Final Draft), Leiden, 18p. (www.eucc.nl and www.coastalguide.org).

VAN LANCKER, V.R.M.; BONNE, W.; GAREL, E.; DEGRENDELE, K.; ROCHE, M.; VAN DEN EYNDE, M.; BELLEC, V.; BRIÈRE, C.; COLLINS, M.B., and VELEGRAKIS, A.F., this volume. Recommendations for for the sustainable exploitation of tidal sandbanks. *Journal of Coastal Research*.

VELEGRAKIS, A.F.; BALLAY, A.; POULOS, S.; RADZEVIČIUS, R.; BELLEC, V., and MANSO, F., this volume. European marine aggregates resources: Origins, usage, and dredging techniques. *Journal of Coastal Research*.

VELEGRAKIS, A.F.; COLLINS, M.B.; OWRID, G., and HOUGHTON, A., 2001. Submerged sandbanks of the European Shelf Waters. *In*: JONES, S. (ed.), *Implementation of the EU HABITATS Directive Offshore: Natura 2000 sites for reefs and submerged sandbanks*. Volume II: Northeast Atlantic and North Sea, WWF *Report*, 44-85.

WOUTERS, J. and DE SMET, L., 2001. The Legal Position of Federal States and their Federated Entities in International Relations - The Case of Belgium. Working Paper No 7. Institute for International Law, 32p.

Journal of Coastal Research	SI	51	39-52	West Palm Beach, Florida	Summer 2010

Morphodynamic Models Used to Study the Impact of Offshore Aggregate Extraction: a Review

Déborah Idier[1*], Saskia Hommes[1], Christophe Brière[1], Pieter C. Roos[1], Dirk-Jan R. Walstra[3,4], Michiel A.F. Knaapen[5] and Suzanne J.M.H. Hulscher[1]

[1] University of Twente
WEM, P.O. Box 217
7500 AE Enschede
The Netherlands

[*] Present address: BRGM, Service ARN
3 av. C. Guillemin
45060 Orléans cédex 2
France
d.idier@brgm.fr

[3] WL | Delft Hydraulics
PO Box 177
2600 MH Delft
The Netherlands

[4] Delft University of Technology
Faculty of Civil Engineering and Geosciences
PO Box 5048
2600 GA Delft
The Netherlands

[5] University of Southampton
Centre for Coastal Processes
Engineering and Management
Southampton, SO14 3ZH
United Kingdom

ABSTRACT

This review highlights three morphodynamics modelling approaches, used for offshore marine aggregate extraction impact assessment. These approaches are based upon examples of (1) full process-based models; (2) idealised process-based models; and (3) conceptual models. Illustrated also is the way in which these models, applied for extractions on flat bed or sandbanks, can complement each other, towards the estimation of Coastal State Indicators (CSIs). This review leads to the conclusion that, for an optimal environment assessment, there are two main approaches: (1) either combine and couple the models, in order to simulate the full morphodynamics of the system over a long time-scale, taking into account also short-term events, or (2) use a set of existing models, knowing precisely their applicability to the CSI's and the reliability of their predictions, rather than using only the best model, available presently.

ADDITIONAL INDEX WORDS: *aggregate extraction, impact, morphodynamics, modelling, sandbanks, coastal state indicator*

INTRODUCTION

Marine aggregates have become recently a strategic mineral resource. Indeed, terrestrial aggregate resources are decreasing, such that large marine aggregate extraction is now being considered, or is already in progress. Thus, it is necessary to assess the impact of offshore marine aggregate extraction on offshore morphology; this can be undertaken by estimating the future trends of coastal systems, due to these extractions. The formulation of so-called Coastal State Indicators (CSIs) can assist in addressing these coastal management questions. The CSIs are a reduced set of parameters that can simply, adequately and quantitatively describe the dynamic-state and evolutionary trends of a coastal system (Van Koningsveld, Davidson, and Huntley, 2005).

Within the EUMARSAND project (2002-2005, Bonne, this volume), marine aggregate exploitation issues were addressed through the application of a wide range of scientific approaches (based upon geology, sedimentology, physics, ecology and engineering). The integration of these approaches can improve significantly both resource management and the knowledge of the impacts of aggregate extraction, on the state and dynamics of the inner continental shelf and coastal environments. In particular, morphodynamic modelling can contribute to increasing this knowledge, e.g., in terms of near-field modelling of the physical and ecological impacts of offshore sand and gravel mining; improvement in the understanding of 'bed regeneration' processes; and the far-field modelling of the effects of dredging on adjacent coastlines). Within the framework of the EUMARSAND Project, the morphodynamic modelling of experimental sites was set up with models which are based upon the description of small-scale processes (Brière *et al.*, this volume; Van Den Eynde *et al.*, this volume). The model calibration and the validation of the numerical results were performed against high-quality field observations. For this reason, fieldwork was undertaken in the North Sea and the Baltic Sea. The Kwintebank (located within a tidal environment) was selected as the field investigation site in the North Sea, whilst the area Tromper Wiek (non-tidal environment) was examined in the Baltic Sea (Garel and Lefebvre, this volume).

Over the last decade, several other European projects have been concerned with the modelling of the impact of aggregate extraction, as outlined below.

- The SANDPIT project (Van Rijn *et al.*, 2005) was the most recent European project (2002-2004), whose overall objective was to develop reliable prediction techniques and guidelines, to better understand, simulate and predict the morphological behaviour of large-scale sand mining pits/areas, likewise, to understand the associated sand transport processes at the middle and lower (offshore) shoreface, together with the surrounding coastal zone.

DOI: 10.2112 / SI51-004.1 received 11 January 2007; accepted in revision 19 June 2007.

- HUMOR (Besio *et al.*, 2008; Dodd *et al.*, 2008) was a European project (2001-2004), with the aim to develop reliable assessment and forecasting techniques, to better understand, model and predict the physical and geomorphological processes governing medium- and long-term natural changes of the coastal zone, including the impact of anthropogenic activities. The emphasis was on the role that large-scale morphological features play, in long-term coastal evolution.
- CSTAB was a European project (1992-1995), which focused on Circulation and Sediment Transport around Banks, based upon *in-situ* measurement and numerical modelling (O'Connor *et al.*, 1994).

In this contribution, we focus upon the offshore impacts of offshore aggregate extraction, with the offshore area being the portion of the beach profile that extends seaward from the breaker zone, to the edge of the continental shelf.

One approach for assessing the impact of aggregate extraction, quantitatively, is based upon morphodynamic modelling. Several types of morphodynamic models have been developed. Each approach has its own advantages and disadvantages.

This paper deals with the two following questions: (1) which model concepts are available to assess the aggregate offshore extraction impact?; and (2) how are these models to be used and, possibly, combined for an optimal environmental assessment of offshore marine aggregate extraction in tidal seas?

We focus upon a tidally-dominated environment, paying particular attention to the dynamics of regular sea-bed morphological patterns. Such patterns, such as sandbanks, are potential resources of marine aggregate.

This paper is organised as follows: section 2 incorporates an overview of available morphodynamic modelling approaches in tidally-dominated environments, to address the research question (1) above; Section 3 includes a discussion on how to use and combine the models, with the perspective of estimating coastal state indicators; and, finally, the conclusions are presented in Section 4.

MORPHODYNAMIC MODELS FOR OFFSHORE EXTRACTION IMPACT ASSESSMENT IN A TIDALLY-DOMINATED ENVIRONMENT (QUESTION I)

Model Approaches

Coastal characteristics result generally from many physical processes, which interact at various temporal and spatial scales. The concept of scales is important in modelling processes and in the selection of a model, or type of model. Here, three main classes have been distinguished:

- The full process-based models (FPBM), which describe small-scale processes and resolve physical equations in the physical space (x,y,z,time);
- The idealised process-based models (IPBM), which take into account processes relevant to the scale of interest and resolve physical equations partly in the spectral space (wave vector, time), partly in the physical space;
- The conceptual models (CM), which aim to describe the general behaviour of a phenomenon, without describing the details of the underlying physical processes.

Here, this particular model classification is preferred, instead of the commonly used temporal- or spatial-scale classification (e.g. short-term model, medium-term model and long-term model). Indeed, it is worthwhile to note that some approaches are more applicable over different time scales.

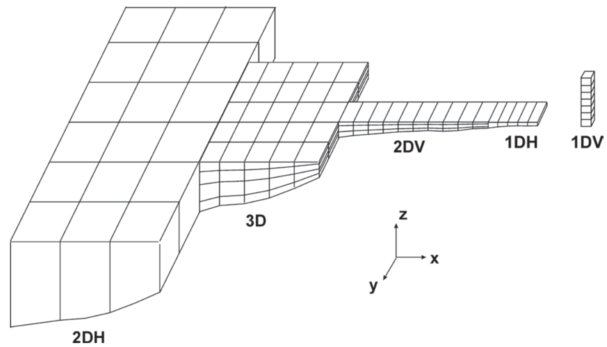


Figure 1. Discretisation levels for full process-based models. Note: the horizontal plane is (x,y). (Idier et al., present paper).

For instance, the stability analysis concept, which falls in the IPBM class, can be applied for long-term morphodynamics studies (e.g. sandbank dynamics (Huthnance, 1982)), as well as for short-term morphodynamics studies (e.g. ripple dynamics (Blondeaux, 1990)).

It may be noted that, within the process-based models, several aspects can be distinguished:

- Spatial dimensions of the model geometry (Figure 1): 1DV (V for the vertical, 0 the horizontal dimension); 1DH (H for horizontal, 1 horizontal dimension. The variables are integrated over the water depth); 2DV (V for vertical); 2DH (H for horizontal, 2 horizontal dimensions. The variables are integrated over the water depth); and 3D (three-dimensional. For instance, the velocity components are computed in the three directions x,y,z, at any location in the x,y,z space);
- Hydrodynamic processes: waves, tidal currents, wind-induced currents, and wave-current interactions;
- Sedimentary processes: suspension, bedload, and heterogeneous sediment mixtures;
- Bed evolution, related to (divergent) sediment transport.

Full process-based models (FPBM)

Theoretically, full process-based models rely upon processes alone which, in principle, should enhance their generic applicability. These models start commonly, from a number of more or less standard models of the constituent processes (waves, current, sediment transport); these are coupled through a bottom evolution equation.

De Vriend and Bakker (1993) have identified two types of full process-based models: initial sedimentation erosion (ISE) models; and medium-term morphodynamic (MTM) models. ISE models assume a fixed bed level whereas, in MTM models, the bed level is updated, on a time-scale which cannot be substantially larger than the hydrodynamic time-scale. MTM model applications are used regularly, nowadays, on time-scales of 5-20 years; this is due, not only to enhanced computer power and model robustness improvement, but also because of more reliable input reduction techniques (see, for example, Latteux (1995), for tides, and Chesher and Miles (1992), for waves). Application of these models at longer time-scales is still hampered by the fact that inaccuracies accumulate within a long-term morphological prediction; this is because of the approximations of the implemented physics, inaccuracies of the numerical schemes and schematised boundary forcing (input reduction). When these inaccuracies become of a similar order of magnitude as the physical phenomena being studied, it is not appropriate to extend further (in time) a process-based simulation.

Morphostatic models (ISE) permit the investigation of the initial response of system, to a perturbation/human intervention, i.e. not to determine towards which equilibrium, or instability, the system will develop. The solution to these limitations is to utilise morphodynamic models. However, in practice, there is often a need to interpret the results of initial transport computations, without having to resort to full morphodynamic simulations. One approach is to investigate the initial sedimentation/erosion rates; however, this method is flawed, in many respects: initial disturbances of the bathymetry have led to a very scattered pattern. For example, De Vriend *et al.*, (1993) have studied the morphodynamics of a 'sandy bump', subjected to a steady current. These investigations have shown that sedimentation/erosion patterns tend to migrate in the direction of transport; this is a behaviour which is not represented in the initial sedimentation/erosion patterns. Thus, several methods have been developed, to extend the time-scale towards a longer morphodynamic time-scale. Latteux (1995) has proposed several methods, such as tide-lengthening. This approach, which is adequate to study propagative features such as sandbanks (Latteux, 1995), consists of increasing the morphological time-step, by a so-called morphological factor (typically, N = 100 to 1000); this is such that full process-based morphodynamic models can now be applied, at time-scales of ~5 to 10 years (medium-term models). Such methods are implemented in many morphodynamical models. Roelvink (2006) developed another method, which assumes that the overall flow and wave patterns do not change for small bed level changes. This assumption is used also in the "continuity correction" of many morphological models. The tidally-averaged transport rate is a function of the flow and wave patterns (which do not vary on a morphological time-scale), and the local water depth (which varies on a morphological time-scale). Thus, given a certain set of current and wave conditions, transport at a particular location is only a function of water depth ($\left|\vec{S}\right| = A(x,y)h^{-b}$); here, h denotes water depth and b is a constant. In this case, the value of A at each horizontal point (x,y) can be derived directly from the local water depth and the initial transport rate, which may be computed using a sophisticated transport model. This approach means that the downslope preference of bedload (within the initial transport rate), as well as wind-driven current effects (within the transport rate, averaged over a tidal cycle) is included. A combination of the sediment balance equation, together with the equation cited, requires very little computational effort (this method has been implemented in Delft3D-RAM, Rapid Assessment Module). Within morphodynamically active areas, such as estuaries and outer deltas, the RAM method may still work well enough to be applied as a rapid updating scheme. As soon as the seabed change becomes too large, full simulation of the hydrodynamics and sediment transport is carried out for a number of input conditions. A weighted-average sediment transport field is then determined, which is the basis for the next RAM computation over, for example, a year. An important observation can be made that (costly) computations, to update wave, flow and transport fields, can be carried out in parallel; this, in addition to the simplified updating scheme, leads to a significant reduction in the simulation time (compared to a FPBM approach). With this approach, i.e. the coupling of the hydrodynamic FPBM Delft3D and the RAM module, morphodynamic simulations (covering decades to centuries) are feasible, in terms of computational effort. However, experience of applying such a process-based model, on time-scales longer than 50 years, is limited.

Finally, all of these models suffer from variability in, and errors associated with, the input and the boundary conditions.

Idealised process-based models (IPBM)

Idealised process-based models are morphodynamic models, intended especially to describe the dynamics (generation, growth, maintenance) of regular sea-bed patterns. Such models are based also upon physical equations, such that they have almost the same limits as the full process-based models, in relation to lack of knowledge (or parameterised incorporation) of small-scale processes. However, the models are developed and used for well-defined applications, to isolate certain phenomena, e.g. sandbank generation. Compared to the full process-based models, idealised models assume simplified geometry, inputs and boundary conditions; and such, IPBM are generally much less expensive, computationally. The simplified inputs imply that the hydrodynamic forcing is quite simplified, and that, at least untill now, the extreme events are not described explicitly. As inputs are simplified, this implies they have been designed mainly to provide information (preferred wavelength, orientation, saturation height, or shape for certain conditions) on the free behaviour (natural evolution without any temporal change in the forcing) of the system (e.g., sandbank generation over a flat bed).

The IPBM models assume an initial sea-bed perturbation which is, mathematically, infinitesimal with, for instance, the amplitude being several orders of magnitude less than the water depth. Subsequently, the aim of these models is to determine whether this seabed perturbation will grow, or decay, with time; likewise how it will evolve. Hereinafter, as a starting point of a stability analysis, a physically-relevant and exact solution of the constituent equations is required. For example, for an application to offshore bedforms, the basic state (the solution of the zeroth-order equations) is that of a flat bed. Therefore, the hydrodynamic and bed evolution equations are solved for an initial flat bed, leading to horizontally-uniform solutions. This basic state is perturbed by arbitrary small periodic bed waves, denoted by a 2D wave-vector (the module is inversely proportional to the wavelength and the direction is perpendicular to the bedform crests), allowing for all combinations of bed wavelengths and orientation. For some wave-vectors, these perturbations decay with time; for others, the basic state becomes unstable and some of the disturbances will grow. Thus, evolving into a regular pattern of finite amplitude. An important aspect of the idealised process-based models is that the equations are solved partly in spectral space (the space of wavelength and the orientation of bedforms) and partly in the physical space, instead of in the physical space of the full process-based models (e.g., Delft3D). For cases of uniformity in both horizontal directions, the equations are even solved fully in the spectral space. (Dodd *et al.* (2003) have undertaken a review of the different types of stability analysis). The two main classes are the linear and the non-linear stability models. The first approach yields information on the initial stage of formation (linear interactions only): for instance, for bedform generation, the assumption of a bedform amplitude much smaller than the water depth is related directly to this linear approach. If larger bedforms are considered, non-linear interactions occur and higher-order terms in the bed amplitude have to be taken into account.

Conceptual models (CM)

The conceptual models, also referred to as behaviour-oriented models, attempt to describe the general behaviour of a phenomenon, without entering into details of the underlying physical processes. The derivation of these models is based often upon both measurements and physical conservation (for instance the sediment-mass balance). Hanson *et al.* (2003) have provided an overview of these methods, for use in coastal regions.

A typical conceptual model focussing upon offshore dredging has been developed by Knaapen and Hulscher (2002). These investigators developed a model describing the regeneration of sand waves, following their removal, to increase the water depth for navigation. Based upon the stability model of Hulscher (1996), together with the knowledge that sand waves reach equilibrium with a finite height, Knaapen and Hulscher (2002) assumed that the sand wave amplitude A follows the equation:

$$\frac{\partial A}{\partial t} = a_1 A - a_2 A^3$$

Where A is the bedform amplitude, coefficient a_1 is related to the linear growth and a_2 to the equilibrium height. This generic equation, referred usually to as the Landau equation, appears in many weakly non-linear stability analyses (Dodd *et al.*, 2003), in which the coefficient a_2 can be derived from the (mathematical) weakly non-linear analysis. Knaapen and Hulscher (2002) showed how the coefficients a_1 and a_2 can be derived, using data and the linear model. The coefficient a1 could be deduced from the stability model of Hulscher (1996). Alternatively, the coefficients a_1 and a_2 could be estimated by fitting this model to the results of any other model. This remark is important, if there is only limited information available on the regeneration of larger sand patterns, for which the time-scales are even larger.

ASMITA (Aggregated Scale Morphological Interaction between a Tidal inlet and the Adjacent coast; Stive and Wang, 2003) provided another example of a behaviour-oriented model. This model describes the evolution of a tidal inlet, towards a new equilibrium forced by external conditions or geometric interventions. This concept was applied firstly to the Wadden Sea by Eysink (1990), who derived an analytical expression for the morphological evolution of a disturbance, from the equilibrium state for a single element. ASMITA is an extension and aggregation of the ESTMORF model (Stive et al., 1998). Aggregation is related to the fact that each morphological element is characterised by only one variable, i.e. its equilibrium volume. The underlying principle is that each element (delta, channel, flat) attempts to reach a new equilibrium state. Although ASMITA was originally not designed to investigate the effects of sand extraction, the concepts can be applied also to this problem. Instead of identifying morphological units, the schematisation can be based also upon a computational grid. The exchange between the cell-interfaces is determined by advection and diffusion of the sediment. The advective sediment exchange can be estimated from the residual tidal motion predicted by a process model (e.g., Delft3D or Telemac). Sediment diffusion is based upon an estimate of the equilibrium sediment concentrations, which depends upon the ratio between the actual water depth and an equilibrium depth (typically, the undisturbed ambient water depth).

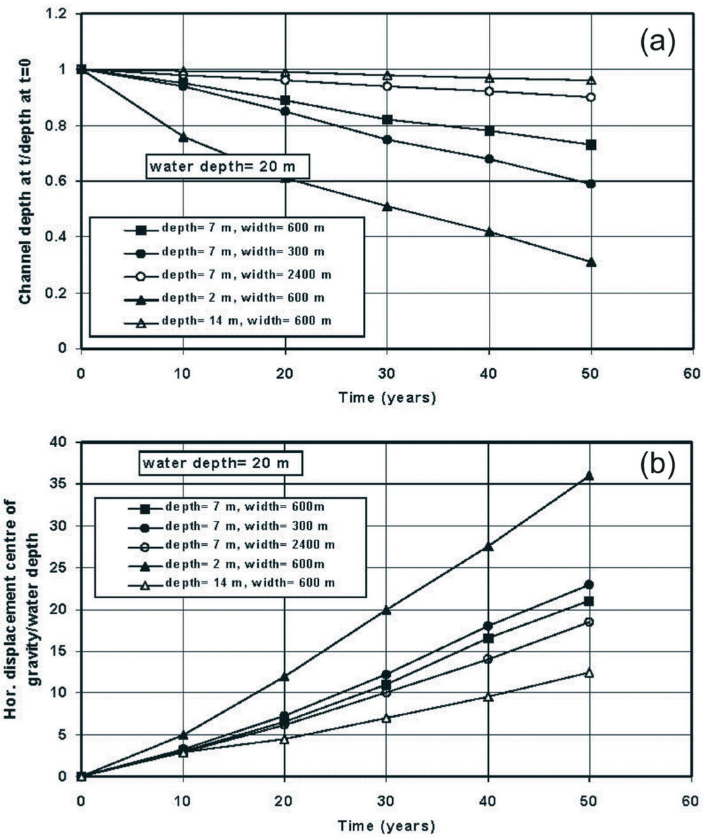


Figure 2. Influence of channel dimension on sedimentation and horizontal displacement of channel, after 50 years (Van Rijn and Walstra, 2002). Note: results obtained with SUTRENCH.

All of these conceptual models are based upon a number of assumptions, such as, for instance, that a dredged sandwave will recover its original amplitude; these have to be checked carefully, independently when, using these models.

Offshore Impact of Offshore Extraction

Offshore extraction on a flat bed

The offshore impact of offshore extraction, on a flat bed, has been studied using the two types of models: full process-based and idealised process-based models. For conceptual models, indications on possible future use are provided.

Full process-based models (2DV, 2DH and 3D). Several levels of complexity of full process-based models have been applied to, then compared with similar cases. Van Rijn *et al.* (1999), studied the morphodynamics of a trench, using SUTRENCH; this is a 2DV model, based upon advection-diffusion equations for computing the bed sedimentation in channels under varying wave and flow conditions. The model calculates, in a time-dependent mode, sediment transport in response to currents and waves, as well as changes in bed levels. Using this model, the influence of the channel dimension on sedimentation and the induced horizontal displacement of the channel, over 50 years, has been studied (Figure 2). The study predicts that the water depth outside the mining pit has the greatest influence on its morphological evolution (Figure 2,

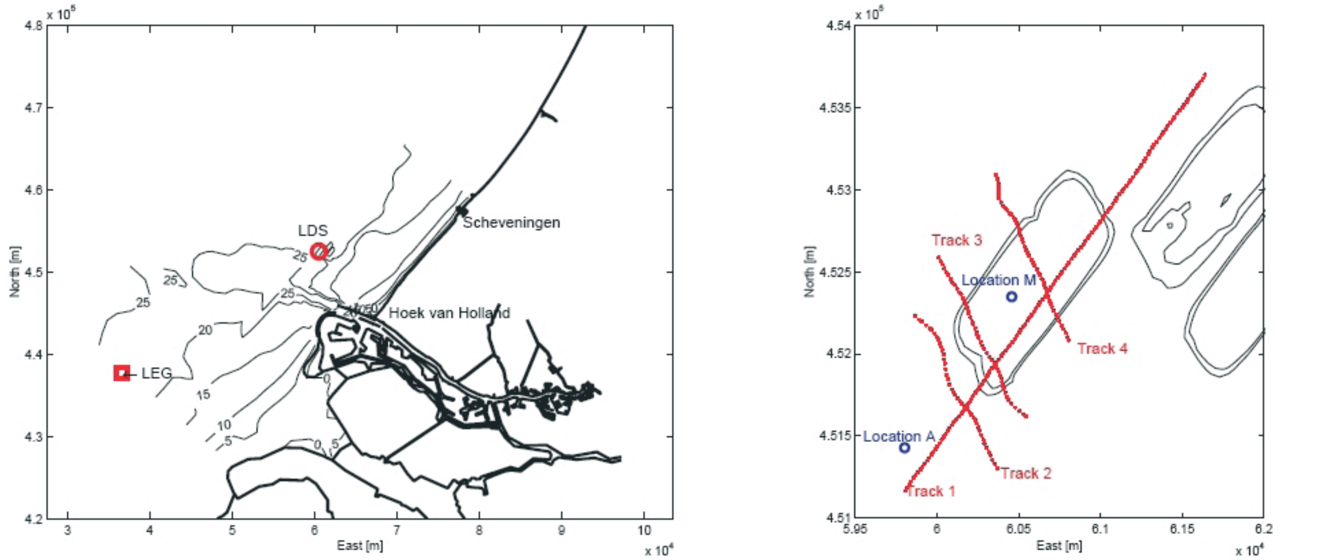


Figure 3. Plan view of LDS (LDS is the pit location), measurement locations and measured tracks.(a) : overview of pit location (LDS is pit location; LEG is the offshore wave station); (b) : plan view of LDS, with measurement locations (blue) and tracks (red). (from Walstra *et al.*, 2002).

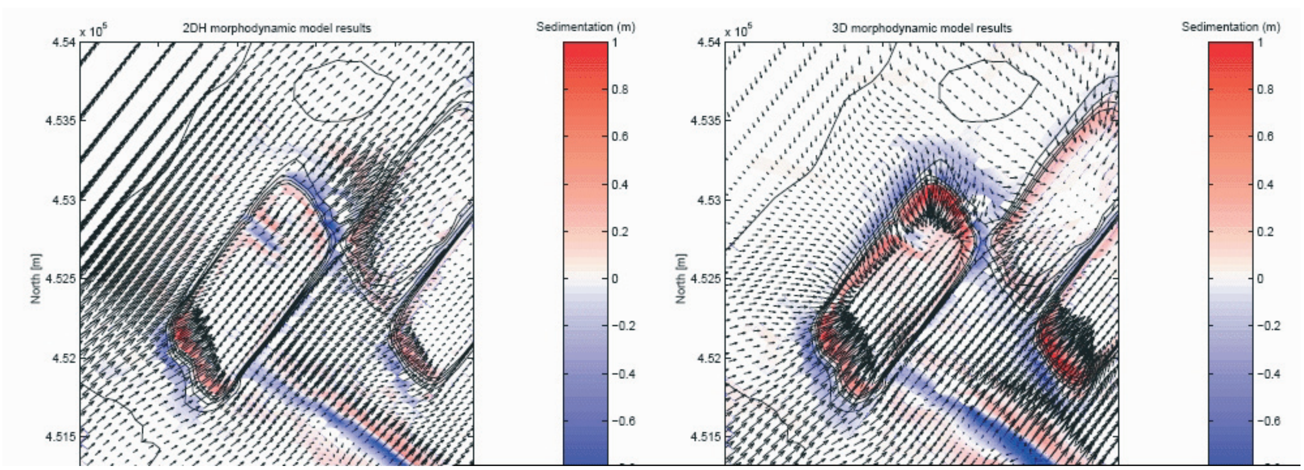


Figure 4. Sedimentation-erosion and yearly residual transport calculated in 2DH (a) and 3D (b). (from Van Rijn *et al.,* 2003).

upper panel); this is in response to the effect of water depth on the sediment transport capacity. In contrast, the pit geometry and its dimensions have much less effect on the morphological evolution of the pit. Figure 2 (lower panel) shows also that wide pits have a larger morphological time-scale than deep pits, which have also a smaller migration rate; this is "favourable" as it minimises the impact on the coastline. However, comparison with 2DH models shows the importance in reproducing the flow contraction that occurs in the trench, which was not included in the SUTRENCH simulations.

WALSTRA *et al*. (2003) validated the Delft3D model in both depth-averaged (2DH) and 3D-mode. In the sediment transport module, the model takes into account bedload, suspension and wave effects. The 2DH model has been used to study the sedimentation-erosion, as well as the annual residual transport, in an offshore pit in the North Sea; this was located 10 km off the Dutch coast, near the Hoek van Holland (Figure 3). These results (Figure 4a) have been compared to the results obtained with the 3D model, Delft3D (Figure 4b). Both models predict that most changes occur in the immediate vicinity of the pit, with erosion just outside the pit and sedimentation mainly on the pit slopes. However, the 3D simulation resulted in significant larger changes in the morphology. In particular, sedimentation on the longshore pit slopes is more pronounced in the 3D results; this is caused mainly by secondary cross-shore flows, related to the presence of the pit and density-driven flows (visible clearly in the residual transports patterns). The 2DH simulation predicts northeasterly transport, parallel to the main tidal direction; this leads to morphological changes occurring mostly on the pit slopes, perpendicular to the

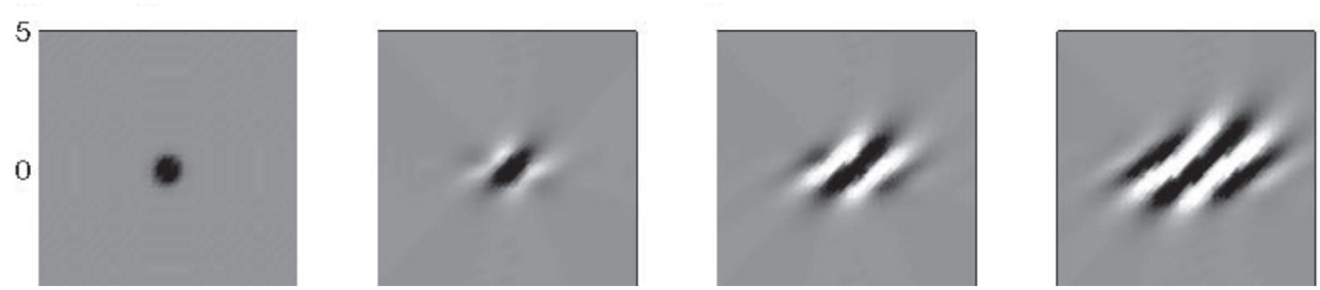


Figure 5. Plan view of the evolution of a sandpit, created on a flat bed, subject to tidal flow (M2 and M4). The deeper parts are shown in black, with the shallower parts white, the undisturbed seabed is grey. Domain size: approximately 70 x 70 km². (Roos and Hulscher, 2003).

main tidal direction, related to the acceleration and deceleration of the flow. However, the 3D simulation predicts that the pit location LDS attracts sediment from all directions, which results in southward transport over the northern part of the pit. Based upon surveys of the pit area, Walstra *et al.* (1997) concluded that the 3D morphodynamic simulations provided a more accurate prediction. However, such a conclusion cannot be validated definitively, because of the absence of reliable measured seabed changes (i.e. the observed bed changes were of the same order as the measurement error). Moreover, the relative small time-scale considered (one year) was too short to draw any definite conclusions.

Idealised process-based models. Using an idealised process-based modelling approach, Roos and Hulscher (2004) investigated the morphodynamic effects of creating a large-scale sandpit (2m deep, 15km length, and width of 1km), in a flat region of the offshore seabed (in a water depth of 20m). The results show that flow contraction occurs, increasing the water flux inside the pit. Such convergence of the streamlines of the depth-averaged flow, inside the pit, can be explained by: the continuity law of the flow entering and leaving the pit, the reduced friction inside the pit, due to the increased depth, and the adaptation length.

The morphodynamic implication of this phenomenon is a gradual deformation of the sandpit in the preferred direction of sandbank formation, together with the appearance of additional humps next to the pit (Figure 5).This morphodynamic response is related directly to the inherent instability of an initially flat seabed, which develops into a pattern of tidal sandbanks over a time scale of about 1000 years (Huthnance,

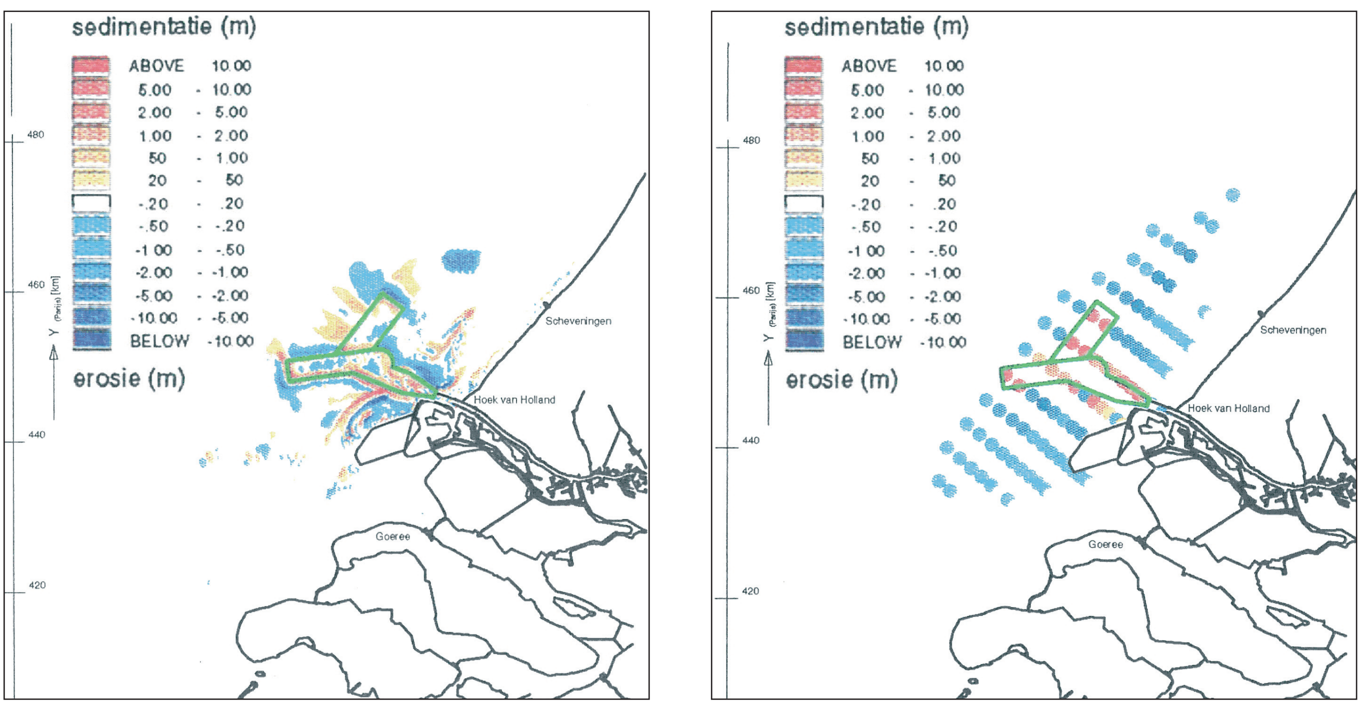


Figure 6. Predicted relative bottom changes due to sand extraction (bottom changes of the land reclamation are ignored, extraction area indicated by green polygon): (a) plot of the predicted changes, after 50 years, with Delft3D-RAM; (b) plot of the predicted changes, after 300 years, with ASMITA.

1982). The results display also pit migration in the direction of the tidal asymmetry with the response depending upon the pit geometry. Futhermore, the inclusion of sandwave formation processes leads to higher rates of pit migration (ROOS *et al*., 2005).

Conceptual model. To date, conceptual models relating to an offshore sand pit have still to be published. The lack of measured data makes it difficult to validate such models. Some conceptual models have been applied to study seabed dynamics, in the case of sand pit extraction (see the ASMITA model (next paragraph on combined models)), but they are not designed to reproduce the dynamics of the pit itself. A possible approach could be to examine a sand pit resulting from mining, as an initial perturbation from the equilibrium flat bed. Assuming that the interference effects (Figure 5) of ROOS and HULSCHER (2004) are avoided, relaxation theory assumes then that the infilling of the pit will be:

$$\frac{\partial D}{\partial t} = a_1 D$$

In the case of a negative growth parameter (a_1<0), the depth *D* of the pit will decrease, exponentially to zero. The value of this growth parameter has to be estimated; presently, this can not be determined from measurements. As the seabed dynamics on the length scales being examined will take place on very long time-scales (over decades), a reliable calibration would require surveys spanning decades. Nevertheless, process-based models reveal that the dynamics of such a pit depends strongly on the shape, size and orientation of the pit (ROOS and HULSCHER, 2004; VAN RIJN *et al*., 1999, WALSTRA *et al*., 2003). This conclusion implies that calibration of the conceptual model should be applied to a wide range of pit sizes, shapes and orientations. It will be a long time before such measurements, on a wide range of pits, would be available, i.e. regarding the number of all possible pit size, shapes and orientation to span, as well as the long morphological time-scale associated to pit dynamics. Alternatively, the conceptual model could be fitted against a combination of outputs from process-based models. Once the conceptual model is tuned against results of various process-based models runs, it could be a rapid, yet reliable, and therefore a useful decision-making tool for seabed mining management.

Combined models. In WALSTRA *et al*. (1997), Delft3D (a full process-based model) and ASMITA (a conceptual model) were applied simultaneously, to investigate the large-scale extraction of 1 billion cubic meters of sand for land reclamation (Maasvlakte-2), at the Rotterdam harbour in the Netherlands (Figure 6). Delft3D-RAM simulations, over 50 years, predicted that the effects of the sand extraction (a lowering of 10 m, inside the green box in Figure 6) were confined to the immediate surroundings of the extraction area. The ASMITA simulation, covering a 300 year period, reveals that the morphological effects are present over a significantly larger area (the effects on the coast were not included). An important advantage in using the ASMITA conceptual model was the possibility to perform a sensitivity analysis, over the 300 year period. The sensitivity analysis concluded that the model predictions were robust, i.e. parameter variation resulted in linear, or almost linear, effects on the model output.

Offshore extraction on sandbanks

Sandbanks are characteristic of continental shelves with a high supply of sand and sufficiently strong tidal currents. The Belgian continental shelf, in the southern part of the North Sea, is covered abundantly with these large structures and has been studied extensively (LANCKNEUS *et al*., 2001). All three model types (full process-based, idealised process-based, and conceptual models) have been used for studying the offshore extraction from sandbanks.

Full process-based models (2DH). FPBM models are used often for investigating the behaviour of the sea bed; their application to sandbank morphodynamics is not straightforward

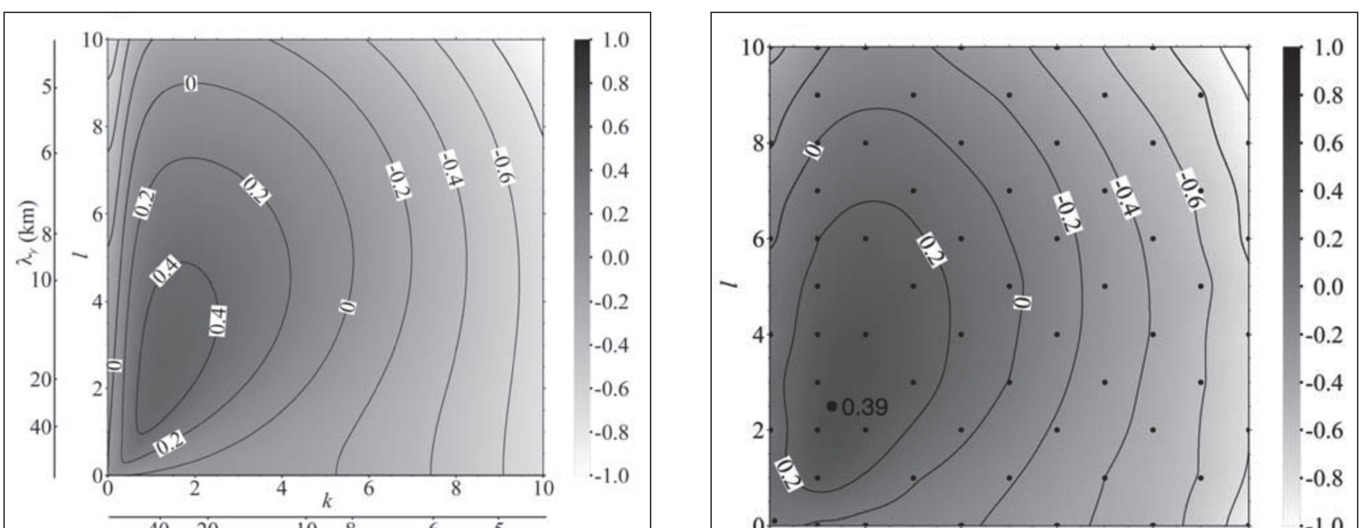


Figure 7. Dimensionless growth rate: (a) idealized process-based model (linear stability analysis); (b) full process-based model (Telemac). Note: on the Figure, wave number k is in the direction of the tidal current, whereas wave number l is perpendicular. Water depth=30 m. Grain size=0.5 mm. Strikler coefficient=55 m1/3s-1. Depth integrated velocity=1 m/s. Morphological time-scale=303 years. (from Idier and Astruc,2003).

and only limited applications have been undertaken, especially on the influence of sand extraction from sandbanks. However, part of the dynamics has been studied; for instance, the ability of a FPBM to reproduce sandbank generation (Idier and Astruc, 2003). Hydro-sedimentary patterns of dredged sandbanks have also been modelled (Deleu *et al.*, 2004); these studies as described below.

Based upon idealised process-based model results (linear 2DH stability analysis), together with those of a full process-based model (Telemac), Idier and Astruc (2003) have studied the linear and non-linear behaviour of large-scale underwater bedform patterns, such as sandbanks. The model is based upon depth-integrated hydrodynamic equations, with a quadratic bottom friction law (Telemac2D), together with a bed load sediment transport model including a bottom slope effect (Sisyphe, a module of the Telemac package). Firstly, the stability of a flat sand bed subject to a simple tidal current was computed, using the Telemac model. Small amplitude sinusoidal bedforms are superimposed upon the flat bed. They are characterised by a single wavelength and orientation, relative to the current. The growth rate of this eigenmode has been defined as:

$$\frac{\partial h}{\partial t} + \vec{\omega}_a . \vec{\nabla} h = \omega_g h$$

with h the bedform amplitude, ω_g the growth rate and $\vec{\omega}_a$ the migration rate. Good agreement with the linear stability results was found (Figure 7). Secondly, the Telemac model was used to investigate the non-linear behaviour of the instability, for a simple tidal current; more specifically, to estimate the saturation height of the theoretically most-amplified mode. Thirdly, a Landau equation, whose coefficients are computed from the previous results, was used to predict the temporal evolution of the bedform amplitude from its initial infinitesimal amplitude to saturation. A comparison with the characteristics of continental shelf sandbanks shows that the model provides a reasonable estimation of the temporal dynamics of these large-scale bedforms. The saturation height appears to be slightly overestimated, which is due to the study hypothesis (the study is focused on the temporal variations of one mode, assuming that the "linearly most amplified" mode will be the dominant mode in the non-linear regime). However, this study has shown that full process-based models are able to reproduce the generation of bedforms, whose characteristics are close to those of the sandbanks; it has shown also a part of the sandbank height saturation processes, since for large enough amplitudes, the model is able to provide negative growth rate for modes which were amplified initially. Furthermore, this publication provides an example of how to combine various approaches (here, full process-based model (Telemac), idealised process-based model (linear stability analysis), and conceptual model (Landau equation)).

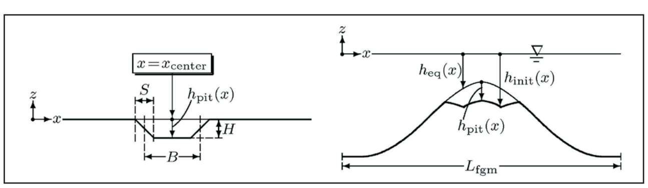


Figure 8. Definition sketch of a sandpit, as created in a one-dimensional equilibrium profile of a tidal sandbank (after Roos, 2004): (a) pit geometry h_pit(x), showing width B, depth H (and slope length S), (b) the same pit, now created at the crest of a tidal sandbank in morphodynamic equilibrium h_eq(x). Notes: (i) the pit location relative, to the bank profile, is an additional characteristic of sand extraction (compared to the flat-bed case) and (ii) the model assumes alongbank uniformity, i.e. the banks and pits are infinitely long.

The Hinder Banks (lying to the North Sea) and the Flemish Banks are non-idealised sandbanks studied within the framework of the CSTAB project (and also the BUDGET -Lankneus *et al.*, 2001- MAREBASSE -Van Lancker *et al.*, 2007- or EU-MARSAND projects). Within the CSTAB project, Williams *et al.* (2000) applied a three-dimensional model to the Middelkerke Bank. The model included tidal currents, wind waves and sediment transport. The results reveal the presence of a clockwise residual circulation of water around the bank, which is consistent with theory. Further, all of the studies undertaken showed that the sandbanks are areas of a changing spatial depositional budget, due to complex hydrodynamic forcing. Likewise, sandbanks should be seen as part of a system of swales and sandbanks. Such results assist in understanding the temporal and spatial evolution of tidal sandbanks.

Another example of a full process-based model applied to sandbanks is a study undertaken by Deleu *et al.* (2004) in which the Westhinder Bank (Belgian continental shelf) has been modelled using a morphostatic model; this consists of an hydrodynamic module, mu-HAB, and a sedimentary module, mu-SEDIM. These investigations provided information on current pattern and sediment circulation around the bank.

Idealised process-based model. In the field, two types of sandbanks are found: tidal sandbanks (sandbanks oriented counter-clockwise to the main current in the Northern Hemisphere) and shoreface-connected ridges (sandbanks lying closer to coastline and oriented clockwise to the main storm induced current). The extraction of marine aggregate has been studied for both of these features.

The stability model presented above (Section 2.3.1) considers a flat bed and, as such, is thus not suitable for studying the impact of sand extraction from tidal sandbanks. For this

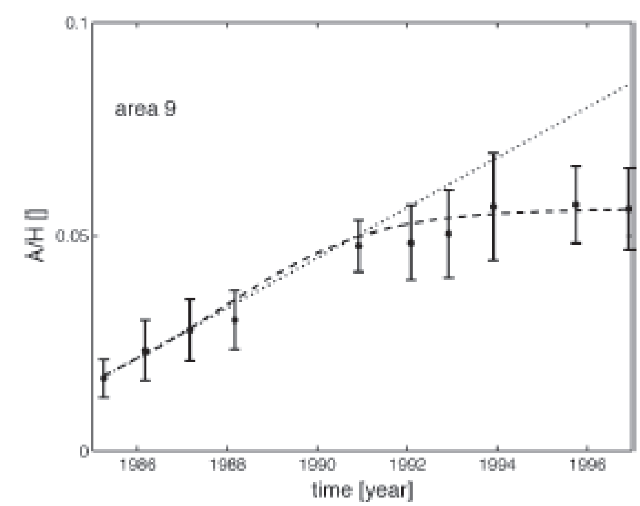


Figure 9. Prediction of the sand wave growth in Bisanseto Channel (Japan). The model is based upon the Landau equation (dashed line) and the linear trend analysis (dotted line), both based upon a model parameter tunning on the first three measurements (before 1968). (from Knaapen and Hulscher, 2002).

purpose, the finite amplitude equilibrium profiles were obtained, with the non-linear sandbank model provided by Roos *et al.* (2005). Sand extraction from a tidal sandbank can be seen as a local perturbation of such a profile (Figure 8). Roos (2004) showed that, after creating such a pit, the system shifts to a new equilibrium state. The corresponding time-scales are of the order of a century; they are shortest for deep and narrow pits created in the crests of the banks. It is important to realise that the above model approach considers sand extraction from each individual bank, within a periodic profile; thus, all of the banks are considered to be identical. As a result, the potential interaction between a sandbank, with a pit and surrounding banks (without a pit), cannot be studied. Such a limitation (lack of localisation) is inherent in such an idealised model.

Elsewhere, a stability analysis approach has been used by De Swart and Calvete (2003) to study the impact of extraction on shoreface-connected ridges. The model is based upon non-linear stability analysis. The main processes taken into account were: storm-driven currents; 2DH shallow-water equations; bedload and suspended sediment transport; the action of waves; net currents; and seabed slopes. In particular, these investigations have shown that, following the local removal of sand, the system tends to return to its original equilibrium state. This gradual process, occurring over several centuries, is associated with a supply of sand, from both the outer shelf and the nearshore zone. Thus, extraction of sand from the shelf (shoreface-connected ridges), together with the dredging of navigation channels, may have negative implications for the stability of the adjacent beach.

Conceptual models. To the knowledge of the authors, there is only one conceptual model which has been proposed, in relation to offshore dredged sandbanks (Hommes, Hulscher, and Stolk, submitted). Previously, Knaapen and Hulscher (2002) applied a conceptual model to dredged sandwaves, assuming that they will recover their initial amplitude, after dredging. The growth of such tidal sandwaves followed a logistic equation, as illustrated in Figure 9:

$$\frac{\partial A}{\partial T} = a_1 A - a_2 A^3$$

In Hommes, Hulscher, and Stolk, submitted, this model is adjusted to predict the regeneration of 'sand ridges' (technically, the same as sandbanks), following dredging (Figure 10). Parameter settings have been estimated from the sandbank study of Hulscher (1996). A value for the linear growth parameter a1 was estimated, based upon the physical processes and for typical North Sea conditions. The non-linear damping parameter a2 was estimated from bathymetric data available for sandbanks. Assuming that the sandbanks are in equilibrium with prevailing current conditions, i.e. no temporal change, the equation reduces to:

$$a_2 = \frac{a_1}{A^2}$$

The coefficient a_2 was estimated by assuming an equilibrium sandbank height of 15 m, this is a typical height for the Zeeland ridges. The model gives the recovery period, which is the time taken for the dredged bedform to reach its former height. The influence of the dredging depth on the recovery period was investigated, e.g., assuming that the crest of the sandbank will be lowered by 2 m and, using these coefficients, the recovery period would be about 400 years. After tuning the model against a combination of field measurements, idealised process-based models and full process-based models, the model's simplicity makes it a very useful tool for designing optimal sandbank mining strategies.

This approach, based upon a logistic equation, assumes a lowering of the complete sand bank. The dependency on horizontal pit size (shown in Figure 2) can be incorporated only by pit-size dependent model coefficients; likewise, the effect of pit migration needs to be negligible.

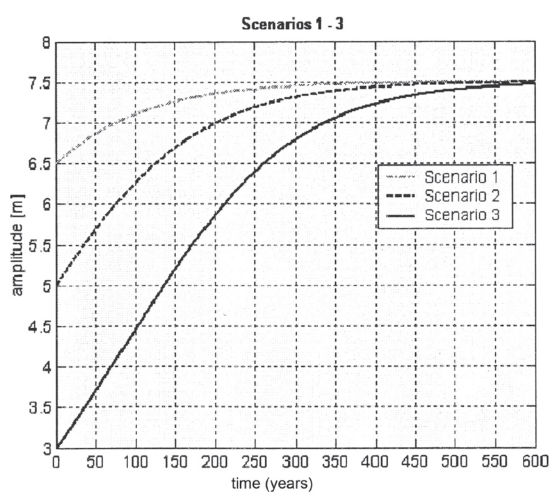


Figure 10. Results obtained from an amplitude-evolution model. In the model runs, the amplitude before dredging (A0) was taken as 7.5 m, which is similar to the amplitude of the Zeeland ridges (see text). The scenarios shown are: scenario 1 (dredging depth=2m); scenario 2 (dredging depth=5m); and scenario 3 (dredging depth=9m). (from Hommes, Hulscher, and Stolk, submitted).

Discussion on nearshore impact of offshore extraction

The influence of waves on sediment transport is stronger, generally, in the nearshore area. However, not all of the available offshore models integrate such wave-induced sediment transport processes. However, the offshore models can assist also in the evaluation of coastal dynamics, as they are able to explain how mining activities influence sediment transport patterns towards the shore. One impact of a bed depression on the adjacent coastline is the modification of the induced wave propagation. Such modification could have a drastic effect on the shoreline. The study of the relationship between the nearshore area and offshore sand extraction is still under investigation, e.g., using field measurements, it is difficult to relate properly offshore sand extraction and beach evolution.

Full process-based modelling has been used previously within the CSTAB project (MacDonald and O´Connor, 1996). The project included modelling and field experiments undertaken on the Middelkerke Bank (the Belgian continental shelf) and the adjacent Nieuwpoort beaches. On the basis of field observations, these investigations concluded that sandbanks afford substantial protection to the coast and that this effect may be reduced by rising mean sea level and dredging activities.

The relationship between sandbanks and the shoreline was investigated also in the project "Understanding the Behaviour

Table 1. *Synthesis on the long-term approaches.*

	Advantage	Drawback	Outputs	Time/space scale
Lesser *et al.* (2004), with Delft2D/3D (full process-based)	Quite reliable results, on the short- or mid-term (Van Rijn *et al.*, 1999; Tonnon *et al.*, 2007; Sutherland *et al.*, 2004; Nicholas *et al.*, 2004)	Highly sensitive to quality of local boundary and initial conditions Time-consuming, for sensitivity analysis	Current Wave Sediment flux Bed evolution	Few meters to hundreds km Minutes to decades
Roos and Hulscher (2004) (idealised process-based)	Process analysis (geared to describe an isolated phenomenon, in an idealized case, eg, sandbank dynamics)	Hard to set up a stability analysis model. Problem of validation of this approach (Peters and Hulscher, 2006). cannot be used in site-specific situations, e.g. the Kwinte Bank.	Current Sediment flux Bed evolution	Few meters to hundreds km Decades to century
Hommes *et al.* (submitted) (conceptual)	Not time-consuming. Easy to use	Field data required Require qualitative support from process-based model results, or from field experience (check if the model is appropriated for the considered configuration ?)	pit/sandbanks amplitude	Event scale, or long-term

and Engineering Significance of Offshore and Coastal Sand Banks" (Whitehouse, 2001). The influence of bank changes, on coastal sediment transport and morphodynamics was assessed using numerical coastal process-based models (Southgate and Brampton, 2001), which showed that the beach generally supplies the banks, if the sand is exchanged between the beach and the bank. Other field studies have confirmed this behaviour: beach-bank exchange occurs, for example, at Donna Nook on the Lincolnshire Coast (UK).

Idealised process-based models, not specifically nearshore models, can also be used. For example, a stability analysis has been performed on shoreface-connected sand ridges by de Swart and Calvete (2003). In addition to the offshore impact, this study provides information on the nearshore impact of offshore extraction on the ridge.

Hanson *et al.* (2003) have provided an overview of nearshore models (especially, conceptual models), to study the impact on the shoreline, including waves.

Main characteristics of the three approaches: examples

Examples show how the three approaches complement each other. Table 1 lists some of their characteristics: advantages, disadvantages, outputs, and time/space scales; the latter are somewhat related. This relationship can be shown using linear stability analysis, where the morphological time-scale is related to the spatial scaling. For instance, in Idier and Astruc (2003), the morphological time-scale (hundreds of years) is related to the tidal excursion length (hundreds of kilometres).

In general, engineering studies use FPBM to analyse morphodynamic changes; they appear more reliable, because they

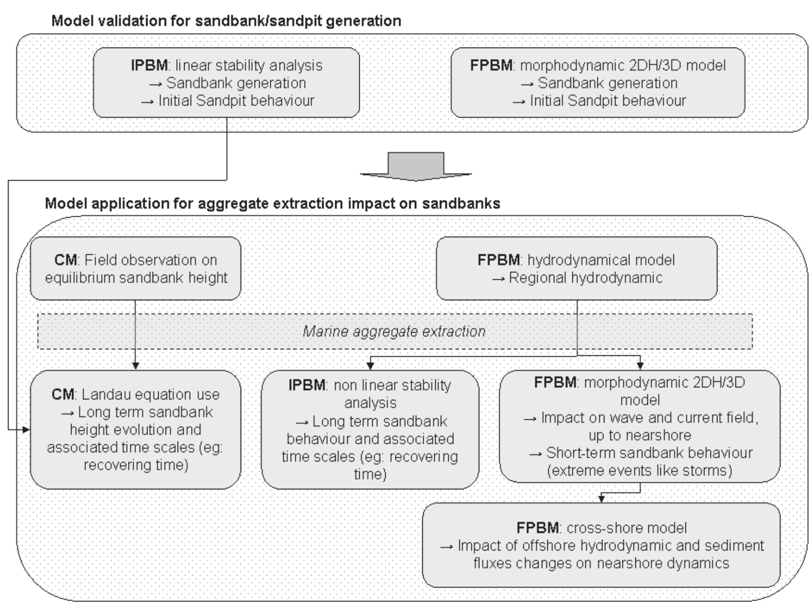


Figure 11. Schema example of model coupling for the impact study of offshore aggregate extraction, in a sandbank area. Terms: IPBM - Idealized process-based model ; FPBM - Full process-based model; and CM - Conceptual model.

contain descriptions of all the processes. Occasionally, a CM is used: ASMITA for problems around tidal inlets (Kragtwijk *et al*., 2004), and the one-Line model (Demir *et al*., 2004) for coastal changes. The IPBM has so far been used only rarely; these models are a combination of the CM (which is intuitive and easy to understand) and the complete FPBM. The models contain most, but not all, of the processes; they are difficult to understand (less intuitive), especially if non-linear effects are incorporated. However, they can provide relevant information (to orders of magnitude) on long-term temporal and spatial scales (Peters and Hulscher, 2006).

Each of these model approaches is dependent upon location and the hydro-sedimentary conditions of the surroundings. For instance, FPBM models need sufficiently refined bathymetric data, in order to establish relevant computational grids. IBPM can require also a range of regional data, in case it is applied "point by point", as in Van der Veen *et al*. (2006). Here, a stability analysis model is applied to the whole of the North Sea, using GIS data for input parameters. For example, CM models require sedimentary data (ASMITA), or the temporal evolution of the bathymetry (the Landau approach).

Upon the model being set up, a general problem with them is their validation: in the absence of long-period time-series, it is difficult to ascertain the model accuracy.

DISCUSSION ON THE USE OF MODELS TOWARDS COASTAL STATE INDICATORS

Coastal State Indicators

From a Coastal Zone Management (CZM) perspective, the possibility of sand extraction is determined by physical, socio-economic and administrative contexts. Rational CZM will be based upon an integrated analysis of the various components. A coastal manager will require a rational decision-making process,that is both transparent and reproducible. Strategic CZM objectives that are sometimes vague need to be translated into (specific) operational objectives. An important component of this process is the definition of a set of Coastal State Indicators (CSIs). Each indicator is related to a specific coastal-user function, e.g. coastal safety, navigation, offshore infrastructure.

The first question on the use of the models is: which model or approach is the most appropriate for estimating coastal state indicators?

For example, a number of indicators are listed below, together with examples of models which could be used to estimate the indicator.

- Sand budget in the offshore, extending to the nearshore zone: numerical morphodynamic model (Delft3D) (Class: FPBM)
- Wave height: numerical wave model (SWAN, REF-DIF) (Class: FPBM)
- Tidal current: numerical current model (Delft3D) (Class: FPBM)
- Sandbank height: non-linear stability analysis (Roos *et al*., 2004) (Class: IPBM)
- Recovering time, after extraction: Landau equation (Class: CM)
- Short-term sandbank height variability (extreme events): numerical morphodynamic model (Delft3D) (Class: FPBM)

These offshore models can be used also as boundary conditions for engineering cross-shore models, to estimate Coastal State Indicators:

- beach profile : cross-shore model UNIBEST-TC, SBEACH, CROSMOR (class: FPBM);
- coastline accretion/erosion: longshore model GENESIS, UNIBEST-CL+, LITPACK (class: FPBM).

Discussion on Model Use

This review has presented several types of established models, for assisting in the assessment of the impact of marine aggregate extraction, on either a flat bed or within sandbanks. The approaches followed are: full process-based; idealised process-based; and conceptual modelling. On the basis of these studies, the main physical processes to take into account appear to be: tidally-, wind-driven flows and flow contraction phenomena, requiring a 2DH description; bedload transport (including the bed slope effect); and the wave-stirring effect, in the case of extraction on finite amplitude bedforms. All of these models are dependent, in a more or less detailed way, upon location and hydro-sedimentary conditions of the surroundings.

Each of these model approaches provides relevant information, on different aspects of the problem: time-scales; seabed stability; and hydrodynamic modification. Thus, it appears worthwhile to couple these models, to establish a broader view of the system behaviour, e.g. from aggregate extraction to the equilibrium return of the system. Full process-based sandbank models were designed initially for short- and mid-term applications, whereas idealised process-based, together with conceptual sandbank/sand spit models, are designed for long-term forecasts. Thus, combining these different model approaches would lead to a temporal and spatial continuity in coastal dynamics. For instance, this could help to better assess long-term morphodynamics, taking into account threshold effects associated with extreme events (e.g. breaching generation).

An example of how to use and couple each of the three approaches, to study aggregate extraction impact, is shown in Figure 11. The full-process model could be calibrated using available short-period survey data. The idealised process model might be calibrated against the same data or, if required, against a combination of the data and some short-period runs of the full process-based model. These models should then be able to provide some preliminary forecasts of the impact of the sand mining. However, both models take a long time to run, so it is impractical to analyse the consequences of all possible sizes of pits, together with their shapes and orientations. It would be more efficient to fit a conceptual model to the process-based models, to analyse the wide range of possible pit dimensions. Subsequently, the most suitable pit could be analysed, using the process-based models, to ensure that the results are reliable. Running different models, associated with varying the model parameters within realistic boundaries, will result in an estimate of the accuracy of the predictions.

However, it should be noted that morphodynamic model validation is often hampered by a lack of reliable measurements of long-term bathymetrical changes and associated hydrodynamical parameters (primarily, waves and wind). Thus, there is a need also to acquire and provide such datasets. Peters and Hulscher (2006) have shown also that, without full validation, models can still assist in the decision-making process, concerning large-scale sand mining. Indeed, focussing on the use of a new model (IPBM, stability analysis) in decision-making for offshore large-scale sand extraction, these investigations have attempted to: (1) evaluate whether model validation assists the decision-makers; and (2) explore how to improve the model and its use. It appears that validation will reduce only one component of the uncertainties; as such, it is insufficient to assist decision-makers. Even if they are not validated, models can still provide “early warnings”. This observation is confirmed by the willingness of one of the decision-makers involved in large-scale sand extraction to use a new model approach (based upon stability analysis) that is not fully validated (Peters and Hulscher, 2006). Such a study has identified how to improve the model, together with its use, by decision-makers, based upon the Constructive Technology Assessment (CTA) method. This approach modulates the interaction between the model design process and the decision-making process. Starting with a new model and interacting with managers, leads to feedbacks between model design and the decision-making process, to demonstrate how the new model can be improved. Such an improvement has led to the modelling study performed by Roos and Hulscher (2003).

To estimate as many CSIs as are presently available, it is possible to use a set of existing models. Hommes, Hulscher, and Stolk, submitted, have investigated whether using such a set of models is more helpful in addressing management questions, than using only the best model within this set. The selected models were assessed in terms of: (1) their applicability to the CSIs; and (2) the reliability of their predictions. Hommes, Hulscher, and Stolk, submitted, quantified the prediction skill of the models, based upon these two parameters. These investigations concluded that, by using a set of models, it is possible to address more management questions effectively; this is compared to using only the best model available. Using this set of models increases substantially the prediction capability.

CONCLUSIONS

This review provides an overview of: (1) the model concepts available to assess the impact of aggregate offshore extraction; (2) how to utilise these models, to obtain an optimal environmental assessment of offshore marine aggregate extraction, in tidal seas.

Three main concepts have been identified: the full process-based models; the idealised process– based models; and the conceptual models. Until now, the idealised process-based model has been the approach which has been applied most, for investigating the morphodynamics of a dredged flat bed or sandbanks. Full process-based models have been used mainly to study the morphodynamics of a pit, sandbank generation and the influence of the dredging of sandbanks on hydro-sedimentary patterns. Only a limited number of dredging studies have been undertaken using conceptual models. One exception is a study concerned with the recovery time of dredged sandbanks. The main conclusion of this review is that none of the models have been validated, to provide reliable predictions of the impact of large-scale mining, on the morphodynamic stability of the region. However, the different approaches complement each other, supplying the end-user with a range of ‘tools’ for investigating the impact. As validation over (long) periods of interest is not yet possible, the only way to obtain a reliable insight into the future impacts is to combine the different modelling approaches and, concurrently, deal with the uncertainty of the forecasts. A suite of models or coupled models appears to provide the most complete description of the system behaviour (flat bed or sandbanks), following extraction. All of these models are still dependent upon location and the hydro-sedimentary conditions of the surroundings.

For an optimal environmental assessment, two main approaches are: (1) either combine and couple the models, in order to simulate the full morphodynamics of the system over a long time-scale, taking into account also short-term event; or (2) use a set of *existing* models, knowing precisely their applicability to the CSIs and the reliability of their predictions, rather than using only the best model, available presently.

Each of the models presented in this contribution, classified into one of the (3) approaches, can still be improved and benefit from on-going research, e.g. on sediment transport. In particular, the full process-based and the idealised based-model, would benefit from such an improvement. However, the conclusions drawn here would not be modified significantly.

ACKNOWLEDGEMENTS

The authors are grateful to the EUMARSAND project for its financial support (European Contract Number: HPRN-CT-2002-00222), as well as to the researchers of the project Partners, for fruitful discussions.

LITERATURE CITED

Besio, G., Blondeaux, P., Brocchini, M., Hulscher, S.J.M.H., Idier, D., Knaapen, M., Nemeth, A.A., Roos, P.C. and Vittori., G., 2008. The morphodynamics of tidal sand waves: a model overview. *Coastal Engng. - Special Issue on HUMOR* (to appear).

Blondeaux, P., 1990. Sand ripples under sea waves - Part 1. Ripple formation. *Journal of Fluid Mechanics*, 218, 1-17.

Bonne, W., this volume. European Marine Sand and Gravel Resources: Evaluation and Environmental Impact of Extraction - an introduction. *Journal of Coastal Research.*

Brière, C.; Roos, P.; Garel, E., and Hulscher, S., this volume. Modelling the morphodynamic effects of sand extraction from the Kwinte Bank, Southern North Sea. *Journal of Coastal Research.*

Chesher, T.J. and Miles, G.V., 1992. The concept of a single representative wave for use in numerical models of long term sediment predictions. *In*: *Hydraulic and Environmental Modelling : Coastal Waters*. Ashgate Publishing Ltd (ed.), Aldershot, pp.371-380.

Deleu, S.; Van Lancker, V.; Van den Eynde, D., and Moerkerke, G., 2004. Morphodynamic evolution of the kink of an offshore tidal sandbank: the Westhinder Bank (Sourthern North Sea). *Continental Shelf Research*, 24, 1587-1610.

Demir, H.; Otay, E.N.; Work, P.A., and Borekci, O.S., 2004. Impacts of dredging on shoreline change. *Journal of Waterway Port Coastal and Ocean Engineering-ASCE*, 130(4), 170-178.

De Vriend, H.J. and Bakker, W.T., 1993. Sedimentary processes and morphological behaviour models for mixed-energy tidal inlets. *WL|Delft Hydraulics report H1887*

De Vriend, H.J.; Zyserman, J.; Nicholson, J.; Roelvink, J.A.; Péchon, P., and Southgate, H.N., 1993. Medium-term 2DH coastal area modelling. *Coastal Engineering*, 21, 193-224.

Dodd, N.; Blondeaux, P.; Calvete, D.; De Swart, H.E.; Falques, A.; Hulscher, S.J. M.H.; Rozynski, G., and Vittori, G., 2003. Understanding coastal morphodynamics using stability methods.

Journal of coastal research, 19(4), 849-865. *ISSN. 0749-0208*.

Dodd, N.; Stoker, A.; Garnier, R.; Vittori, G.; Santos, F.; Brocchini, M.; Soldini, L.; and Losada, M., 2008. Use of numerical models in evaluating the importance of land-based sediment sources: a case study from La Barrosa Beach, Spain. *Coastal Engng. - Special Issue on HUMOR* (to appear).

Eysink, W.D., 1990. Morphological response of tidal basins to change, *Proc. 22nd International Conference on Coastal Engineering*, July 2 – 6, vol. 2. ASCE, Delft, 1948– 1961.

Garel, E. and Lefebvre, A., this volume. Investigating sand advection and extraction processes at gravel dredged pits, based upon hydrodynamics measurements (Tromper Wiek, Baltic Sea). *Journal of Coastal Research*.

Grunnet, N.M.; Walstra, D.-J.R. and Ruessink, B.G., 2004. Process-based modelling of a shoreface nourishment. *Coastal Engineering*, 51(7), 581-607.

Hanson, H.; Aarninkhof, S.; Capobianco, M.; Jimenez, J.A.; Larson, M.; Nicholls, R.J.; Plant, N.G.; Southgate, H.N.; Steetzel, H.J.; Stive, M.J.F., and de Vriend, H.J., 2003. Modelling of coastal evolution on yearly to decadal time scales. *Journal of Coastal Research*, 19(4), 780-811.

Hommes, S.; Hulscher, S.J.M.H., and Stolk, A., submitted. What can existing mathematical models contribute to managing offshore sand extraction? *Ocean & Coastal Management*.

Hulscher, S. J. M. H., 1996. Tidal-induced large-scale regular bed form patterns in a three-dimensional shallow water model. *Journal of Geophysical Research,* 101(C9), 20, 727-744.

HUMOR project, Human Interaction with large-scale Coastal Morphological Evolution, European Research project (available on the website, http://www.ugr.es/~humor/#, 2001-2004).

Huthnance, J. M., 1982. On one mechanism forming linear sand bank. *Est. Coast. Shelf. Sc.* 14, 74-99.

Idier, D. and Astruc, D., 2003. Analytical and numerical modeling of large-scale rhythmic bedform dynamics. *J. Geophys. Res.,* 108 (C3), p. 3060, *doi:10.1029/ 2001JC001205*.

Knaapen, M.A.F. and Hulscher, S.J.M.H., 2002. Regeneration of sand waves after dredging, *Coastal Engineering*, 46(4), 277-289.

Kragtwijk, N.G.; Zitman, T.J.; Stive, M.J.F., and Wang, Z.B., 2004. Morphological response of tidal basins to human interventions. *Coastal Engineering*, 51(3): 207-221.

Lanckneus, J.; Van Lancker, V.; Moerkerke, G.; Van Den Eynde, D.; Fettweis, M.; De Batist, M., and Jacobs, P., 2001. Investigation of the natural sand tramnsport on the Belgian Continental Shelf (BUDGET), *Final Report*. Federal Office for Scientific, Technical and Cultural Affairs (OSTC). 104 p. + 87 p. (Annex).

Latteux, B., 1995. Techniques for long-term morphological simulation under tidal action, *Marine Geology*, 126, 129-141.

Lesser, G.R.; Roelvink, J.A.; Van Kester, J.A.T.M., and Stelling, G.S., 2004. Development and validation of a three-dimensional morphological model. *Coastal Engineering*, 51(8-9), 883-915.

MacDonald, N.J. and O'Connor, B.A., 1996. The effect of rising sea level on the coast adjacent to the Flemish Banks. *Journal of Marine Systems*, 7, 133–144.

O'Connor, B.A.; Williams, J.J.; Oebius, H.; Sarmento, A., Collins, M.B.; Dias, J.A.; Huntley, D.A.; Fredsoe, J., and Oldfield, F., 1994. Circulation and Sediment Transport Around Banks, 2nd End of Year Report. Liverpool, UK: University of Liverpool, Department of Civil Engineering, *Rep. No. CE/14/94*, 340 p.

Peters, B.G.T.M. and Hulscher, S.J.M.H., 2006. Large-scale offshore extraction: What could be the results of interaction between model and decision process? *Ocean and coastal management,* 49, 164-187.

Roelvink, J.A., 2006. Coastal morphodynamic evolution techniques. *Journal of Coastal Engineering*, 53(2-3), 277-287.

Roos, P.C., 2004. Seabed pattern dynamics and offshore sand extraction. The Netherlands: University of Twente, Ph.D. thesis, *ISBN 90-365-2067-3*, 166 p.

Roos, P. C.; Blondeaux, P.; Hulscher, S. J. M. H., and Vittori, G., 2005. Linear evolution of sandwave packets. *J. Geophys. Res.,* 110, F04S14, *doi:10.1029/2004JF000196*.

Roos, P.C. and Hulscher, S.J.M.H., 2003. Large-scale seabed dynamics in offshore morphology: modeling human intervention. *Rev. Geophys.* 41(2), pp.1010, *doi:10.1029/2002RG000120*.

Roos, P.C. and Hulscher, S.J.M.H., 2004. Modelling the morphodynamic effects of different design options for offshore sandpits. *In*: Hulscher, Garlan, and Idier (eds.), *Marine Sandwave and River dune Dynami*cs Proceeding.

Roos, P.C.; Hulscher, S.J.M.H.; Knaapen, M.A.F., and Van Damme, R.M.J., 2004. The cross-sectional shape of tidal sandbanks: Modeling and observations. *Journal Geophysical Research,* 109, F02003, *doi:10.1029/2003JF000070*.

Sandpit Project (available on the website, http://sandpit.wldelft.nl/mainpage/mainpage.htm)

Southgate, H.N. and Brampton, A.H., 2001. Coastal morphology modelling. A guide to model selection and usage. *HR Wallingford report SR 570*.

Stive M.J.F.; Capobianco, M.; Wang, Z.B.; Ruol, P.;, and Buijsman, M.C., 1998. Morphodynamics of a tidal lagoon and adjacent coast, In: Balkema, A.A. (ed.), *Physics of Estuaries and Coastal Seas: 8th International Biennial Conference on Physics of Estuaries and Coastal Seas*, 1996, Rotterdam, pp. 397-407.

Stive, M.J.F. and Wang, Z.B., 2003. Morphodynamic modelling of tidal basins and coastal inlets. *In*: Lakkhan, C. (ed.), *Advances in coastal modelling*. Elsevier Sciences, pp. 367-392.

Sutherland, J.; Walstra, D. J. R.; Chesher, T. J.; Van Rijn, L. C., and Southgate, H.N., 2004. Evaluation of coastal area modelling systems at an estuary mouth. *Coastal Engineering*, 51(2), 119-142.

de Swart, H.E. and Calvete, D., 2003. Non-linear response of shoreface-connected sand ridges to interventions. *Ocean Dynamics 2003*, 53, 270-277.

Tonnon, P.K.; Van Rijn, L.C. and Walstra, D.J.R., 2007. The modelling of sand ridges on the shoreface, *Coastal Engineering,* 54(4), 279-296.

Van Den Eynde, D.; Giardino, A.; Portilla, J.; Fettweis, M.; Francken, F., and Monbaliu, J., this volume. Modelling the effects of sand extraction on the sediment transport due to tides on the Kwinte Bank. *Journal of Coastal Research*.

Van Koningsveld, M.; Davidson, M. A., and Huntley, D. A., 2005. Matching science with coastal management needs; the search for appropriate coastal state indicators. *Journal of Coastal Research*, 21(3), 399-441.

Van Lancker, V.; Du Four, I.; Verfaillie, E.; Deleu, S.; Schelfaut, K.; Fettweis, M.; Van Den Eynde, D.; Francken, F.; Monbaliu, J.; Giardino, A.; Portilla, J.; Lanckneus, J.; Moerkerke, G., and Degraer, S., 2007. Management, research and budgetting of aggregates in shelf seas related to end-users (Marebasse). Final Scientific Report. Belgian Science Policy, 125p.

Van Rijn, L.C.; Walstra, D.J.R.; Aarninkhof, S.G.J., and Hoogewoning, S.E., 1999. Modelling of sedimentation of dredged trenches and channels under the combined action of tidal currents and waves. *Proc. of 4th Coastal Sediments Conf.*, Long Island, New York, pp 2355-2370.

Van Rijn, L.C. and Walstra, D.J.R., 2002. Morphology of pits, channels and trenches. Part I: Literature review and study approach, *WL|Delft Hydraulics*, *Report Z3223*.

Van Rijn, L.C.; Soulsby, R.L.; Hoekstra, P., and Davies, A.G. (eds.), 2005. SANDPIT: Sand Transport and Morphology of Offshore Sand Mining Pits. Process knowledge and guidelines for coastal management. *End document May 2005*, EC Framework V *Project No. EVK3-2001-00056*, Aqua Publications, The Netherlands.

Van der Veen, H. H.; Hulscher, S. J. M. H. and Knaapen, M. A. F., 2006. Grain size dependency in the occurrence of sand waves.. *Ocean Dynamics*, 56, 228-234, *doi: 10.1007/s10236-005-0049-7*

Walstra, D.J.R.; Reniers, A.J.H.M.; Roelvink, J.A.; Wang, Z.; Steetzel, H.; Aarninkhof, S.G.J.; Van Holland, G., and Stive, M.J., 1997. Long-term effects of the Maasvlakte2 land reclamation and the associated sand extraction alternatives (in Dutch). *WL | Delft Hydraulics report Z2255.*

Walstra, D.J.R.; Van Rijn, L.C.; Boers, M., and Roelvink, J.A., 2003. Offshore Sand Pits: Verification and Application of Hydrodynamic and Morphodynamic Models. *Coastal Sediments 2003.*

Whitehouse (ed.), 2001. Understanding the behaviour and engineering significance of offshore and coastal sand banks. *Report SR 512*, HR Wallingford, for the contract CSA3051.

Williams, J.J.; MacDonald, N.J.; O'Connor, B.A., and Pan, S., 2000. Offshore sand bank dynamics*, Journal of Marine Systems*, 24, 153–173.

Journal of Coastal Research	SI	51	53-62	West Palm Beach, Florida	Summer 2010

Aggregate extraction from tidal sandbanks: Is dredging with nature an option? Introduction

Vera R.M. Van Lancker[1*], Wendy Bonne[2*], Adonis F. Velegrakis[3] and Michael B. Collins[2,4]

[1] Ghent University, Renard Centre of Marine Geology
Krijgslaan 281, S8, 9000 Gent, Belgium

* Present address: Royal Belgian Institute of Natural Sciences. Management Unit of the North Sea Mathematical Models
Gulledelle 100, B-1200 Brussels, Belgium
vera.vanlancker@mumm.ac.be

[2] AZTI - Tecnalia / Marine Research Division
Herrera kaia portualdea z/g, 20110 Pasaia (Gipuzkoa)
Spain

* Present address: Marine Environment Service, Directorate General Environment, Federal Public Service Health, Food Chain Safety and Environment, Federal Government of Belgium
Victor Hortaplein 40 box 10
1060 Brussels, Belgium

[3] University of the Aegean, Department of Marine Sciences, School of Environment, University Hill, Mytilene 81100
Greece

[4] School of Ocean and Earth Science. National Oceanography Centre, Southampton
European Way, Southampton, SO143ZH
United Kingdom

ABSTRACT

Sandbanks are considered as primary targets for the marine aggregate industry, not only because of considerations related to resource quality and operational advantages, but also due to the notion that natural sediment transport processes that form and maintain sandbanks are able to counterbalance the loss of sediment due to extraction. This paper introduces: (a) the problems related to the assessment of the impacts of aggregate extraction from tidal sandbanks; and (b) the multidisciplinary and integrated research that was undertaken on the potential for regeneration of the most intensively exploited area of the Kwinte Bank (Flemish Banks, Belgian Continental Shelf), following the cessation of extraction on this part of the sandbank. We assert that the results of a 30-year monitoring of exploitation effects along the Kwinte Bank have put in doubt the universal notion of *'dredging with nature'*. The elongated depressions that have been observed in the most heavily exploited areas provide a clear signal that more detailed information and thorough assessment are required in order to understand and predict the most likely evolution of the bank's hydro-sedimentary regime and its natural and anthropogenically-induced dynamics.

ADDITIONAL INDEX WORDS: *Belgian Continental Shelf, bank maintenance processes, marine aggregates, environmental impact assessment, Flemish Banks, seabed regeneration.*

INTRODUCTION

Sandbanks are one of the primary sources of material for the marine aggregate (MA) industry, due to (BATE *et al.*, 1997): (a) their large sedimentary volumes; (b) their shallow water depths; (c) the suitability of their sediments to be used as aggregates; and (d) their convenient (sub-parallel) orientation in relation to the tidal flow which makes dredging operations easier and safer. In addition, the sedimentary processes that are associated with presently 'active' sandbanks (e.g. DYER and HUNTLEY, 1999) may restore sediment lost to extractive processes; thus, sandbanks may be regarded as preferable aggregate resources, in terms of sustainability. MA extraction from sandbanks takes place in many areas, such as the Bristol Channel/Severn Estuary (UK) (JAMES, PHILPOTT, and JENKINS, 2005), the southern North Sea (see below) and the US (DRUCKER, WASKES, and BYRNES, 2004), Australian (QUEENSLAND, 2005) and Taiwanese (CHEN, 2005) inner continental shelves.

DOI: 10.2112 / SI51-005.1 received 17 January 2007; accepted in revision 27 February 2008.

Sandbanks are common features of the European continental shelves (e.g. VELEGRAKIS *et al.,* 2001), particularly in the energetic and sediment-rich Atlantic and North Sea environments. They are formed and maintained under the influence of particular hydro- and sediment dynamic regimes (e.g. PATTIARATCHI and COLLINS, 1987), with most of them having been formed during, or following, the last (Flandrian) marine transgression. Sandbanks can be differentiated into relict (e.g. KENYON *et al.*, 1981) and modern sedimentary bodies (e.g. COLLINS *et al.*, 1995). Relict (or moribund) banks were formed under hydraulic regimes that were different from the conditions that operate in contemporary contexts (e.g. REYNAUD *et al.*, 1999) and are not actively involved in the contemporary sedimentary processes. Contrastingly, contemporary (or active) banks are the result of modern flow-sediment interaction (e.g. STRIDE, 1982; WRIGHT, 1995).

The majority of the large modern tidal sandbanks are linear and asymmetric in cross-section (DYER and HUNTLEY, 1999). Sandbanks are found often in groups (JOHNSON and BALDWIN, 1986), and have lengths of up to 60 km, widths of up to 3 km, and heights of between 3 and 40 m above the surrounding seabed (VELEGRAKIS *et al.*, 2001). Their flanks have slopes varying between 0.25° to 3° and they are covered commonly with subaqueous dunes (ASHLEY *et al.*, 1990) of varying dimensions. In most cases, there is a spatial differentiation in the textural characteristics of the surficial sediments of subtidal sandbanks (e.g. Lanckneus *et al.*, 2001; McCave and Langhorne, 1982; Parker, Lanfredi, and Swift, 1982; Pattiarachi and Collins, 1987; Van Lancker, 1999; Velegrakis *et al.*, 2007), which is likely the result of the interplay between tidally- and wave-induced sediment transport processes. The internal architecture of sandbanks varies also. Some banks show a complex internal architecture, suggesting multiphase formation (e.g. Berne *et al.*, 1994; Trentesaux, Stolk, and Berne, 1999), whereas others are characterised by a simple internal structure (e.g. Collins *et al.*, 1995); these differences may be related to the antecedent morphology and the type of substrate of the area, as well as the broader sedimentary regime within which the banks have formed.

The sedimentary character (i.e. nature of the sediment and its mobility) of the sandbanks exerts a primary control on the nature of benthic ecosystems that evolve upon and with them. Sandbanks can support important benthic epifaunal assemblages (Kaiser *et al.*, 2004; Van Hoey, Degraer, and Vincx, 2004), comprising particular seabed habitats that likely differ from those found within adjacent seabed areas (e.g. Tyler and Shackley, 1979; Vanosmael *et al.*, 1982). In addition, these may represent important nursery, fishing and, in the case of shallow banks, seabird feeding grounds (e.g. De Groot, 1980). Therefore, extraction of aggregates has the potential to cause undesirable ecological and fisheries impacts (e.g. Drucker, Waskes, and Byrnes, 2004).

A responsible approach to the management and regulation of MA operations requires that the effects of extraction should be monitored. This monitoring should focus not only on the sediment dynamics and morphodynamics of the bank *per-se*, but also on the hydrodynamics and sedimentary fluxes of surrounding areas (Bastos, Paphitis, and Collins, 2004; Berthot and Pattiaratchi, 2005; McNinch and Wells, 1999; and Otto, 1998). Complex issues exist regarding the potential effects of sediment extraction on neighbouring coasts, as nearshore sandbanks can play an important role in wave energy distribution and dissipation. It is posited that intensive sediment extraction may lead to morphological changes in the configuration of the sandbank (e.g. Van Lancker *et al.*, this volume), which in turn, may result in the redistribution of wave energy impinging upon the neighbouring coasts, modification of the littoral drift and coastal morphodynamics and, ultimately, coastal erosion (e.g. MacDonald and O'Connor, 1996; Suter, Mossa, and Penland, 1989). As yet, there is no clear or conclusive view regarding such impacts in the relevant scientific literature (e.g. Boers and Jacobsen, 2000; Brampton, Evans, and Velegrakis, 1998; Queensland, 2005). In many cases, the study of such effects has been hampered by the lack of baseline information and long-term morphological time-series. This is because in many cases where environmental monitoring schemes have been established, these have been concerned only with the short-term (less than 10 years) effects of extraction.

The objective of the present contribution is to present the monitoring methodologies/strategies that have been developed to evaluate the impacts of MA extraction from tidal sandbanks, focusing on the 30-year Belgian experience. The paper also introduces the research activities that were undertaken to study the physical and ecological evolution of the intensively exploited Kwinte Bank (Flemish Banks, Belgian Continental Shelf) since the cessation of the MA extraction activities in this area and to discuss the ability of the natural sedimentary processes to compensate for the losses due to extraction.

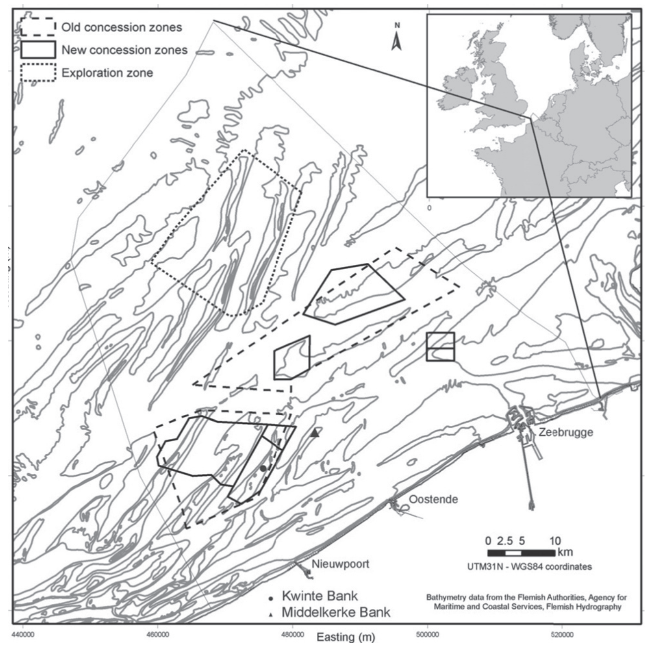


Figure 1. Past and present marine aggregate concession zones, Belgian Continental Shelf.

SAND EXTRACTION ON THE BELGIAN CONTINENTAL SHELF

Aggregate (sand) extraction from the Belgian Continental Shelf commenced in earnest in 1976; the environmental effects of which have been studied since 1979. MA concession zones are located beyond a 12 km distance from the coastline and are concentrated around the linear sandbanks (Figure 1.) in water depths ranging between -5 and -22 m MLLWS (mean lowest low water, at spring tides). With a view to confining operations to surficial sediment layers, existing regulations restrict sediment removal for each extraction activity to a maximum permitted penetration of 0.50 m beneath the sediment surface.

Although the Belgian concession zones occupy relatively large areas of the seabed, most of the extraction has been concentrated to a restricted number of very confined areas. During the 30-years of extraction, nearly 99% of the total MA production (Figure 2.) has originated from certain sections of the Kwinte Bank, of the Flemish Bank Group (Figure 1.). The fact that intense dredging effort was strongly localised became particularly clear from 1996 onwards, when the dredging vessels were equipped with Electronic Monitoring Systems (EMS 'black-boxes'). The EMS navigation information showed that most of the extraction has been taking place over the northwestern and middle sections of the Kwinte Bank. The operational rational driving this heavy concentration of the dredging activity is related to: (a) the consistent quality of the aggregate material in these areas; and (b) the cost-effective distance of these areas from the landing facilities (i.e. the MA wharfs).

In 1999, clear evidence emerged that the extraction was having significant impacts on the morphology of the Kwinte Bank. A depression (hereafter called *'the central depression'*) of 5 m deep, 700 m wide and 1 km long had developed along

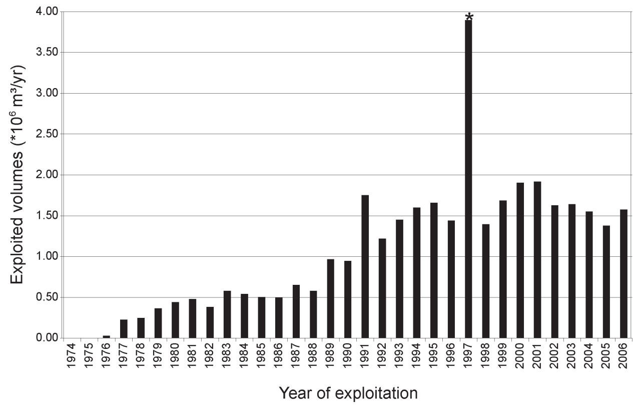


Figure 2. Exploited volumes from the Belgian Continental Shelf. (*): Increased rate of extraction in 1997 due to offshore works (Source: Fund for Sand Extraction).

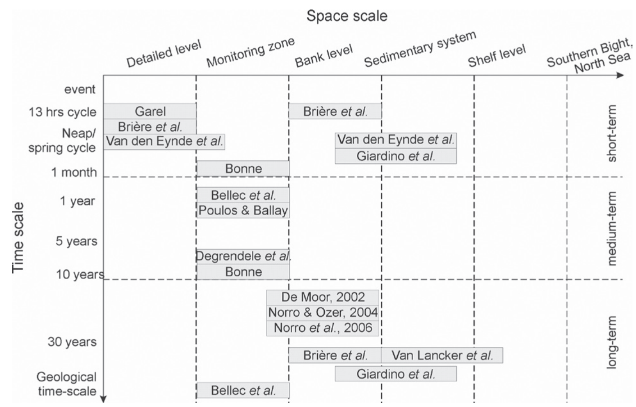


Figure 3. Space-time plot of the different investigations undertaken during the monitoring of the environmental impacts of sand extraction from the Kwinte Bank, most of which are presented in this Special Volume.

Table 1. *Physical characterisation of the Kwinte Bank area (following ICES, 2003).*

Bathymetry/topography of the general area: – 7 to –20 m MLLWS.
Distance to the nearest coastlines: Nearest section of the concession, 12 km; major extraction activities at +/- 16.5 km.
Geological history of the deposit: Several sedimentary units can be distinguished; the upper units are of Late Holocene age (Maréchal and Henriet, 1983; Trentesaux et al., 1999).
Source of the material: The upper layer of the bank is representative of the present hydrodynamic regime (Trentesaux et al., 1999). The southern part of the sandbank consists of fine sands, whereas medium- to coarse-grained sediments characterise the middle and northern part (Lanckneus, 1989; Verfaillie et al., 2006).
Type of material: Mainly quartz sand, for the industry Round Sand 0/2, 1480 kg/m².
Sediment particle size distribution: Generally 200-300 µm; coarser grain sizes (enriched with shell hash) occur locally; they are more common to the north. Mostly, unimodal sediment distributions (Bellec et al., this volume)
Extent and volume of the deposit: The Quaternary part of the bank is +/- 300 x 106 m³ (based on seismic network of Maréchal and Henriet, 1983).
Stability and/or natural mobility of the deposit: The Flemish Banks are generally stable (Van Cauwenberghe, 1971), although a slight erosional trend has been identified recently for the region (De Moor, 2002); the bedforms have a maximum migration rate of 20 m (Lanckneus et al., 2000; Degrendele et al., this volume).
Thickness of the deposit and consistency over the extraction area: The thickness of the Quaternary deposits decreases progressively from the SW to the NE with a maximum along the central part (20-21 m). The shape of the upper, tidally-dominated, sedimentary unit is difficult to estimate (Maréchal and Henriet, 1983; Le Bot et al., 2003, for a synthesis).
Nature of the underlying deposit, and any overburden: The substratum is composed of compact Tertiary clay (Kortrijk Formation), which outcrops in the swales (Le Bot et al., 2003, for a synthesis).
Local hydrography including tide and residual water movements: A tidal range of 4-5 m (Springs) (macrotidal). Maximum current velocities are around 0.9 to 1.0 m/s on the top and the western side of the Kwinte Bank during a spring tide and around 0.4 to 0.5 m/s during neap tide. Along the western flank, the residual currents are following the bank towards the northeast, while on the eastern flank of the bank; the residual currents are in the opposite direction, to the southwest (Van den Eynde et al., this volume). These directions change under varying wave conditions (Giardino et al.)
Wind and wave characteristics: SSW to SW winds, 3 to 4 Bf are most common, winds > 6 Bf blow from the WSW to NW; waves of 0.50–1 m in height and a period of 3.5 – 4.5 s are most common; waves > 3m originate from the W to WNW (Ministerie Van De Vlaamse Gemeenschap, 1993)
Average number of storm days per year: 40 days (winds of > 10 m/s) (calculated from Hydro-meteo database, Flemish Hydrography, period 1996-2001).
Estimate of bed-load sediment transport (quantity, grain-size, direction): Erosion/deposition of 7-14 g/m² (modelling over 15 days); transport direction varies over the bank (Van den Eynde et al., this volume). For the adjacent Middelkerke Bank, the bedload sediment fraction mode varied from 180-212 µm in the south to 250-300 and 425-500 µm in the north (Vincent et al., 1998).
Topography of the seabed, including occurrence of bed forms: Main extraction takes place where large to very-large dunes (height: 4-6 m; wavelength > 100 m) occur (Degrendele et al., this volume).
Existence of contaminated sediment and their chemical characteristics: no published reports.
Natural [background] suspended sediment load under both tidal currents and wave action: Fettweis et al. (2006) indicates SPM concentrations of 9-250 mg/l with an average of 26 mg/l. Mostly, <10 mg/l is found. The average particle sizes range from 122-198 µm. Their size spectra are bimodal indicating the existence of flocs. Measurements were performed at 0.8 and 3 m above the bottom. More than 6% of the SPM consists out of particulate organic matter.

Table 2. *Biological characterisation of the Kwinte Bank area (following ICES, 2003).*

Flora/fauna within the area likely to be affected by aggregate dredging (e.g., pelagic and benthic community structure), taking into account temporal and spatial variability): Diversity and abundance of macrobenthic communities are very low, typically for well-sorted mobile sands. A Nephthys cirrosa community is present on the slopes of the bank, and a transitional species association between the Nephthys cirrosa and Ophelia limacina-Glycera lapidum communities on the summit ('crown') of the sandbank. In the swales, an Abra alba-Mysella bidentata community occurs, shifting to a transitional species association between the Nephtys cirrosa and Abra alba-Mysella bidentata communities, at shallower depths towards the bank (Bonne, 2003).
Information on the fishery and shell fishery resources, including spawning areas, with particular regard to benthic spawning fish, nursery areas, over-wintering grounds for ovigerous crustaceans, and known routes of migration: The crest of the sandbank has no rich fish or shellfish resources. Still, the Flemish Banks play a key role in the supply of fish larvae from offshore waters towards more sheltered onshore nursery areas (Vincx et al., 2003).
Trophic relationships (e.g., between the benthos and demersal fish populations by stomach content investigation): The rich Abra alba-Mysella bidentata community, occurring in the swales, is of exceptional importance, serving as a key food resource for scoters or demersal fishes (Degraer et al., 1999). The area is a key-site for wintering Little Gull, Red-throated Diver, Razorbill and Guillemot (Seys et al., 1993, 1999; Maes et al., 2000; Vincx et al., 2003) and act as a feeding ground for Sandwich Tern during the breeding season (Seys et al., 1999; Vincx et al., 2003).
Presence of any areas of special scientific or biological interest in or adjacent to the proposed extraction area, such as sites designated under local, national or international regulations: Special areas of conservation (Habitat and Birds Directive) are designated just to the south of the Kwinte Bank.

the middle section of the bank (see Figure 3. of Degrendele *et al.,* this volume). Thus, in 2003, the Belgian Government closed down MA extraction operations in this area for a period of, at least, 3 years to allow the regeneration of the bank.

ENVIRONMENTAL SETTING OF THE KWINTE BANK

The environmental setting of the Kwinte Bank will be described in detail in subsequent contributions in this volume. Thus, a summary is presented here which in keeping with the ICES guidelines (ICES, 2003) provides a description of the physical (Table 1.) and biological (Table 2.) setting of MA extraction areas.

PREVIOUS STUDIES ON THE EFFECTS OF EXTRACTION FROM THE KWINTE BANK

On the Belgian Continental Shelf, there is relatively abundant information on the effects of MA extraction on exploited sandbanks. Extensive information also exists on the nature and dynamics of a neighbouring (non-exploited) sandbank, the Middelkerke Bank, (Figure 1.), which was obtained mostly within the framework of several European projects (Houthuys, Trentesaux, and De Wolf, 1994; Lanckneus, De Moor, and Stolk, 1994; Pan *et al.,* 2007; Trentesaux *et al.*, 1994; Trentesaux, Stolk, and Berne, 1999; Vincent, Stolk, and Porter, 1998; and Williams *et al.,* 2000).

Nevertheless, the monitoring studies related to MA extraction have not been conclusive. Until 1993, it was believed that aggregate extraction had no major effect on the total volume of the Kwinte Bank. Rzonzef (1993) had suggested that: (a) aggregate extraction had influenced only the upper bank volume and the morphology of the intensively-exploited areas; (b) the total sediment volume had not been affected by the extraction; and (c) there were indications of a natural recovery of the exploited sections of the bank, through a natural sand replenishment mechanism which balanced the rates of extraction and the rates of natural replenishment. It was thought that such a maintenance mechanism would regenerate the sediment volume of the upper section of the bank following natural erosive phases (due to storms) and anthropogenic removal (MA extraction) of sediments. Nevertheless, Rzonzef (1993) also stressed that there were questions related to the ability of the adjacent source areas to supply the necessary sediment required to maintain regenerative processes.

However, alternative conclusions were drawn following the analysis of long-term sediment volumetric data. De Moor (2002) demonstrated that all the Flemish Banks (both exploited and non-exploited) had been subject to erosion. The swales between the banks were found to have remained either stable or slightly erosional. However, erosion rates seemed higher in areas located close to the extraction sites. For the Kwinte Bank, analysis of the topographic information obtained during the period 1987-2000 (4-5 surveys/yr) showed (Norro and Ozer, 2004; Norro *et al.*, 2006): (a) a total bank volume decrease (with a high level of confidence)**,** with an annual rate of ~1.5 %; and (b) that this volume decrease was greater than the volume of MA extracted during the same period. These results suggested that MA extraction was not likely to be the single factor controlling the observed sediment volume decrease, which raised the question whether extractive activities *'had perturbed the dynamic balance of the bank?'* (Norro *et al.*, 2006). To answer this question and permit the authorities to obtain information that would allow the establishment of statistically significant criteria with regard to the long-term sustainability of the resource, it was argued that the frequency of observations should be increased (i.e. to more than 4-5 surveys/yr).

Meanwhile, multibeam technology, in combination with EMS information (see above), clearly revealed the physical impacts of extraction by identifying deep, elongated depressions on the crown of the sandbank along the areas of concentrated MA extraction (Degrendele *et al.*, this volume). Aggregate extraction activities shifted to the north when the central depression was closed down in 2003. Presently, a depression has also been observed in the latter area (Degrendele *et al.*, this volume). It must be noted that the northern part of the Kwinte Bank was already under severe pressure in the past and, since 1987, a decrease in the bank's volume has been reported (Rzonzef, 1993).

De Moor and Lanckneus (1993) and Heyse and De Moor (1996) investigated a possible sediment transport link between the Flemish Banks and the adjacent beaches. The volumetric evolution of the Kwinte Bank and the adjacent, non-exploited, Middelkerke Bank was compared to volume changes in a section of the coast behind the two sandbanks (De Moor, 1993; 1996). There were no indications for a direct causal relationship. A residual sand transfer between the banks and the coast was deemed improbable owing to: (a) the inshore sandbank-swale morphology; (b) the presence of muddy bottom sediments in the nearshore zone; (c) the highly rectilinear character of the nearshore tidal flow; and (d) the anti-clockwise pattern of bedload circulation around the banks. Following a detailed investigation of the coastal sediment dynamics, Van Lancker (1999) also argued that there was a strong likelihood that any major sand supply from offshore to the nearshore would be trapped in well-defined sediment convergence zones before reaching the beaches.

METHODOLOGICAL FRAMEWORK PAST AND PRESENT PRACTICES

Geological and physiographic monitoring investigations have been carried out by, or, on behalf of, the Belgian Federal Government (Fund for Sand Extraction) within Belgian MA extraction areas. For the initial survey programmes, single-beam bathymetric observations were regularly obtained together with sediment samples. The bathymetry track lines were defined along fixed routes, which followed the designated lanes of the radio-hyperbolic Decca chain (De Moor, 2002). These widely spaced run-lines covered entire sandbanks, both exploited and non-exploited. Some of these banks were surveyed 4-5 times a year, permitting the estimation of sediment volume changes. Although the accuracy of volume changes on the basis of these older observations was constrained by navigational and water depth measurement errors (e.g. Bowyer, 1992), statistically significant volumetric trends could still be derived (for details, see Norro and Ozer, 2004). In addition, side-scan sonar imagery was used to study the bedform distribution and dynamics; the results suggested a convergence of sand streams towards the crests of the sandbanks (De Moor, 1985; De Moor, 1986a; De Moor and Lanckneus, 1988; Lanckneus and De Moor, 1991; 1994). Finally, seismic profiling was used to explore the internal architecture of the banks and to obtain a rough estimate of the volume of the sediment resource (De Moor, 1986b; Maréchal and Henriet, 1983).

Since 1999, multibeam technology has been used for bathymetric mapping and monitoring of the Flemish sandbanks. During bathymetric surveys, seabed backscatter intensity has also been recorded in order to allow an assessment of surficial sediment characteristics. Detailed resource maps, combining water depth and backscatter information have been constructed. However, direct ground truth sampling for environmental monitoring purposes (with an observation frequency of 3-4 times a year) has mainly been restricted to predefined areas. These sites are mainly confined to the intensively dredged areas (having a total surface area of 1 km^2), as well as to a 'control' site that is deemed to suitably represent the natural evolution of the seabed (see Degrendele *et al.*, this volume).

A deep depression on the crown of the Kwinte Bank (see Figure 3., Degrendele *et al.,* this volume) was first identified from survey results in 1999. This finding strongly suggested that a programme of further research was urgently required to investigate the environmental impacts of MA extraction. This body of further research and its results are discussed in the current Special Volume and relate to (Figure 3.): (a) the geo-environmental characterisation of the central depression of the Kwinte Bank on the basis of the acoustic characteristics of the seabed, sediment sampling and high resolution seismics (Bellec *et al.,* this volume); (b) the depression morphodynamics, before and after the cessation of the extraction operations, on the basis of repeated bathymetric observations (Degrendele *et al.,* this volume); (c) the establishment of sediment transport pathways, based upon grain-size distributions and trends (Poulos and Ballay, this volume); (d) the effect of the depression on the local hydrodynamics (Garel, this volume); (e) the effects of morphological changes on the tidally-induced sediment transport and morphodynamics, based on modelling experiments (Brière *et al.,* this volume; and Van den Eynde *et al.,* this volume); (f) the sediment dynamics of the area under wave/current interaction, also on the basis of modelling experiments (Giardino, Van den Eynde, and Monbaliu, this volume); and (g) the ecological impact of aggregate extraction, on the basis of changes in the macrobenthic communities (Bonne, this volume). Finally, Van Lancker *et al.,* this volume, provide a synthesis of the above results together with recommendations for a range of practices that are considered to offer a more sustainable approach to the management and regulation of extraction from tidal sandbanks. The large-scale hydrodynamic and sedimentary framework is discussed in Van Lancker *et al.* (2007).

SANDBANK MAINTENANCE MECHANISMS AND MA EXTRACTION

On the basis of the long-term data series, it would appear that, despite the original intention to '*dredge with nature*', the overall volume of the Kwinte Bank has diminished with time (De Moor, 2002; Norro *et al.*, 2006). These findings contrast with the results of a previous assessment (Rzonzef, 1993) and put in doubt the notion that maintenance mechanisms of tidal sandbanks have the capacity to balance MA extraction in this region. Some 8 years after the initial observation of an extraction-induced depression and 3 years after the cessation of extraction activities, no significant sediment accumulation has been observed (Degrendele *et al.*, this volume). However, it must be noted that the most significant morphological changes were observed after the late 1990's, following an intensification of MA extraction (see Figure 2.).

Still, sandbank maintenance mechanisms are considered to control the conservation of the sandbank-swale equilibrium, which is related to the particular hydrodynamic, and sediment transport regimes associated with tidal sandbanks (e.g. Dyer and Huntley, 1999). Based on field observations, crests of sandbanks are identified mostly as bedload convergence zones (e.g. Pattiarachi and Collins, 1987) and, as such, storm- and/or anthropogenically-induced sediment losses might be counterbalanced by a natural sediment supply. For the sandbanks of the southern North Sea (e.g. Houthuys, Trentesaux, and De Wolf, 1994; Van Lancker, 1999; Vincent, Stolk, and Porter, 1998; and Williams *et al.,* 2000) and the sand ridges of the US

Gulf and Atlantic inner continental shelves (Hayes and Nairn, 2004), it was shown that waves play also an important role in the maintenance processes of sandbanks. As such, significant decreases in bank heights/volumes, as a result of intensive MA extraction, might influence wave dissipation/refraction and modify wave-induced sand dynamics (and that related to wave/current interaction) and, thus, sandbank equilibrium. If, in addition, an increased storminess and surge frequency is further confirmed (e.g. Solomon *et al.*, 2007), the effects of MA extraction could be more severe in the future. Taking into account a 1 m mean rise in sea-level, over a 100 year period and assuming stable sandbanks, Macdonald and O'Connor (1996) have predicted that the average wave energy impacting upon the Flemish coast would increase by the order of 10 %, by 2130. Whether this effect would be associated with a reduction in sandbank heights is unclear.

Finally, the regional availability of suitable sediments for the regeneration of the extracted deposits should be taken into account. If particular sediment fractions are targeted for extraction, then both the availability of such sediments in the adjacent areas and the ability of the prevailing sediment dynamic regime to transport and deposit them into the affected area should be considered carefully. In many cases, local patches of coarser sediments are being extracted; these are neither readily available nor plentifully supplied to the inner continental shelves by the present hydro-sedimentary regime (e.g. Velegrakis *et al.*, this volume).

If the main objective is to allow MA extraction only in areas where the natural sedimentary processes would be able to compensate the extraction-related impacts completely or, at least, satisfactorily, then much more research is required prior to the selection of the extraction sites. In particular, the resource availability should be better quantified, as well as the natural sediment transport processes and their spatial variability. This would help in recommending thresholds in relation to the broad quantities that may be extracted from tidal sandbanks with minimal risk.

CONCLUDING REMARKS

Sandbanks are considered as primary targets for the MA industry, not only because of considerations related to resource quality and operational advantages, but also due to the notion that the natural sediment transport processes that form and maintain sandbanks are able to 'heal' or, at least, ameliorate the physical impacts of extraction and potentially regenerate sediment deposits. The results of a 30-year monitoring of exploitation effects along the Kwinte Bank (Flemish Banks, Belgian Continental Shelf) have put in doubt this universal notion of *'dredging with nature'* and has made clear that more detailed information is required on the bank hydrosedimentary regime and its natural and anthropogenically-induced dynamics.

This paper has introduced: (a) the problems related to the assessment of impacts of aggregate extraction from tidal sandbanks; and (b) the detailed research that was undertaken on the potential for regeneration of the most intensively exploited area of the Kwinte Bank following cessation of extraction operations on this part of the sandbank. The history of the 'follow-up monitoring' of the extraction effects, highlights that information availability/discontinuity and the temporal and spatial scales over which observations are obtained and interpreted, can significantly influence the assessment of impacts of MA extraction. The establishment of appropriate monitoring schemes is necessary in order to define in detail both the morphological evolution of exploited banks and the hydro-sedimentary processes and dynamics associated with sandbank regeneration. It is hoped that the research presented in this Special Volume will contribute towards the improvement of the extent and scope of monitoring schemes and promote a more science-based approach to the management of seabed resources.

ACKNOWLEDGEMENTS

The fieldwork undertaken on the Kwinte Bank was a joint research initiative between the Belgian Science Policy project, Marebasse ('Management, Research and Budgeting of Aggregates in Shelf Seas related to End-users', contract EV/02/18A) and the EU-RTN FP5 project EUMARSAND (contract HPRN-CT-2002-00222). Time-series of sediment samples were collected within the framework of the Belgian Science Policy project, SPEEK (EV/02/38A). The Management Unit of the Mathematical Model of the North Sea and Scheldt Estuary provided additional instrumentation and logistical support. The Captain, officers and crew of *R/V Belgica* and *R/V Zeeleeuw* (Flemish Institute of the Sea) are acknowledged warmly for their support. The Belgian Fund for Sand Extraction (FPS Economy, SME's, Self-employed and Energy) is acknowledged considerably for the supply of historical data geological and multibeam data, expertise and the approval for using the multibeam echosounder on the *R/V Belgica*. This publication also contributes to the MESH project (Mapping European Seabed Habitats, http://www.searchmesh.net) that received European Regional Development Funding, through the INTERREG III B Community Initiative (http://www.nweurope.org).

LITERATURE CITED

Ashley, G.M.; Boothroyd, J.C.; Bridge, J.S.; Clifton, H.E.; Dalrymple, R.W; Elliot, T.; Flemming, B.W.; Harms, J.C.; Harris, P.T.; Hunter, R.E.; Kriesa, R.D.; Lancaster, N.; Middleton, G.V.; Paola, C.; Rubin, D.M.; Smith, J.D.; Southard, J.B.; Terwindt, J.H.J., and Twitchell, D.C. JR., 1990. Classification of large-scale subaqueous bedforms: a new look at an old problem. *Journal of Sedimentary Petrology*, 60, 160-172.

Bastos, A.C.; Paphitis, D., and Collins, M.B., 2004. Short-term dynamics and maintenance processes of headland-associated sandbanks: Shambles Bank, English Channel, UK. *Estuarine, Coastal and Shelf Science*, 59, 33-47.

Bate, R.; Velegrakis, A.F.; Brand, C.; Collins, M.B., and Nunn A., 1997. *Deep water and inshore aggregates exploitation*. Research Report for the Countryside Council of Wales, 91pp.

Bellec, V.; Van Lancker, V.; Degrendele, K.; Roche, M., and Le Bot, S., this volume. Geo-environmental characterization of the Kwinte Bank in relation to sand extraction. *Journal of Coastal Research*

Berne, S.; Trentesaux, A.; Stolk, A.; Missiaen, T., and De Batist, M., 1994. Architecture and long-term evolution of a tidal sandbank. The Middelkerke Bank (southern North Sea). *Marine Geology*, 121, 52-72.

Berthot, A. and Pattiaratchi, C., 2005. Maintenance of headland-associated linear sandbanks: modelling the secondary flows and sediment transport. *Ocean Dynamics*, 55(5-6), 526-540.

Boers, M. and Jacobsen, J.J., 2000. *Sand mining at sea banks. Effects on wave conditions along the coast of the Zeeland and South Holland islands in the Netherlands*. Den Haag: Ministry of Transport, Public Work and Water Management.

Bonne, W., 2003. *Benthic copepod communities in relation to natural and anthopogenic influences in the North Sea*. Gent, Belgium: University of Gent, Ph.D. thesis, 289p.

Bonne, W., this volume. Ecological characterization and changes of the Kwinte Bank central depression in relation to sand extraction. *Journal of Coastal Research*.

Bowyer, J.K., 1992. Basin changes in Jervis Bay, New South Wales: 1894-1988. *Marine Geology,* 105, 211-224.

Brampton, A.; Evans, C.D.R., and Velegrakis, A.F., 1998. *South Coast Mobility Study*. London: CIRIA PR 65, 219p.

Brière, C.; Roos, P.C.; Garel, E., and Hulscher, S.J.M.H., this volume. Modelling the morphodynamic effects of sand extraction from the Kwinte Bank, Southern North Sea. *Journal of Coastal Research*.

Chen, C.C., 2005. *Geological and Resource Survey Offshore Waisanting Bar*. Internal Report of the Energy and Resources Laboratories, Industrial Technology Research Institute.

Collins, M.B.; Shimwell, S.J.; Gao, S.; Powell, H.; Hewitson, C., and Taylor, J.A., 1995. Water and sediment movement in the vicinity of linear banks: the Norfolk Banks, southern North Sea. *Marine Geology*, 123, 125-142.

Degraer, S.; Vincx, M.; Meire, P., and Offringa, H., 1999. The macrozoobenthos of an important wintering area of the common scoter (*Melanitta nigra*). *Journal of the Marine Biological Association of the United Kingdom*, 79, 243-251.

Degrendele, K.; Roche, M.; Schotte, P.; Van Lancker, V.; Bellec, V., and Bonne, W., this volume. Morphological evolution of the Kwinte Bank central depression before and after cessation of aggregate extraction. *Journal of Coastal Research*.

De Groot, S.J., 1980. The consequences of marine gravel extraction on the spawning of herring. Culpea harangus, Linne. *J. Fish. Biol*., 16(6), 605-611.

De Moor, G., 1985. Shelf bank morphology off the Belgian coast. Recent methodological and scientific develoments. *Recent Trends in Physical Geography*, 20, 47-90.

De Moor, G., 1986a. Geomorfologisch onderzoek op het Belgisch Continentaal Plat. *Tijdschrift van de Belg. Ver. Aardr. Studies, BEVAS*, 2, 133-174.

De Moor, G., 1986b. Het Continentaal Plat van de Noordzee gedurende het Kwartair. *Water*, 31, 6-9.

De Moor, G., 1993. Chapter 10. Beach dynamics in the Middelkerke Area. *In*: De Moor, G. and Lanckneus, J. (eds.), *Sediment mobility and morphodynamics of the Middelkerke Bank. Final Report*. MAST Project-0025-C. Relationship between Seafloor Currents and Sediment Mobility in the Southern North Sea. Gent, RUMACOG, pp. 10.01-10-12.

De Moor, G., 1996. Chapter 7. Task 1: Assessment of volumetric and morphologic evolution trends on the Middelkerke area. Subtask 1.5: Chronosequential beach profiling, 32 p. *In*: Heyse, I. and De Moor, G. (eds.), *Sediment transport and bedform mobility in a sandy shelf environment (STARFISH). Final report.* MAST project. Contract MAS2-CT92-0029. Universiteit Gent, Gent (B); Brussel, Commission of European Community, Directorate General XII.

De Moor, G., 2002. Évaluation de la morphodynamique sous-marine en Mer du Nord méridionale au cours de la période 1985-1995 (Evaluation of sea-floor sediment dynamics in the Flemish Banks (southern North Sea) between 1985 and 1995). *Géomorphologie : relief, processus, environnement*, 2, 135-150.

De Moor, G. and Lanckneus, J., 1988. Acoustic teledetection of seabottom structures in the Southern Bight. *Bull. Soc. Belg. Géol*., 97(2), 199-210.

De Moor, G. and Lanckneus, J. (eds.), 1993. *Sediment mobility and morphodynamics of the Middelkerke Bank. Final Report.* MAST Project-0025-C. Relationship between Seafloor Currents and Sediment Mobility in the Southern North Sea. Gent: Universiteit Gent, RUMACOG, 255p.

Drucker, B.S.; Waskes, W., and Byrnes, M.R., 2004. The US minerals management service outer continental shelf sand and gravel program: Environmental studies to assess the potential effects of offshore dredging operations in federal waters. *Journal of Coastal Research*, 20(1), 1-5.

Dyer, K.R. and Huntley, D.A., 1999. The origin, classification and modeling of sand banks and ridges. *Continental Shelf Research*, 19, 1285-1330.

Fettweis, M.; Francken, F.; Pison, V., and Van den Eynde, D., 2006. Suspended particulate matter dynamics and aggregate sizes in a high turbidity area. *Marine Geology,* 235(1-4), 63-74.

Garel, E., this volume. Tidally-averaged currents and bedload transport over the Kwinte Bank, Southern North Sea. *Journal of Coastal Research*.

Giardino, A.; Van den Eynde, D., and Monbaliu, J., this volume. Wave effects on the morphodynamic evolution of an offshore sand bank. *Journal of Coastal Research*.

Hayes, M. and Nairn, R., 2004. Natural maintenance of sand ridges and linear shoals on the US Gulf and Atlantic continental shelves and the potential impacts of dredging. *Journal of Coastal Research*, 20(1), 138-148.

Heyse, I. and De Moor, G. (eds.), 1996. *Sediment transport and bedform mobility in a sandy shelf environment (EU-MAST STARFISH). Final report*. Gent, University of Gent (B): Research Unit of Marine and Coastal Geomorphology.

Houthuys, R.; Trentesaux, A., and De Wolf, P., 1994. Storm influences on a tidal sandbank's surface (Middelkerke Bank, southern North Sea). *Marine Geology*, 121, 23-41.

ICES Advisory Committee on the Marine Environment, 2003. Annex 2: ICES guidelines for the management of marine sediment extraction. *ICES Cooperative Research Report* 263, 210-215.

James, J.W.C.; Philpott, S.L., and Jenkins, G.O., 2005. Marine aggregates in the Bristol Channel and Severn Estuary. *In*: Bassett, M.G.; Deisler, V.K., and Nichol, D. (eds.), *Urban Geology in Wales: 2*. National Museum of Wales Geological Series No. 24, Cardiff, pp. 222-229.

Johnson, H.D. and Baldwin, C.T., 1986. Shallow siliciclastic seas. *In*: Reading, H.G. (ed.), *Sedimentary environments and facies*. Oxford (UK): Blackwell Science, pp. 229-282.

Kaiser, M.J.; Bergmann, M.; Hinz, H.; Galanidi, M.; Shucksmith, R.; Rees, E.; Darbyshire, T., and Ramsay, K., 2004. Demersal fish and epifauna associated with sandbank habitats. *Estuarine, Coastal and Shelf Science*, 60(3), 445-456.

Kenyon, N.H.; Belderson, R.H.; Stride, A.H., and Johnson, M.A., 1981. Offshore tidal sandbanks as indicators of net sand transport and as potential deposits. *International Association of Sedimentologists, Special Publication,* 5, 257-268.

Lanckneus, J., 1989. A comparative study of sedimentological parametres of some superficial sediments of the Flemish Banks. *In*: Henriet, J.P. and De Moor, G. (eds.), *The Quaternary and Tertiary Geology of the Southern Bight, North Sea.* Brussels: Ministry of Economic Affairs Belgian Geological Survey, pp. 229-241.

Lanckneus, J. and De Moor, G., 1991. Present-day evolution of sandwaves on a sandy shelf bank in the Southern Bight. *Oceanologica Acta*, 11, 123-127.

Lanckneus, J. and De Moor, G., 1994. Bedforms on the Middelkerke Bank, southern North Sea. *In*: Flemming, B.W. and Bartholoma, A. (eds.), *Tidal signatures in Modern and Ancient Sediments*. Oxford (UK): Blackwell Science, pp. 33-52.

Lanckneus, J.; De Moor, G., and Stolk, A., 1994. Environmental setting, morphology and volumetric evolution of the Middelkerke Bank (Southern North Sea). *Marine Geology*, 121, 1-21.

Lanckneus, J.; Van Lancker, V.; Moerkerke, G.; Van den Eynde, D.; Fettweis, M.; De Batist, M., and Jacobs, P., 2001. *Investigation of natural sand transport on the Belgian continental shelf: BUDGET (Beneficial usage of data and geo-environmental techniques). Final report.* Brussels: Federal Office for Scientific, Technical and Cultural Affairs (OSTC), 104 + 87pp. Annex.

Le Bot, S.; Van Lancker, V.; Deleu, S.; De Batist, M., and Henriet, J.P., 2003. *Tertiary and Quaternary geology of the Belgian continental shelf*. Scientific Support Plan for a Sustainable Development Policy. SPSD II North Sea. Brussels: PPS Science Policy publication D/2003/1191/12, 75p.

Macdonald, N.J. and O'Connor, B.A., 1996. Changes in wave impact on the Flemish Coast due to increased mean sea level. *Journal of Marine Systems*, 7(2-4), 133-144.

Maes, F.; Cliquet, A.; Seys, J.; Meire, P., and Offringa, H., 2000. *Limited Atlas of the Belgian Part of the North Sea*. Brussels: The Prime Minister's Services, Federal Office for Scientific, Technical and Cultural Affairs, 31p.

Maréchal, R. and Henriet, J.P., 1983. *Seismisch onderzoek op het Belgisch continentaal plat. Eerste faze. Ontginningszone 2.* Brussel: Ministerie van Economische Zaken. Administratie van het Mijnwezen, 32p.

McCave, I.N. and Langhorne, N., 1982. Sand waves and sediment transport around the end of a tidal sandbank. *Sedimentology,* 24, 507-527.

McNinch, J.E. and Wells, J.T., 1999. Sedimentary processes and depositional history of a cape-associated shoal, Cape Lookout, North Carolina. *Marine Geology*, 158(1-4), 233-252.

Ministerie Van De Vlaamse Gemeenschap, 1993. *Kust 2002. Deel 1. De zeewerende functie van de kust. Stand van zaken*. Brussel: Administratie Waterinfrastructuur en Zeewezen, AWZ, 82p.

Norro, A. and Ozer, J., 2004. Long term volumetric evolution of an exploited sandbank. Case study on the Belgian North Sea Kwintebank. *Journal of Coastal Research,* Special Issue No. 39, 1-6.

Norro, A.; Pichot, G.; Pison, V., and Ozer, J., 2006. Bidimensional approach to the volumetric evolution of an exploited sandbank. ICES *Journal of Marine Science*, 63(1), 176-186.

Otto, S., 1998. Off-shore sand banks and their role in coastal sedimentary processes: The Welsh coast of the outer Severn Estuary, SW Britain. *In*: Bennett, M.R. and Doyle, P. (eds.), *Issues in Environmental Geology: a British Perspective.* London (UK): Geological Society, pp. 326-373.

Pan, S.; Macdonald, N.; Williams, J.; O'Connor, B.A.; Nicholson, J., and Davies, A.M., 2007. Modelling the hydrodynamics of offshore sandbanks. *Continental Shelf Research*, 27(9), 1264-1286.

Parker, G.; Lanfredi, N.W., and Swift, D.J.P., 1982. Seafloor response to flow in a southern hemisphere sand ridge field: Argentine inner shelf. *Sedimentary Geology,* 33, 195-216.

Pattiaratchi, C.B. and Collins, M.B., 1987. Mechanisms for linear sandbank formation and maintenance in relation to dynamical oceanographic observations. *Progress in Oceanography*, 19, 117-176.

Poulos, S.E. and Ballay, A., this volume. Grain size trend analysis for the determination of non-biogenic sediment pathways at the Kwinte Bank (Southern North Sea), in relation to sand abstraction. *Journal of Coastal Research*.

QUEENSLAND, 2005. *Moreton Bay Sand Extraction Study. Summary of Findings*. Brisbane (AU): Queensland Government, Environmental Protection Agency, Queeensland Park and Wildlife Service, 16p.

Reynaud, J.Y.; Tessier, B.; Berne, S.; Chamley, H., and De batist, M., 1999. Tide and wave dynamics on a sand bank from the deep shelf of the Western Channel approaches. *Marine Geology*, 161(2-4), 339-359.

Rzonzef, L. (ed.), 1993. *Effekten op het marien leefmilieu van de zand- en grindwinningen op het Belgisch kontinentaal plat*. Syntheseverslag. Brussel: Annalen der Mijnen van Belgie, 2, 49p.

Seys, J.; Meire, P.; Devos, K., and Kuijken, E., 1993. *De kust- en Vlaamse Banken: ecologisch belang, raakvlakken met andere functies en beheerssuggesties.* Hasselt: Conceptrapport Inst. voor Natuurbehoud, 132p.

Seys, J.; Offringa, H.; Van Waeyenberge, J.; Meire, P., and Kuijken, E., 1999. *Ornithologisch belang van de Belgische maritieme wateren: naar een aanduiding van kensoorten en sleutelgebieden*. Brussel: Instituut voor Natuurbehoud, Nota IN A74, 30p.

Solomon, S.; Qin, D.; Manning, M.; Chen, Z.; Marquis, M.; Averyt, K.B.; Tignor, M., and Miller, H.L.E., 2007. *IPCC, 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 996p.

Stride, A.H., 1982. *Offshore Tidal Sands. Process and Deposition*. London: Chapman & Hall, 222p.

Suter, J.R.; Mossa, J., and Penland, S., 1989. Preliminary assessment of the occurrence and effects of utilisation of sand and aggregate resources of the Luisiana inner shelf. *Marine Geology*, 90, 31-37.

Trentesaux, A.; Stolk, A.; Tessier, B., and Chamley, H., 1994. Surficial sedimentology of the Middelkerke Bank (southern North Sea). *Marine Geology*, 121, 43-55.

Trentesaux, A.; Stolk, A., and Berne, S., 1999. Sedimentology and stratigraphy of a tidal sand bank in the southern North Sea. *Marine Geology*, 159, 253-272.

Tyler, P. A. and Shackley, S. E., 1979. The benthic ecology of linear sandbanks: A modified *Spisula* sub-community. *In*: Collins, M.B.; Banner, F.T.; Tyler, P.A.; Wakefield, S.J., and James, A. (eds.), *Industrialised Embayments And Their Environmental Problems: A Case Study Of Swansea Bay*, Pergamon Press, pp. 539-554.

Vanosmael, C.; Willems, K. A.; Claeys, D.; Vincx, M., and Heip, C., 1982. Macrobenthos of a sublittoral sandbank in the Southern Bight of the North Sea. *Journal of the Marine Biological Association of the United Kingdom*, 62, 521-534.

Van Cauwenberghe, C., 1971. Hydrografische analyse van de Vlaamse Banken langs de Belgische kust. *Het Ingenieursblad*, 40(19), 563-571.

Van den Eynde, D.; Giardino, A.; Portilla, J.; Fettweis, M.; Francken, F., and Monbaliu, J., this volume. Modelling the effects of sand extraction on the sediment transport due to tides on the Kwinte Bank. *Journal of Coastal Research*.

Van Hoey, G.; Degraer, S., and Vincx, M., 2004. Macrobenthic community structure of soft-bottom sediments at the Belgian Continental Shelf. *Estuarine, Coastal and Shelf Science*, 59(4), 599-613.

Van Lancker, V. (1999). *Sediment and morphodynamics of a siliciclastic near coastal area, in relation to hydrodynamical and meteorological conditions: Belgian continental shelf*. Ghent University, unpublished Ph.D thesis, 194p.

Van Lancker, V., Du Four, I., Verfaillie, E., Deleu, S., Schelfaut, K., Fettweis, M., Van den Eynde, D., Francken, F., Monbaliu, J., Giardino, A., Portilla, J., Lanckneus, J., Moerkerke, G. and Degraer, S. (2007). *Management, research and budgetting of aggregates in shelf seas related to end-users (Marebasse).* Brussel (B), Belgian Science Policy (D/2007/1191/49), 139 pp. + DVD GIS@SEA + Habitat Signature Catalogue.

Van Lancker, V.R.M.; Bonne, W.; Garel, E.; Degrendele, K.; Roche, M.; Van den Eynde, M.; Bellec, V.; Brière, C.; Collins, M.B., and Velegrakis, A.F., this volume. Recommendations for the sustainable exploitation of tidal sandbanks. *Journal of Coastal Research*.

Velegrakis, A.F.; Collins, M.B.; Owrid, G., and Houghton, A., 2001. Submerged sandbanks of the European Shelf Waters. *In*: Jones, S. (ed.), *Implementation of the EU HABITATS Directive Offshore: Natura 2000 sites for reefs and submerged sandbanks. Volume II: Northeast Atlantic and North Sea.* WWF Report, pp. 44-85.

Velegrakis, A.F.; Collins, M.B.; Bastos, A.C.; Paphitis, D., and Brampton, A., 2007. Seabed sediment transport pathways investigations: review of scientific approach and methodologies, *In*: Balson, P.S. and Collins, M.B. (ed.), *Coastal and Shelf Sediment Transport*. Geological Society of London, Special Publication, 274, pp. 127-146.

Velegrakis, A.F.; Ballay, A.; Poulos, S.; Radzevičius, R.; Bellec, V., and Manso, F., this volume. European marine aggregates resources: Origins, usage, prospecting and mining techniques. *Journal of Coastal Research.*

Verfaillie, E.; Van Lancker, V., and Van Meirvenne, M., 2006. Multivariate geostatistics for the predictive modelling of the surficial sand distribution in shelf seas. *Continental Shelf Research,* 26(19), 2454-2468.

Vincent, C.E.; Stolk, A., and Porter, C.F.C., 1998. Sand suspension and transport on the Middelkerke Bank (southern North Sea) by storms and tidal currents. *Marine Geology*, 150, 113-129.

Vincx, M.; Bonne, W.; Cattrijsse, A.; Degraer, S.; Dewicke, A.; Steyaert, M.; Vanaverbeke, J.; Van Hoey, G.; Stienen, E.; Van Waeyenberghe, J.; Kuijken, E.; Meire, P.; Offringa, H.; Seys, J.; Volckaert, F.A.M.; Gysels, E.; Hellemans, B.; Huyse, T., and Pampoulie, C., 2003. *Structural and functional biodiversity of North Sea ecosystems: species and their habitats as indicators for a sustainable development of the Belgian continental shelf. Final report*. Brussels: The Prime Minister's Services, Federal Office for Scientific, Technical and Cultural Affairs, 83p.

Williams, J.J.; Macdonald, N. J.; O'Connor, B.A., and Pan, S., 2000. Offshore sand bank dynamics. *Journal of Marine Systems*, 24(1-2), 153-173.

Wright, L.D., 1995. *Morphodynamics of inner continental shelves*. Boca Raton: Marine Science Series, CRC Press, 233p.

Journal of Coastal Research	SI	51	63-76	West Palm Beach, Florida	Summer 2010

Geo-environmental Characterization of the Kwinte Bank

Valérie K. Bellec[1*], Vera Van Lancker[1], Koen Degrendele[2], Marc Roche[2] and Sophie Le Bot[1***]**

[1] Ghent University, Renard Centre of Marine Geology
Krijgslaan 281, S8, 9000 Gent, Belgium

[*] Present address: Geological Survey of Norway
Leiv Eirikssons vei 39
7040 Trondheim, Norway
valerie.bellec@ngu.no

[2] Federal Public Service Economy, SMEs, Self-employed and Energy –
Fund for Sand Extraction
Simon Bolivarlaan 30, WTCIII, B-1000 Brussel, Belgium

[**] Present address: Royal Belgian Institute of Natural Sciences. Management Unit of the North Sea Mathematical Models
Gulledelle 100, B-1200 Brussels, Belgium

[***] Present address: UMR CNRS 6143 "M2C"
University of Rouen
76821 – Mont Saint Aignan, France

ABSTRACT

A detailed geomorphological and sedimentological study has been performed at a tidal sandbank, which has been dredged during 30 years. Localised intensive aggregate extraction created a depression in the central part of the sandbank, upon which the Government decided to close this section of the bank for further exploitation. Multibeam and side-scan sonar technology was used to survey the bank, in combination with extensive ground-truthing. Automated seabed classification was performed, but showed no direct correlation with the mean grain-size; the primary drivers influencing the classification being the sorting of the sediments, the presence of shells and of fine sediments. Very-high resolution seismics revealed the internal architecture of the bank. In the central depression, the upper unit is locally severely dredged.

The central depression is characterized by distinct morphosedimentary facies, compared to the western and eastern part of the bank and the Kwinte swale, adjacent of it. The difference between the western and the eastern part is essentially due to different tidal current characteristics, each having their particular sedimentation-erosion patterns. These processes seem to be rather stable, though the evolution of the sediments in the central depression shows similarities with the Kwinte swale sediment evolution.

Since the depression is somewhat oblique to the normal crestline, it now forms an open transport pathway from the swale up to the crest of the sandbank. This led to a canalization of the flood current which is witnessed mostly by the northwards and faster progression of bedforms. Because of the difference in sediment characteristics between the dredged material and the present-day supply of sand, it is unlikely that natural processes will be able to counterbalance the severe dredging activities.

Moreover, the presence of the central depression is located close to the kink of the sand bank, which is influenced by a high-energy hydrodynamic regime. Its presence could intensify the current action in this area and could enhance the evolution of the bank.

ADDITIONAL INDEX WORDS: *North Sea, sandbank, acoustic imagery, seabed classification, dredging.*

INTRODUCTION

Numerous subtidal sandbanks and dunes (*senso* Ashley, 1990) cover the sea floor of the English Channel and the Belgian Continental Shelf. Some of these sandbanks are exploited or are located near navigation channels; as such, their dynamics and formation have given rise to numerous studies (e.g. Caston, 1981; Caston and Stride, 1970; Deleu *et al.*, 2004; Eisma, Jansen, and Van Weering, 1979; Houbolt, 1968; Kirby and Oele, 1975; Laban and Schüttenhelm, 1981; Le Bot *et al.*, 2000; Le Bot and Trentesaux, 2004; Stride, 1988; Trentesaux *et al.*, 1994; Van Lancker and Jacobs, 2000; Vincent, Stolk and Porter, 1998; and Williams *et al.*, 2000).

Off the Belgian coast, some parts of the sandbanks are dredged intensively. The exploitation of marine sand began in 1976 and, from 1979 onwards, the extraction activities have been monitored. The annual extraction evolved gradually, from 370,000 m^3, in 1979, to 1,700,000_m^3, in the middle of the 1990's. In 2001, the extraction exceeded 1,900,000 m^3; however, the last 2 years, the production has stabilized around 1,600,000 m^3 (Degrendele *et al.*, this volume).

One of the sandbanks, the Kwinte Bank, has been exploited intensively. In fact, two areas, located on this bank, represent 25 % of the total extraction on the Belgian continental shelf. One of these areas corresponds to the "central depression" (Degrendele *et al.*, this volume); it has a depth of 5 m, is 700 m wide and 1 km long, and is located in water depth at around 10-15 m MLLWS (Mean Lowest Low Water at Springs) (Figure 1.). Since February 2003, the marine aggregate extraction has been prohibited at this particular location, because of the creation of a more than 5 m depth formation, for a duration of 3 years, allowing a potential recovery of the area.

The closure of the depression has led to increased effort to study the environmental impact of sand extraction activities. The aim of this paper is the geo-environmental characterisation of the central depression. Since the dredging occurred

DOI: 10.2112 / SI51-006.1 received 15 January 2007; accepted in revision 27 March 2008.

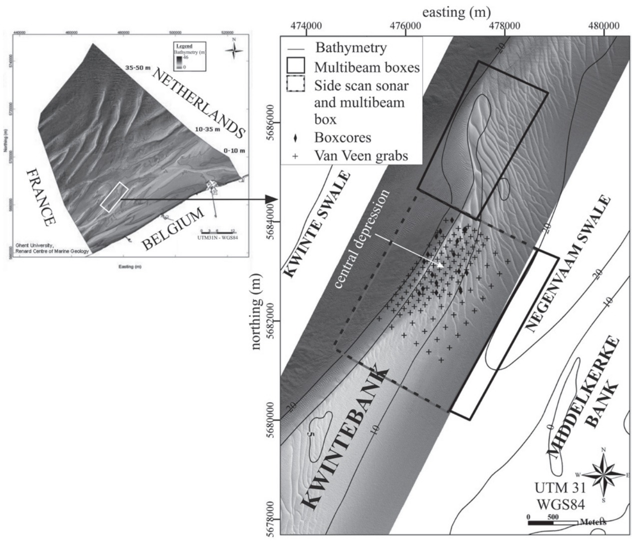


Figure 1. Location of the Kwinte Bank and the different measurement and sampling areas. Left: Bathymetric map of the Belgian continental shelf (Renard Centre of Marine Geology, Ghent University). Right: Bathymetry of the Kwinte Bank (Fund for Sand Extraction), and location of the presented geophysical and sedimentological measurements.

near the crest of the bank, it was important to evaluate whether this had an effect on the morphosedimentary behaviour of the different parts of the sandbank. Knowledge was needed on the grain-size distributions in the area, both from a (re)source perspective, as well as for the evaluation of the sedimentary material in transport. The study of the morphology focuses on the bedforms and the effects dredging have upon these. Indirectly, the study of the sedimentary environment can provide indications of what extent the extraction has altered the sediment transport pattern. The results allow having a first impression of the possible regeneration of the depression, after its closure for extraction.

The study is based on the results of high-resolution acoustic tools, such as side-scan sonar and multibeam. Manual and automated seabed classification was performed; these were calibrated with sediment samples (boxcores and Van Veen grabs) and video imagery. Conclusions are drawn on the performance of those techniques related to the characterization of the true nature of the seafloor. Very-high resolution seismics were used to estimate to what level of the bank the extraction took place. Moreover, it provides an estimate of the resource potential and its homogeneity.

ENVIRONMENTAL SETTING

General Morphology and Sedimentology

The Flemish Banks are oriented obliquely, in relation to the maximum tidal currents (De Moor and Lanckneus, 1990). The Kwinte Bank, one of the Flemish Banks, is a SW-NE oriented tidal sandbank (Figure 1.). The sandbank has a height of about 17 m, a length of about 15 km, a width varying from about 2 km in the southern part to about 1 km in the northern part; it shows an offshore "kink" over its middle part. The minimum water depth is close to -5 m MLLWS, in the southern part of the bank where the bathymetric profiles show a smooth morphology. Most of the sandbank is covered with large to very-large dunes (*senso* Ashley, 1990) with a wavelength of several hundreds of metres, a crest length of several tens of metres and a height varying between 1 and 7 m. In the northern part, very-large dunes are found in areas where the minimum depth is about -8 m MLLWS. Large dunes are present also in the middle part of the bank; their height can reach 2.5 m. The minimum depth, in the swales around the bank, is of the order of -22 m MLLWS. The cross-section of the sandbank is clearly asymmetrical, with the steeper side (slope up to 5 %) facing the NW (De Moor, 1985; De Moor, 1986; and Lanckneus *et al.*, 1989). The gentle eastern slope of the bank can reach ~2 to 3%.

Along the western slope of the sandbank, the sediments coarsen towards the north, from about 240 µm up to 400 µm. Generally, the eastern flank is finer-grained with values around 200 µm in the south (Lanckneus, 1989).

Hydrodynamics and Sediment Transport Pattern

The hydrodynamics around the Kwinte Bank are characterized by semi-diurnal tides of a macrotidal range (4-5 m at springs). The average tidal movement corresponds to an elongated current ellipse, with a southwest-northeast axis. The flood peak and ebb peak currents are oriented towards the northeast and the southwest respectively. These tidal currents are rotating counter clockwise around the Kwinte Bank (Caston, 1972; De Moor, 1986; Houbolt, 1968; and Lanckneus *et al.*, 1989). The velocity of the surface peak currents reaches up to 2 knots (1 m/s) and the flood is the dominant current (De Moor, 1986; and Van Cauwenberghe, 1981).

The direction of sand transport is linked with the tidal currents. On the western part of the bank, the flood transports sand towards the northeast (Garel, this volume). On the eastern part of the bank, the ebb is dominant and transports the sand towards the southwest. The Kwinte Bank receives sand from both adjacent swales, coming from opposite directions, provoking sand up-piling towards the central parts; still the vertical growth is limited by wave and storm action (Caston, 1972; Lanckneus *et al.*, 1989; and Van Veen, 1936). The steep western slope is generally regarded erosional, by the action of the strong flood currents whereas the gentle slope can be considered as an accumulating area (De Moor, 1985; Lanckneus *et al.*, 1989; and Vlaeminck, Gullentops, and Houthuys, 1985).

Geological Background

The Tertiary substratum underneath the Kwinte Bank is composed of compact clay of the Kortrijk Formation (for an overview, see Le Bot *et al.*, 2005) and is locally eroded in the swale, west of the Kwinte Bank. The Quaternary geology of the sandbanks is best studied along the Middelkerke Bank, located adjacent to the Kwinte Bank. Detailed studies showed that this sandbank is composed of seven units, each having a particular lithological composition Trentesaux *et al.*, 1993; Trentesaux, Stolk, and Berné, 1999). A comparison of the present-day morphology with the top Tertiary erosion surface provides a rough volume estimation of $300x10^6$ m^3 for the total Kwinte Bank.

METHODOLOGY

Multibeam and Side-scan Sonar

Acoustic measurements were undertaken in June 2003 (23-27/06/2003) (RV *Belgica* campaign ST0317; report www.mumm.ac.be). A Kongsberg Simrad EM1002S multibeam echosounder was used; this transducer produces 111 beams, arrayed over an arc of 150° and uses two frequencies, 93 and 98 kHz (Kongsberg Simrad, 1999-2001a). The multibeam imagery provides two datasets: the bathymetry allows a description of the morphology of the seabed and, especially, the bedforms; the backscatter provides an estimate of the nature of the sea floor, influenced mainly by sediment texture. The datasets were processed with different software packages: Neptune (Kongsberg Simrad, 1999-2001b), for the data correction and cleaning; Poseidon (Kongsberg Simrad, 1999-2001c), for the correction and mosaicing of the backscatter data and Triton (Kongsberg Simrad, 1999-2001d), for the automated seabed classification. The latter is a multivariate classification of backscatter values and uses different statistical parameters such as standard deviation, pace, quantile and contrast.

The side-scan sonar, a Geoacoustics model 159D, was deployed at the same time as the multibeam data. This would allow a complementary characterization of the bedforms and the nature of the sea floor. Only the 410 kHz frequency was recorded; no interference occurred with the frequency of the multibeam. The side-scan sonar data were processed with the Isis software (Triton Elics). As detailed full-coverage multibeam data of the area already existed, (Fund for Sand Extraction), it was preferred to space the tracklines according to the side-scan sonar coverage, being far larger than the one of multibeam.

Sediment Sampling

During the June 2003 campaign, 17 boxcores were taken to calibrate the side-scan sonar and the multibeam imagery. Three months later (September 2003), a larger area was covered by 120 Van Veen grab samples with a gridding of 150 m inside the depression and 300 m outside it. This area was sampled again in February 2004, October 2004 and February

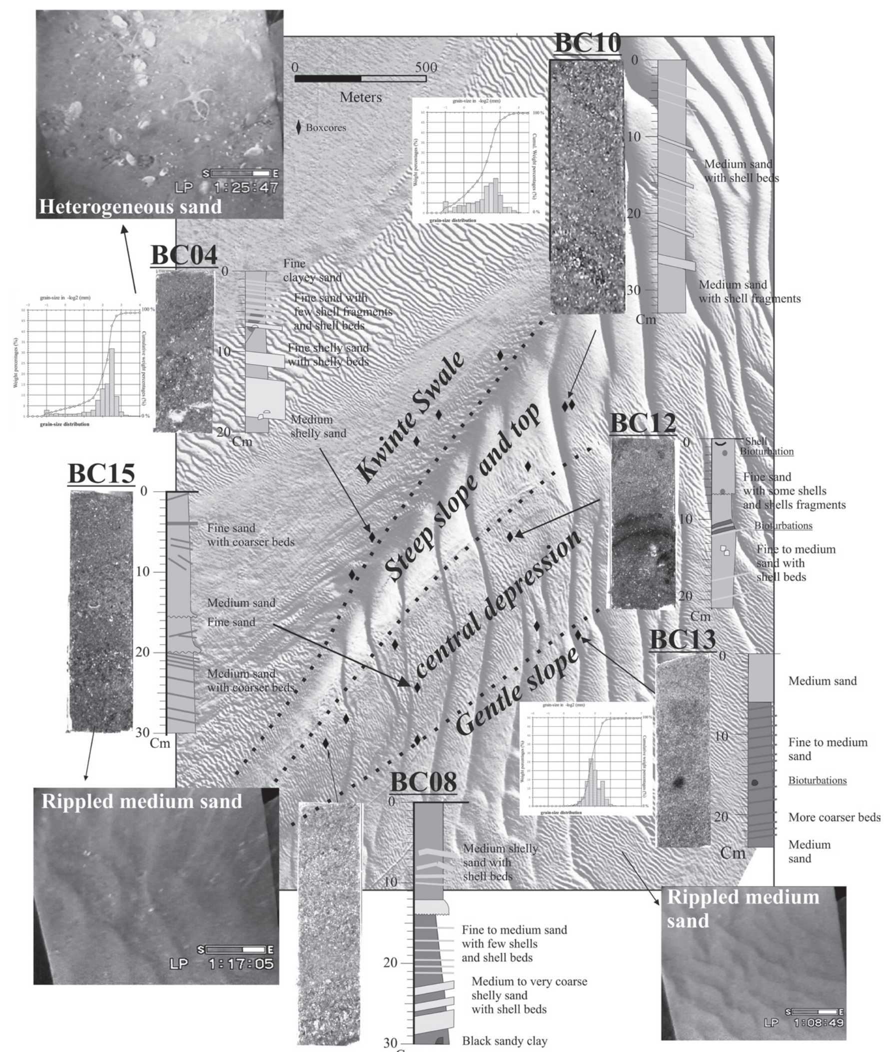


Figure 2. Boxcore interpretation and video imagery (June 2003), in relation to various parts of the sandbank.

Table 1. *Summary of the major sedimentological characteristics of the four environments (September 2003) (the mean value (M) and the range (R) for each environment inside the sampling area, are indicated).*

Environment	Mean grain-size	Sorting	Skewness	Carbonate content
East part (gentle slope)	Fine to medium sand (M: 281 µm, 188-489 µm)	Well to moderately-well (M: 0.59 ϕ, R: 0.27-1.69 ϕ)	Low values (M: -0.18, R: -0.77 - +0.13)	Low (M: 13%, R: 7-27 %)
Central depression	Fine to coarse sand (M: 303 µm, R: 205-552 µm)	Moderate to poor (M: 0.72 ϕ, R: 0.35-1.57 µm)	Variable (M: -0.26, R: -0.64 - +0.26)	Variable (9-31%)
West flank (northern large to very-large dunes, top and steep slope)	Coarse sand (M: 541 µm, R:229-1219 µm)	Poor (M: 1.04 ϕ, R: 0.50-1.69 ϕ)	Very variable (M: -0.21, R: -0.70 - +0.29)	High (> 40%)
Kwinte swale	Fine sand (M: 268 µm, R: 206-461 µm)	Poor (M: 0.92 ϕ, R: 0.48-1.68 ϕ)	Variable (M: -0.39, R: -0.76 - +0.01)	Low (M: 14%, R: 8-21%)

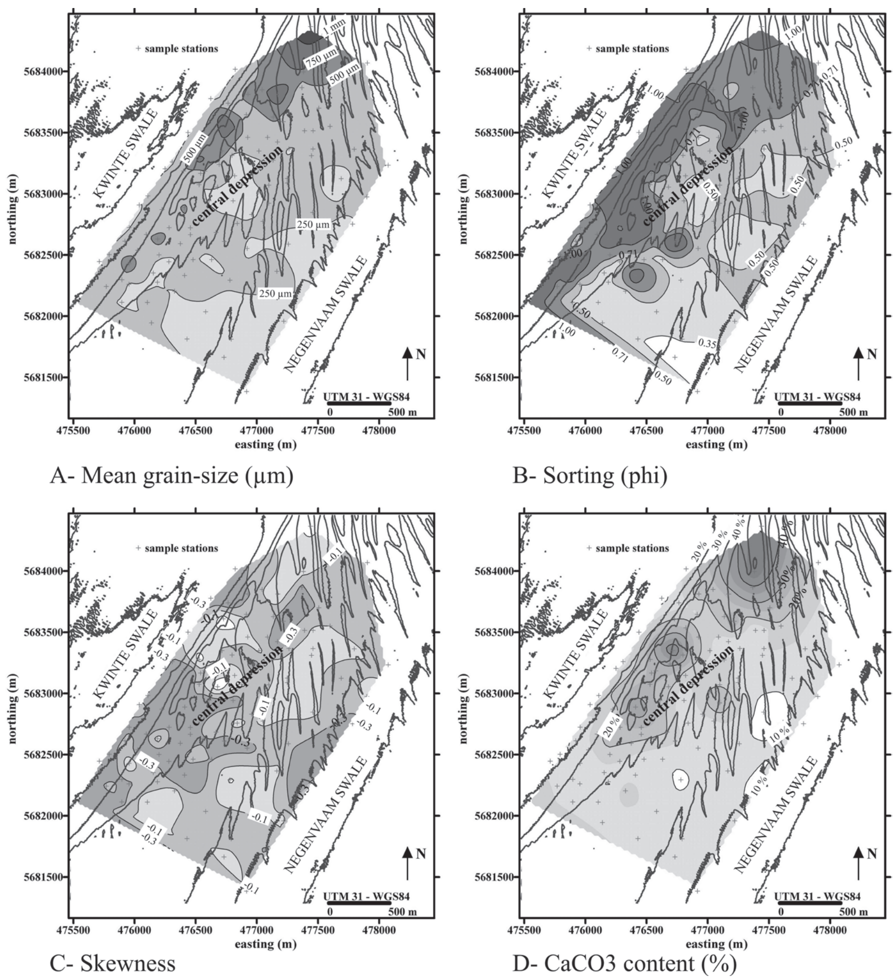


Figure 3. Sedimentological parameters obtained from the Van Veen grab samples (September 2003): A- Mean grain-size: fine sand (light grey) to coarse sand (dark grey), B- Sorting: well-sorted (light grey) to poorly-sorted (dark grey), C- Skewness: enrichment in fine grains (white) to enrichment in coarse grains (dark grey), D- Carbonate content: low values in light grey and high values in dark grey.

2005 (RV *Zeeleeuw*, RV *Belgica*; reports at www.vliz.be and www.mumm.ac.be, respectively).

The boxcores were taken to validate the relationship between the acoustic measurements and the true sedimentary character of the sea floor and become acquainted with the factors controlling the definition of the acoustically-derived seabed classes. Boxcoring permits sampling of the first 20-50 cm of the subsurface. The boxcore content was first described and photographed, after which 2 sub-cores were taken to analyse the stratification and the grain-size of each vertical sub-section. Sediments were sieved on a rack of 2 mm to 75 µm with a ¼ phi interval to permit detailed analysis. The final results were treated statistically according to FOLK and WARD (1957); this allowed obtaining the most relevant sedimentological parameters, such as mean grain-size, sorting and skewness. The calcium carbonate content was determined through calcimetry. Sediment grain-size fractions were classified according to the Wentworth scale (WENTWORTH, 1922).

On the larger grid framework, Van Veen grabs were collected. The positions of the samples were defined on the basis of a 300 m grid along a transversal section over the sandbank and a 150 m grid including the central depression. From each grab, a bag of about 1.5 kg was taken. In the laboratory, the bulk sample was split; the grain-size analyses were similar to those applied to the boxcore samples.

Video Recording

In June 2003, video sequences were obtained at the same locations as the boxcores. The system used was a Simrad underwater video camera, mounted on a small frame. Samples of the video imagery were taken using the Hollywood Pinnacle software.

Seismics

During the June 2003 campaign, a boomer (IKB Seistec boomer/receiver) was used to investigate the internal architecture of the sandbank. Boomer sources combine high frequencies with a broad spectrum and a good repeatability, and seem to offer a good compromise between resolution and penetration (main frequency ~4 kHz with a range of 0.7-7 kHz, a resolution of 20 cm and a penetration of 10–20 m). However, the quality of the data is highly weather dependent. The digital recording

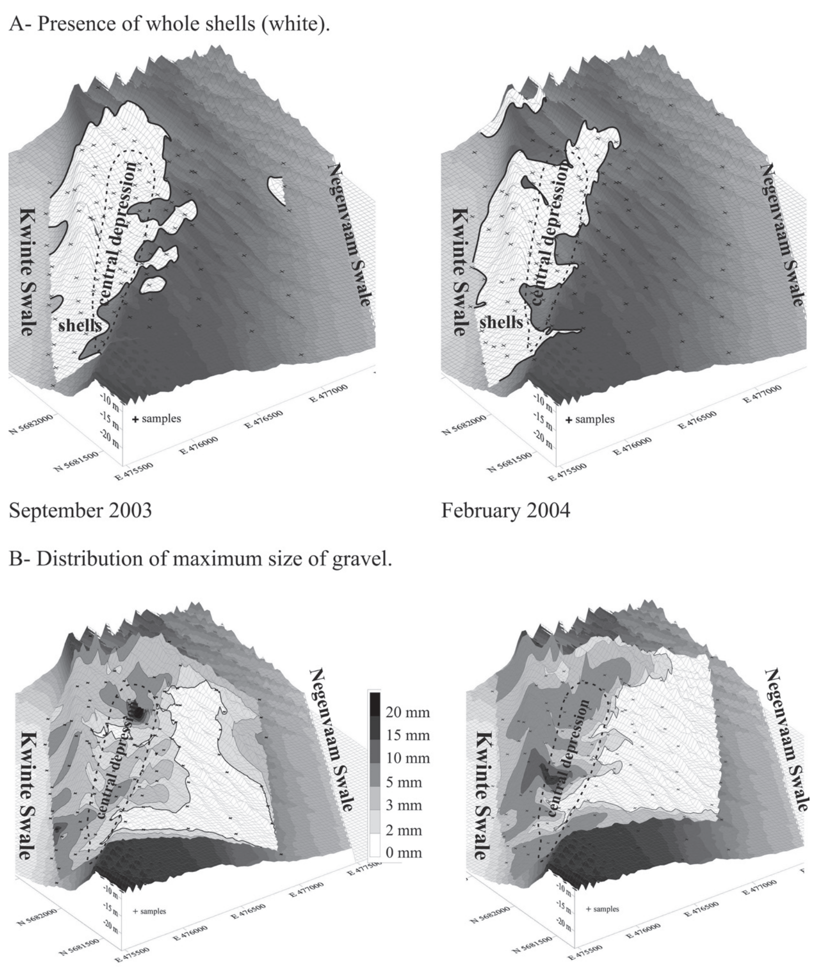


Figure 4. Distribution of the coarse fraction. Sedimentological information is wrapped onto a 3D bathymetry map. Crosses correspond to the sampling stations. A- Presence of whole shells (unbroken). They are only present along the western slope and in the central depression. B- Distribution of the maximum size of gravel.

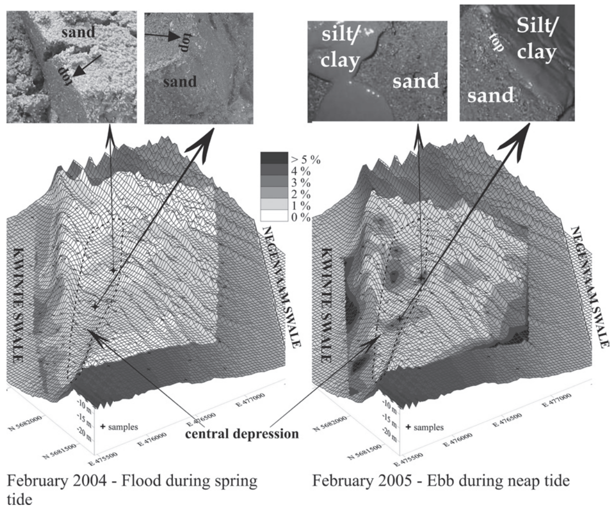


Figure 5. Distribution of the fine-grained sediments (< 75 µm), incorporated within a 3D bathymetric map. Crosses correspond to the sampling stations. In February 2004, the samples have been taken during the flood; there is no mud on the top. In February 2005, the samples have been taken during the ebb; a fine layer of mud is present on the top of the samples. Top: photos of the samples.

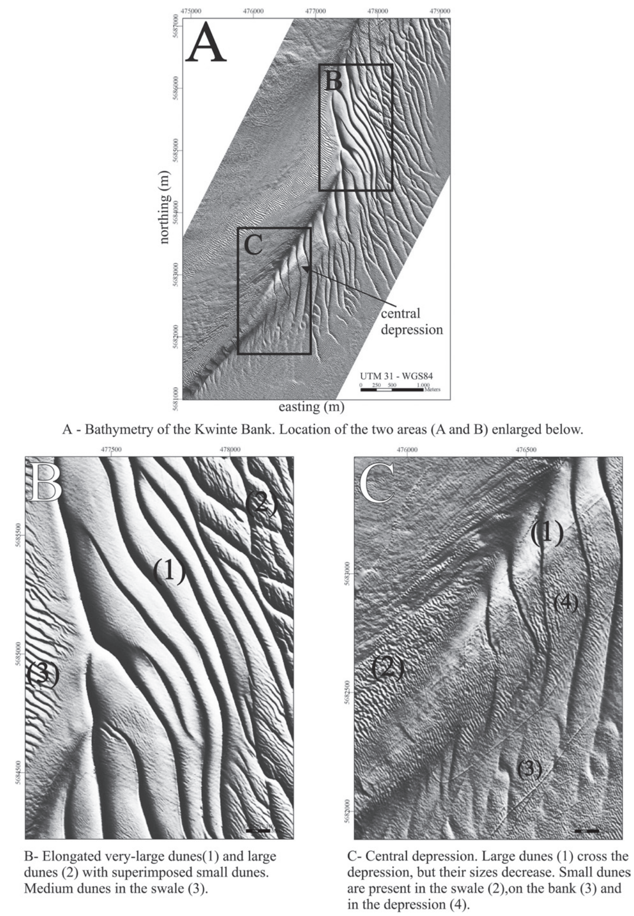


Figure 6. Bedforms on the Kwinte Bank. Bathymetry of the Kwinte Bank (A), the kink in the bank (B) and the central depression (C).

allowed a further processing, including a.o. bandpass filtering, age scaling, deconvolution and swell filtering. Small-scale seismic units and their boundaries were identified. The locations of the measurements are shown on Figure 1.

RESULTS

Sedimentological Characterization, Derived from Boxcoring, Van Veen Grabs and Video Imagery

Samples from the boxcores (June 2003; Figure 2., Annex 1) and from the Van Veen grabs (September 2003; Figure 3.) show the same sediment characteristics and allow to distinguish four lithofacies along the central part of the bank (locations indicated on Figure 2).

Each of these lithofacies has specific characteristics of mean grain-size, sorting, skewness and carbonate content (Table 1) and can be described as follows (east to west):

1) The eastern, gentle slope of the sandbank is characterised by well-sorted, fine to medium sands (mean grain-size of 281 µm). South and north of this central area, the sediments become, respectively, finer (+/- 190 µm) and coarser (+/- 300 µm). The skewness is characterised by low values, indicating a low enrichment in very coarse or very fine sediments. The carbonate content is generally reduced to 15%, whilst no important internal structures can be observed in the boxcores. The video imagery shows small dunes with sediments comprising some shells and shell fragments. No organisms are visible. No big differences of sediment occur between the gentle slope and the western boundary of the Negenvaam swale.

2) The central depression, caused by dredging, is a heterogeneous area. The sorting is variable and the sand is fine to coarse. The internal structure of the upper sediment layer shows shell beds of a few millimetres thick. In fact, this facies is intermediate between facies observed on the western steep slope and along the gentle eastern slope. The first facies is found, for example, near the southern extremity of the depression and comprises a large number of shelly beds (Figure 2.). Towards the gentle slope, the facies becomes more homogeneous. Skewness is the sediment parameter that clearly distinguishes the depression from the gentle and steep slope: it shows a lower mean value than along other areas of the sandbank. Generally, the skewness is negative, but some positive values (enrichment in very-fine sediments) can be found at some places. The carbonate content lies between 10 and 35 %. Video imagery showed shell fragments and complete shells, in the troughs, between the small dunes. The crests of the dunes were devoid of shells.

3) The western border of the central depression and the steep slope of the sandbank, are characterized by poorly sorted sediments. Large shell fragment layers of several centimetres thick occur at the base and are covered with an alternation of finer sand and shell beds of several millimetres thick. Generally, the skewness is negative, but low positive values also occur. The sand is coarse to very coarse and the carbonate content can exceed 40 %. The video imagery shows shell fragments and complete shells, mainly in the troughs of the

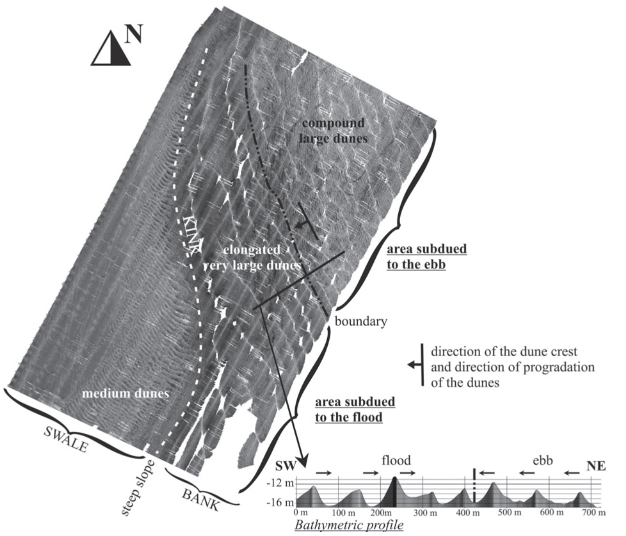


Figure 7. Multibeam backscatter of the “kink” area of the Kwinte Bank. Location of the area is shown on Figure 8.

small dunes. Generally, epibenthic fauna and, in particular, *Echinodermata* are observed (e.g. starfish, brittle stars, and uncovered sea urchin tests).

4) The sediments of the swale, west of the Kwinte Bank (Kwinte Swale), are poorly sorted, due to the presence of gravel and clayey or silty sediments, mixed with fine sand. The skewness is variable. The carbonate content is, generally, down to 20 %.

On an overall basis, the distribution of the coarse fraction (> 3 mm, mostly shells) is limited to the western part of the bank and the central depression (Figure 4.).

A fine layer of mud can appear on the top of the samples inside the central depression (Figure 5.). This occurs when the tidal current are very low in the central depression. This layer was sampled during ebb and slack-water time during a neap tide. So it is difficult to distinguish which condition, between ebb and neap tide, is the most important. During the flood, this layer disappears.

Large and Small-Scale Bedform Morphology

Results from the multibeam and side-scan sonar imagery

The four lithofacies, previously described correspond to particular morphological characteristics:

1) The gentle slope of the sandbank shows large sinuous dunes that amalgamate in some places. Small dunes cover their flanks (Figures 6. and 7.).

2) The contours of the central depression are well pronounced. Interestingly, the large dunes cross the central depression, but they are smaller than those outside the depression (Figure 6C.). The crests of the large dunes within the central depression are more diverted towards the north, than the crests on both sides of the depression, indicating a more rapid movement of the dunes in the depression area due to their smaller height.

3) The western part (steep slope and crest) shows elongated very-large dunes, generally without superimposed small dunes (within the accuracy of the device). In fact, there are two types of large to very-large dunes: (i) higher (up to 5 m) and elongated, located close to the Kwinte Swale (Figure 6B. (1)); (ii) more towards the north and east, belonging to the gentle slope and are smaller (around 2-3 m height) with superimposed smaller bedforms on their slope (compound large dunes) (Figure 6B. (2)).

4) Within the Kwinte Swale, erosional features from currents (furrows), oriented northeast-southwest, are located between two fields of small to medium dunes; these dunes have a southeast-northwest strike (Figure 6B. (3)). The first dune field extends towards the mouth of the central depression, whilst the second terminates on the part of the steep slope, where the offshore kink is present (see above). The crestline of this section of the bank consists of one elongated very-large dune structure.

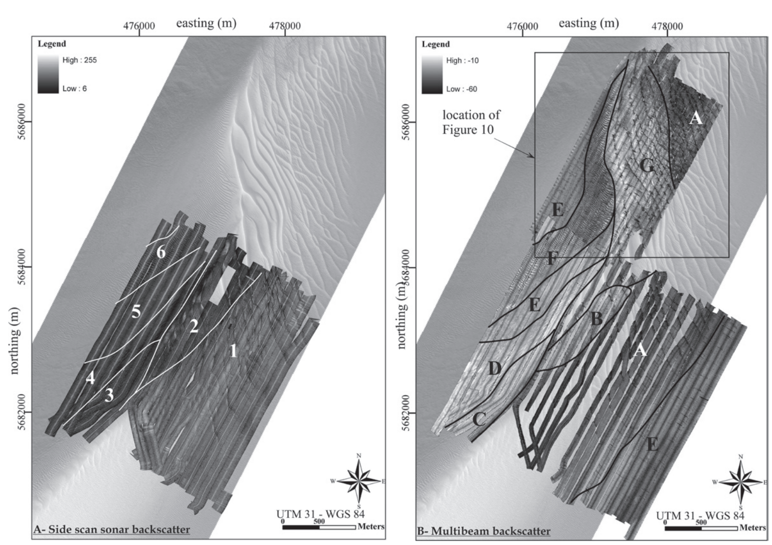


Figure 8. Comparison of the seabed classification, obtained from A- Side-scan sonar imagery and B- Multibeam backscatter. Five classes have been derived from the side-scan sonar imagery (1 to 5) and seven ones from the multibeam imagery (A to G). In the background: bathymetry of the Kwinte Bank.

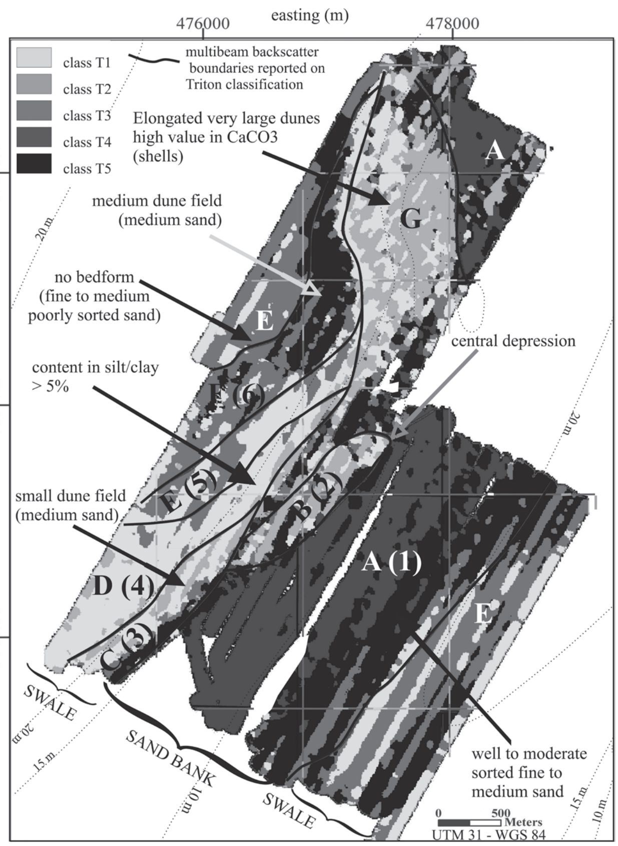


Figure 9. Triton automated seabed classification (Kongsberg Simrad) (classes T1 to T5). Comparison with the manual seabed classification (classes A to G).

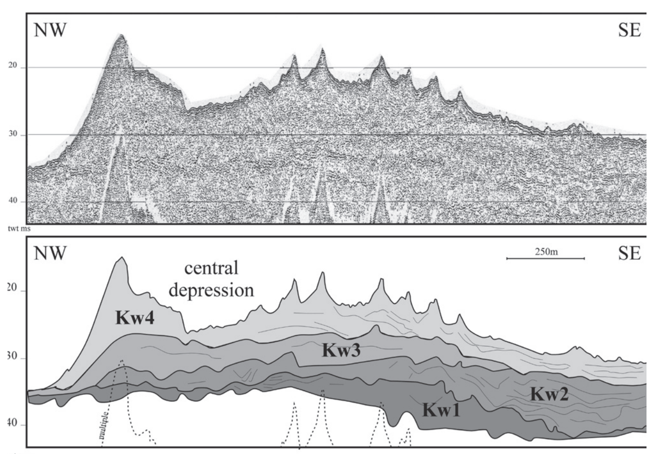


Figure 10. Seismic profile crossing the central depression. In the central depression, the extraction nearly affected the base of the youngest seismic unit Kw4.

Results from seabed classification

Multibeam and side-scan sonar data were used for the seabed classification (Figure 8.). The side-scan sonar imagery was interpreted, manually; this has led to the delineation of 6 classes (Figure 8A.), occurring from southeast to northwest (see below).

- Class 1: represented by large dunes, superimposed with small dunes and a low to moderate reflectivity (gentle slope);
- Class 2: the same large to very-large dune structures, but the reflectivity is stronger (central depression and along the crest of the western part of the sandbank);
- Class 3: small to medium dunes, with a moderate to strong reflectivity (swale, dune field);
- Class 4: furrows with a moderate reflectivity (swale);
- Class 5: devoid of bedforms and a moderate reflectivity (swale);
- Class 6: field of small to medium dunes within the swale.

A seabed classification has been performed on the multibeam backscatter data (Figure 8B.). Similarly, as for the side-scan sonar backscatter, these data are also a function of several parameters such as seabed sediment type, roughness and bedforms. No large differences were detected between the side-scan sonar and the multibeam backscatter. Seven classes were distinguished manually from the multibeam backscatter data (see below).

- Class A: same bedform pattern as Class 1 (see above) (gentle slope), corresponding to large dunes, superimposed with small dunes; a low reflectivity is observed;
- Class B: central depression and similar to Class 2 (see above). It displays a higher reflectivity than the gentle slope;
- Classes C and F: the small to medium dune fields of the swale (classes 3 and 6, see above), with a higher reflectivity for Class C;
- Class D: the furrows of Class 4 (swale, see above), a high reflectivity is observed;
- Class E: different from Class 5 (swale, see above), also a high reflectivity is seen;
- Class G: the elongated very-large dunes, being a part of Class 2 (western part: steep slope and crest of the sandbank, see above) with a reflectivity somewhat lower than the ones of Classes C, D and E.

The automated seabed classification, based on the multibeam backscatter data, allowed discriminating 5 classes (Figure 9.). Classes T1, T2 and T3 are located mainly in the Kwinte swale, and correlate well with the Classes C, D and E, based on a manual interpretation of the multibeam backscatter data. Classes T1 and T2 are, also, found on the elongated very-large dunes (class G). Classes T4 and T5 are situated in particular on the gentle slope of the sandbank (Class A) and along a dune field in the Kwinte Swale (Class F). The central depression is covered mainly with Class T2 and somewhat by the Classes T1, T3 and T4.

Internal Structure of the Bank

The present investigation only focussed on the area around the central depression. The interpretation of the seismic profiles allowed for the discrimination of four units (Kw1-4) (Figure 10.). The oldest ones, Kw1 and Kw2, are bounded by erosive reflectors with medium to good conti-

Table 2. *Correlation between the backscatter, the sea-floor classification and the sedimentological and morphological characteristics.*

Sediment type		**High silt content (> 5 %)**	**High carbonate content**	**Fine to medium well-sorted sand (sandbank)**	**Poorly-sorted, fine to medium sand (swale)**
Morphology (bedforms)		Small dunes, furrows	Elongated very large dunes	Compound large dunes	No bedforms
Backscatter	Classes	C-D	G	A	E
	Values	High	High	Low	Medium
Automated sea-floor classification		T1	T2	T4-T5	T3
Side-scan sonar		3-4	Outside the area	1	5

nuity. The internal structure of Kw1 is composed of some high-amplitude and low discontinuity reflectors. Kw2 shows channel-shaped structures, alternating with more linear reflectors. Kw3 has a bank-shaped form and presents some reflectors parallel to its slopes. Kw4 corresponds to the bank itself. It is covered by dune structures and smaller bedforms. This unit is about 5 to 7 m thick. In this paper, only the relevance of the data with respect to the impact of aggregate extraction is discussed.

DISCUSSION

Methodologies - Interrelationship of the Acoustic Techniques

The backscatter data from a 95-98 kHz multibeam echosounder, such as the EM1002, can provide an estimate of the nature of the surficial sediments. For a muddy seabed, the signal is strongly absorbed and the values of the backscatter are low. On a rocky or gravelly seafloor, the signal is strongly reflected and the values of the backscatter are high. A flat seabed or areas with well-sorted sediments reflect less the signal than a rough seabed or than poorly-sorted sediments. Other factors contributing to the value of the backscatter relate mainly to sediment compaction and bioturbation (e. g. Ferrini and Flood, 2006; Hughes Clarke *et al*., 1997; and Nitsche *et al*., 2004).

For the present datasets, the multibeam backscatter data range between –40 and –10 dB. This range appears to depend, at a first approximation, upon the sea floor roughness (the presence of small bedforms), sorting and presence of shell. Variations in these three parameters correlate well with the backscatter differences. Coarse sediment is found in the swale where the reflectivity is generally high (Classes C, D and E) and on the elongated very-large dunes (Class G), whereas finer sediments are found on the gentle slope (Class A), and on the fields of the small to medium dunes (Class F), where the reflectivity is low.

This pattern corresponds on the side-scan sonar imagery to the low reflectivity of Class 1 and the higher reflectivity of Classes 2 and 3 and 4.

Although, the reflectivity of the multibeam correlates approximately with the mean grain-size, the results of the sea floor classification (Triton) do not exactly represent this particular parameter. The results show that the Triton automated seabed classification is more sensitive to the content in shells, in fine sediment (Classes T1 and T3) and in the sorting: for example, the difference between Classes T3 and T4-T5 representing fine to medium sand, but poor and well-sorted sand respectively. Classes T1 and T2 represent the coarsest sediments.

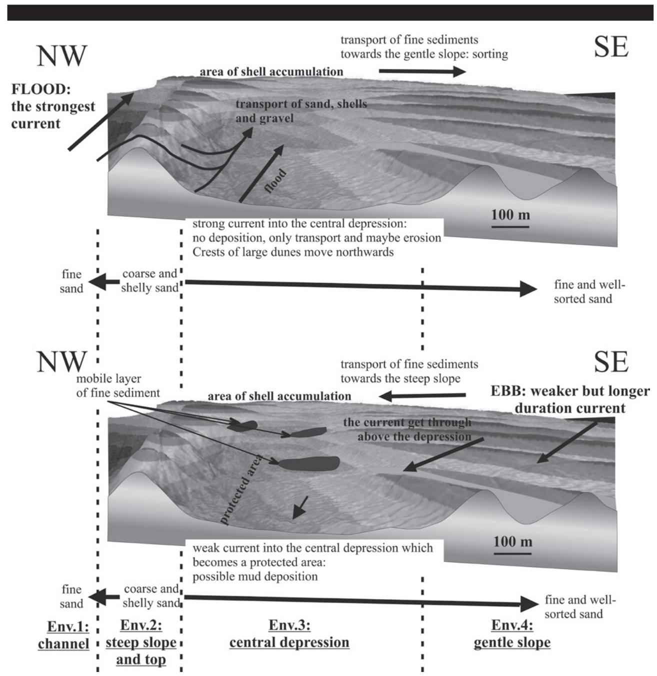


Figure 11. Conceptual model of the sedimentary dynamics associated with the central depression of the Kwinte Bank during flood (top) and ebb (bottom) tide. Env. = environment.

In summary, Classes A/T4-T5 correspond to fine to medium well-sorted sand. However, problems appear with the other classes corresponding to moderate and poorly sorted sand. For example Classes C and D/T1-T2 contain a mixture of fine sand, gravel and silt. They show acoustic characteristics similar to those of Class G, formed by coarse shelly sand. In fact, Class T1 seems to be more sensitive to the silt content and Class T2 to the carbonate content. Class T3, found within both of the swales (Class E) corresponds probably to fine to medium poorly sorted sand (Ceuleneer and Lauwaert, 1987). The different classes and their possible interpretation are summarised in Table 2.

The results of the sea floor classification delineate the region of the central depression as being composed of heterogeneous sediments. This is in accordance to the sedimentological results, based on sampling. The carbonate content is generally less than 20 %. The higher reflectivity of the central depression is also influenced by a more compact nature of the sediments. Whether, this is due to an early compaction decreasing the porosity, a somewhat stronger current action or perhaps the extensive dredging that exposed more consolidated sediment remains to be investigated.

Interpretation of the Four Lithofacies

Around the central depression, four lithofacies were identified, each with its specific sedimentological and morphological characteristics. The findings and their integration with the governing hydrodynamic characteristics are shown in Figure 11.

The Kwinte Swale

Heterogeneous sediments, composed of fine to medium sand containing a considerable amount of shells and epibenthic fauna, form the Kwinte Swale. The silt content, often higher than 5 %, together with coarse gravel was sampled on the seabed. This distribution pattern appears to be rather stable, except for some sporadic high-energy events. Previous studies (Ceuleneer and Lauwaert, 1987) have indicated that the values of the clay and gravel contents within the swales between the Flemish banks can be high and the admixture results in the occurrence of poorly sorted sand. Strong currents can lead to the formation of erosional furrows, eroding the underlying Tertiary clay and pre-Holocene stones (essentially flints). Under high-energy events, these can be transported towards the banks. Moreover, as the banks are oblique (up to 20°) to the tidal ellipses, sediments that are eroded in the swale are transported towards the bank. With sufficient sand available, dune fields form in specific areas.

Western part of the sandbank, steep slope and crest

Heterogeneous medium to coarse shelly sand characterizes the sediments of the elongated very-large dunes along the western part of the sandbank. The strong currents in this area, generally, provoke erosion along the steep slope. The erosional nature of this steep slope is clearly shown when erosion and deposition areas are modelled (Brière *et al.*, this volume; and Van den Eynde *et al.*, this volume). The strong currents on the steep slope (Van den Eynde *et al.*, this volume) allow an active transport of shells and coarse material, which is probably common along the erosive western flank. This transport appears to extend up to the depression, showed by the coarse fraction pathway (Figure 4.). The eastern flank of the central depression seems to form a boundary for the progression of the coarse fractions. Moreover, the transport process likely destroys the shells. They finish up accumulating on the northern elongated very-large dunes, where the shell fragment size is quite homogeneous.

The central depression

The central depression shows patches of fine- to coarse-grained sediments; as such it is an intermediate area between the heterogeneous and poorly-sorted sands of the western flank and the fine- and well-sorted sands of the gentle slope. Before dredging, it is likely to have been associated with similar sedimentation as along the western side (Bonne, 2003; Vanosmael *et al.*, 1982), since the area was a former crestline of the Kwinte Bank. Noteworthy, are the very-large dunes that are clearly lower in height in the depression than outside of it, though the strike of the dunes is continuous from the western part up to the eastern part. From time-series of multibeam imagery (Degrendele *et al.*, this volume), it has been shown that in the depression, the dune sections have a higher rate of mobility.

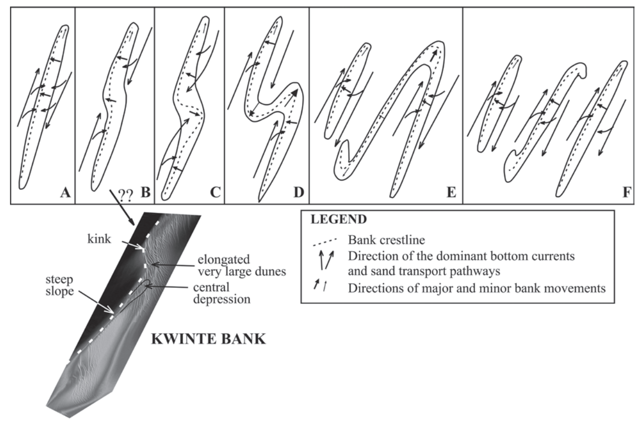


Figure 12. Caston's hypothesis on the evolution of the Norfolk Bank (Caston, 1972) adapted to the Flemish Banks. The morphology of the Kwinte Bank is similar to Stage B condition. A: single bank, B: formation of a kink on the steep slope, C: enlargement of this kink under tidal current action, D: setting of two sandbanks, E: continuation of the process with the initiation of a third sandbank, and E: three sandbanks.

This may allow an easier passage of the currents (Figure 11.) and hence, an increased erosion potential might be expected in this area. Degrendele *et al.* (this volume) observed a deepening of 0.8 m between 1999 and 2003 and erosion processes are still evidenced from hydrodynamic measurements and modelling (Garel, this volume; Brière *et al.*, this volume). However, Degrendele *et al.* (this volume) indicate also that the erosion in the depression appears to have ceased and that the top volume of the sandbank is stable again, since the closure of the depression.

The regeneration of the depression is however problematic, at least on the short-term. From the time-series in sediment sampling and from the subsequent multibeam soundings (Degrendele *et al.*, this volume), no evidence of a significant sedimentation after the cessation of dredging is observed. According to the main sediment transport direction, a southern provenance would be most favourable. Still, if the depression is to be refilled with coarse sand, as was originally the case, there is only a limited availability of this fraction to the south. The only evidence found, is the trapping of shelly material in the depression, likely originating from the coarser western slope of the bank and hence transported with the flood current. Figure 11. also shows the possible trapping of silty sediments in the depression, most probably occurring under ebb and neap tide conditions. If both processes would be continuous over time, this might be a first, but very slow initial stage for a further regeneration of the area.

Eastern part

Finally, opposite to the western part, the gentle slope of the bank is composed of homogeneous fine to medium sand. The large dunes are smaller and are covered with small dunes. The gentle slope is merely subdued to the ebb current. The boundary between the influence of the flood and of the ebb is visible on the multibeam backscatter imagery (Figure 7.); this area corresponds to a bed load convergence zone (e.g. HARRIS *et al.*, 1995).

Evolution of the Sandbank

Several authors have attempted to explain the maintenance of the North Sea sandbanks and mainly attributed this to the convergence phenomena of tidal currents (CASTON, 1972; LANCKNEUS *et al.*, 1989; and VAN VEEN, 1936). Investigations concerned with the Kwinte Bank have agreed upon the volume equilibrium, but they have not explained the evolution of the offshore "kink", located within the middle part of the bank, just to the north of the central depression. This kink is covered with the highest very large dunes; its evolution and current pattern suggests a strong hydrodynamic regime (VAN DEN EYNDE *et al.*, this volume). Previously, CASTON (1972) has explained the presence of such a feature in the Norfolk Banks (Figure 12.) where six stages have been described which could lead to the formation of two new banks. The initial linear tidal bank (Stage A) becomes sinuous under the action of the tidal currents. The sinuosity increases with the formation of a kink (Stages B and C) until there is the development of a double curve (Stage D), associated with the ebb and flood channels. The new channels lengthen considerably, until they break through the sandbanks at the location of the kink (Stage E). The parabolic terminal banks leave gaps at the extremities of the channel. The final stage (Stage F) reveals the creation of three banks, out of a single bank.

This hypothesis might be applied to the Flemish Banks for the reasons:

(1) The Norfolk Banks are under a hydrodynamic regime which is very similar to that of the Flemish Banks;

(2) Some of the Flemish Banks show some of the intermediate stages, as presented by CASTON (1972). For example, the Middelkerke Bank and the Oostende Bank have reached Stage D and the Buiten Ratel reveals a kink, resembling the middle bank shown on Stages E and F.

The Kwinte Bank appears to be similar to Stage B, as described for the Norfolk Banks. The formation of the kink is probably due to an increase in the currents and the bottom shear stress at this particular location (WILLIAMS *et al.*, 2000) being responsible for the formation of the elongated very-large dunes (Class G of the multibeam data set) and the medium dune field observed at the base of the sandbank (Class 6 of the side-scan sonar imagery and Class F of the multibeam imagery; Figure 7.). In Figure 7., it can be seen also that the wavelength of the elongated very-large dunes decreased towards the northeast. The small bedforms located further eastwards, have a north-south orientation and appear to be mainly formed by the ebb current. In conclusion, in this area of the kink, there is a convergence of strong forces, provoking instability of the sandbank. DELEU *et al.* (2004) found the same conclusions for the Westhinder kink area, located to the north.

The presence of the central depression, close to the kink, could intensify the current action; this could enhance the evolution of the bank. However, the modelling studies (BRIÈRE *et al.*, this volume) showed that dredged areas are rather insignificant at geological time-scales. Moreover, within existing sandbank groups in the southern North Sea, there might not be enough accommodation space to allow a repartitioning of the bank.

Different Seismic Units of the Banks

From the interpretation of the seismic profiles, the formation of the central part of the Kwinte Bank seems to have occurred in four main phases, separated by three major erosional surfaces. Correlation of the results with the detailed seismic investigations and ground-truthing of the adjacent Middelkerke Bank (TRENTESAUX *et al.*, 1993; and TRENTESAUX, STOLK, and BERNÉ, 1999), suggests that the four units, Kw1-4, are Upper Quaternary in age and have a varying lithological composition. High-amplitude reflectors, likely indicating a coarse sedimentation, characterize the oldest unit and likely reflect the infill of a fluviatile channel. Kw2 is more complex; its geological history merely reflects a channel-barrier facies with an alternation of channels and barriers. This may be related to a marsh, a lagoon or a back-barrier system of a coastal plain and indicates that the sedimentation is rather heterogeneous (TRENTESAUX, STOLK, and BERNÉ, 1999). Kw3 has a sandbank-shaped facies; hence its sedimentation is likely sandy and more homogeneous in nature. Kw4 is the actual tidal sandbank facies, maintained by the present-day hydrodynamic regime. In the central depression, this unit is almost dredged completely.

These results confirm that the sandbank is not a homogeneous piling-up of sand and that not all units are *per se* sandy in nature. It is clear that detailed information is needed on the internal structure of the bank, if adequate resource calculations are to be made. From an environmental perspective, it seems only recommended to dredge the upper subsurface layer, as only these sediments may be renewed by the present-day hydrodynamic regime.

CONCLUSIONS

A detailed geomorphological and sedimentological study has been performed on a tidal sandbank that has been dredged during 30 years. The marine aggregate extraction has led to a depression, in the former crestline of the bank, of up to 5 m. From this, the Government closed down the area for further exploitation.

High-resolution acoustics were used, as also seabed classification tools. Multibeam and side-scan sonar backscatter showed similar results. Automated seabed classification, based on multibeam backscatter, showed no direct correlation with the mean grain-size. The primary drivers were merely the sorting of the sediments, the presence of shells and of fine sediments. Very-high resolution seismics allowed studying the upper 20 m of the sandbank and showed the presence of various seismic units. Of these, only the upper unit is representative of the present-day hydrodynamic regime; this unit is nearly completely dredged along the central depression.

The central depression was clearly distinguished from the morpho-sedimentary environment, characterizing the western and eastern part of the bank and the swale. The differentiation between the western and the eastern part is essentially due to different tidal current characteristics that lead to different erosion-sedimentation processes. These processes seem to be rather stable as each subenvironment had similar overall grain-size characteristics over a period of two years. Within a subenvironment, some evolutionary trends could be distinguished and could be related to seasonal variation. Of note is the evolution of the sediments within the central depression as this was similar to the evolution witnessed for the swale sediments, hence significantly different from what would be expected from a former crestline of a sandbank. The interplay of the flood and ebb current is as follows: (a) The flood is a stronger, but of a shorter duration. It erodes and transports the sediments in bulk, without efficiently sorting it. At such, it induces a resuspension and subsequent sedimentation of coarse sediments, poorly sorted and with high carbonate content. These sediments are transported into the depression and accumulate locally; (b) the ebb tide is weaker, but of longer duration than the flood. It erodes with difficulty the sediments, but its long duration permits an improved sorting of the fine to medium sand fraction. There is no supply in shells, as these are only observed along the western part of the bank.

The presence of the central depression has several influences. It is located along a part of the bank, that is generally dynamic in nature and its position is close to a kink in the sandbank. This could have a positive effect: the high amount of transported sediment could enable a levelling out of the depth differences. However, kink areas are mostly less stable in nature; as such, initial erosion might be accelerated in such areas. The depth of the central depression should allow a trapping of sediment. However, the depression is somewhat oblique to the normal crestline; as such, it now forms an open transport pathway from the swale up to the crest of the sandbank. This has led to a canalization of the flood current; this is witnessed by a decreasing height of the dunes and the fact that the occurrence of shells is restricted to the depression and need to be brought in by the flood. The lower height of the large dunes cannot slow down the current and erosion and transport of sediment is increased. These phenomena likely prevent any significant regeneration of the depression.

If the depression is to regenerate, it will likely need a refill in coarse material, similar to its original sedimentary deposits. However, the present-day hydrodynamic regime is not able to supply this fraction, nor are there any nearby sources that could govern this supply. Nevertheless, there is a constant supply in shells, originating from the western steep slope. Moreover, time windows exist during which fine sediments can settle down. If the shells would be able to trap the finer sediments, this might be a first initiation of a further regeneration.

The major problem for the regeneration of the central depression remains the lack of coarser-grained material that is needed as a basis for a further infilling. As these fractions are not regularly transported, it is unlikely that the natural processes will be able to counterbalance the severe dredging activities. If, from a management perspective, the central depression needs to be restored, it might be envisaged to supply the depression with a basic layer of coarse sediments or shells from, for example, the wastes of the dredged material around this area. This would likely permit a more important trap of sediments and thus initiate a further infill of this depression.

ACKNOWLEDGEMENTS

This study is contained within the research objectives of the projects MAREBASSE (Management, Research and Budgeting of Aggregates in Shelf seas related to End-users, Belgian Science Policy, Contract EV/18A) and EU-MARSAND (European Marine Sand and Gravel Resources: Evaluation and Environmental Impact of Extraction, EC Contract HPRN-CT-2002-00222). Time-series of sediment samplings were collected in the framework of the Belgian Science Policy project SPEEK (EV/02/38A). The authors warmly thank Wendy Bonne, Samuel Deleu and Els Verfaillie for their help. The Management Unit of the Mathematical Model of the North Sea and the Scheldt Estuary (MUMM) provided ship-time, on board the RV *Belgica*. The Flemish Institute of the Sea (VLIZ) granted shiptime on the RV *Zeeleeuw*. The captain and officers are acknowledged for their flexibility and assistance, during the campaigns. The consultancy firm Magelas was responsible for the side-scan sonar recordings.

LITERATURE CITED

Ashley, G. M., 1990. Classification of large-scale subaqueous bedforms: A new look at an old problem. *Journal of Sedimentary Petrology*, 60(1), 160-172

Bonne, W., 2003. Benthic copepod communities in relation to natural and anthopogenic influences in the North Sea. Gent, Belgium: University of Gent, Ph.D. thesis, 289 p.

Brière, C.; Roos, P. C.; Garel, E., and Hulscher, S.J.M.H., this volume. Modelling the morhodynamic effects of sand extraction from the Kwinte Bank, southern North Sea. *Journal of Coastal Research*.

Caston, V. N. D., 1972. Linear sandbanks in the southern North Sea. *Sedimentology*, 18, 63-78.

Caston, G. F., 1981. Potential gain and loss of sand by some sandbanks in the Southern Bight of the North Sea. *Marine Geology*, 41(3-4), 239-250.

Caston, V. N. D. and Stride, A. H., 1970. Tidal sand movement between some linear sandbanks in the North Sea off northeast Norfolk. *Marine Geology* 9(5), M38-M42.

Ceuleneer, G. and Lauwaert, B., 1987. Les sediments superficiels de la zone des "Vlaamse Banken". *Report of the MUMM, ref. MUMM/SED/87/01* to 08, 33 p.

Degrendele, K.; Roche, M.; Schotte, P.; Van Lancker, V.; Bellec, V., and Bonne, W., this volume. Morphological evolution of the Kwinte Bank central depression before and after cessation of aggregate extraction. *Journal of Coastal Research.*

Deleu, S.; Van Lancker, V.; Van den Eynde, D., and Moerkerke, G., 2004. Morphodynamic evolution of the kink of an offshore tidal sandbank: the Westhinder Bank (Southern North Sea). *Continental Shelf Research*, 24(15), 1587-1610.

De Moor, G., 1985. Shelf bank morphology off the Belgian coast. Recent methodological and scientific developments. *In*: Van Molle, M. (ed.), *Recent trends in physical geography in Belgium*. Liber Amicorom L. Peeters VUB, Study series of the Vrije Universiteit Brussel, 20, pp. 47-90.

De Moor, G., 1986. Geomorfologisch onderzoek op het Belgisch Continentaal Plat. *Soc. Belge Et. Géogr.*, 55, 133-174.

De Moor, G. and Lanckneus, J., 1990. Stabilité et apports sédimentaires sur les Bancs de Flandre. *Ann. Soc. Géol. Nord*, CIX, 129-139.

Eisma, D.; Jansen, J. H. F. and Van Weering, T. C. E., 1979. Sea floor morphology and recent sediment movement in the North Sea. *The Quaternary history of the North Sea*, 217-231.

Ferrini, V. L. and Flood, R. D., 2006. The effects of fine-scale surface roughness and grain size on 300 kHz multibeam backscatter intensity in sandy marine sedimentary environments. *Marine Geology*, 228(1-4), 153-172

Folk, R.L. and Ward, W., 1957. Brazos River Bar: a study of the significance of grain-size variables. *Journal of Sedimentary Petrology*, 27, 3-26.

Garel, E., this volume. Short-term hydrodynamics and sediment transport on the Kwinte Bank, southern North Sea. *Journal of Coastal Research*.

Harris, P.T.; Pattiaratchi, C.B.; Collins, M.B., and Dalrymple, R.W., 1995. What is a bedload parting ? *Spec. Publs. int. Ass. Sediment.*, 24, 3-18.

Houbolt, J.J.H.C., 1968. Recent sediments in the Southern Bight of the North Sea. *Geologie & Mijnbouw*, 47(4), 245-273.

HUGHES CLARKE, J. E.; DANFORTH, B.W., and VALENTINE, P., 1997. Areal seabed classification using bakscatter angular response at 95 kHz. *Shallow Water, NATO SACLANTCEN*, Conference proceedings series CP-45, pp. 243-250.

KIRBY, R. and OELE, E., 1975. The geological history of the Sandettie-Fairby Bank area, southern North Sea. *Phil. Trans. R. Soc. Lond.*, A., 279, 257-267.

KONGSBERG SIMRAD., 1999-2001a. EM1002 Multibeam Echosounder, Operator Manual – Base Version. Horten, Norway: Doc. 850-160977, 423p.

KONGSBERG SIMRAD., 1999-2001b. Neptune Bathymetric post-processing. Horten, Norway: Doc. 850-130021, 481p.

KONGSBERG SIMRAD., 1999-2001c. Poseidon Operator Manual. Horten, Norway: Doc. 850-164063C, 90p.

KONGSBERG SIMRAD., 1999-2001d. Triton Instruction Manual. Horten, Norway: Doc. 160146A, 58p.

LABAN, C. and SCHÜTTENHELM, R. T. E., 1981. Some new evidence on the origin of the Zeeland ridges. *Spec. Publs. int. Ass. Sediment.*, 5, 239-245.

LANCKNEUS, J., 1989. *A comparative study of some characteristics of superficial sediments on the Flemish Banks.* Int. Coll. Quat. Tert. Geology Southern Bight, North Sea, May 1984, Ministry of Economic Affairs-Belgian Geological Survey, pp. 29-241.

LANCKNEUS, J.; DE MOOR, G.; DE SCHAEPMEESTER, G., and LIBEER, L., 1989. Acoustic teledetection of shelf bedforms and their meaning for the sediment dynamics. *In*: PICHOT, G. (ed.), *Progress in Belgian Oceanographic Research Brussels*. Prime Minister's Services Science Policy, pp. 147-163.

LE BOT, S.; TRENTESAUX, A.; GARLAN, T .; BERNÉ, S., and CHAMLEY, S., 2000. Influence des tempêtes sur la mobilité des dunes tidales dans le détroit du Pas-de-Calais. *Oceanologica Acta*, 23(2), 129-141.

LE BOT, S. and TRENTESAUX A., 2004. Types of internal structure and external morphology of submarine dunes under the influence of tide- and wind-driven processes (Dover Strait, northern France). *Marine Geology*, 211(1-2), 143-168.

LE BOT, S.; VAN LANCKER, V.; DELEU, S.; DE BATIST, M.; HENRIET, JP., and HAEGEMAN, W., 2005. Geological and geotechnical properties of Eocene and Quaternary deposits on the Belgian continental shelf: a synthesis. *Netherlands Journal of Geosciences*, 84(2), 147-160.

NITSCHE, F. O.; BELL, R.; CARBOTTE, S.M.; RYAN, W.B.F., and FLOOD R., 2004. Process-related classification of acoustic data from the Hudson River Estuary. *Marine Geology*, 209 (1-4), 131-145.

STRIDE, A. H., 1988. Indications of long term episodic suspension transport of sand across the Norfolk Banks, North Sea. *Marine Geology*, 79(1-2), 55-64.

TRENTESAUX, A.; BERNÉ, S.; DE BATIST, M., and CHAMLEY, H., 1993. Architecture interne d'un banc sableux de la Mer du Nord méridionnale. *Comptes Rendus de l'Académie des Sciences de Paris (II)*, 316, 99-106.

TRENTESAUX, A.; STOLK, A.; TESSIER, B., and CHAMLEY, H., 1994. Surficial sedimentology of the Middelkerke Bank (southern North Sea). *Marine Geology*, 121(1-2), 43-55.

TRENTESAUX, A.; STOLK, A., and BERNÉ, S., 1999. Sedimentology and stratigraphy of a tidal sand bank in the southern North Sea. *Marine Geology*, 159(1-4), 253-272

VANOSMAEL, C.; WILLEMS, K. A.; CLAEYS, D.; VINCX, M., and HEIP, C., 1982. Macrobenthos of a sublittoral sandbank in the Southern Bight of the North Sea. *Journal of the Marine Biological Association of the United Kingdom*, 62, 521-534.

VAN CAUWENBERGHE, C., 1981. Stroomatlas 1981. Koninkrijk België, Ministerie van Openharen Werken, Dienst der Kust, Hydrografie Oostende, Vlaamse Banken, Noordzee. Printed by the Dienst van Topografie en fotogrammetrie, Brussel.

VAN DEN EYNDE, D.; FETTWEIS, M.; PISON, V.; PORTILLA, J., and MONBALIU, J., this volume. Hydrodynamics regime, wave characterization and sediment transport pattern in the Kwinte Bank area. *Journal of Coastal Research*.

VAN LANCKER, V.R.M., and JACOBS, P., 2000. The dynamical behaviour of shallow-marine dunes. *In:* TRENTESAUX, A. and GARLAN, T. (eds.), *Marine Sandwave Dynamics, International Workshop, March 23-24 2000.*.France: University of Lille 1, pp 213-220.

VAN VEEN, J., 1936. Onderzoeken in de Hoofden in verband met de gesteldheid der Nederlandsche Kust. Niewve verhandelingen van het Bataafsch Genootschap der proefondervindelijke wijsbeheerte, Rotterdam, 229 p.

VINCENT, C. E.; STOLK, A., and PORTER, C. F. C., 1998. Sand suspension and transport on the Middelkerke Bank (southern North Sea) by storms and tidal currents. *Marine Geology*, 150(1-4), 113-129.

VLAEMINCK, I.; GULLENTOPS, F., and HOUTHUYS, R., 1985. A morphological studt of the Buiten Ratel sandbank. *In*: VAN GRIEKEN, R. and WOLLAST, R. (eds.), *Progress in Belgian Ocenaongraphic Research*. Bruxelles, Belgian Academy of Sciences, pp. 114-124.

WENTWORTH, C. K., 1922. A grade scale and class terms for clastic sediments. *Journal of Geology*, 30, 377-392

WILLIAMS, J. J.; MACDONALD, N. J.; O'CONNOR, B. A., and PAN, S., 2000. Offshore sandbank dynamics. *Journal of Marine Systems*, 24(1-2), 153-173.

Annex 1

Sedimentological parameters of the boxcores, as shown in Figure 2.

Boxcores	Position	Sample depth (cm from the top)	Mean grain-size (μm)	Sorting (ϕ)	Skewness	$CaCO_3$ %	Mode
BC4	Steep slope-swale	1	236	0.65	-0.50	11	unimodal
		3	255	0.82	-0.59	12	unimodal
		17	498	1.28	-0.17	23	bimodal
BC10	Top	6	466	0.81	-0.31	11	unimodal
		22	423	0.58	-0.30	20	unimodal
		32	442	1.07	-0.17	20	bimodal
BC8	Top-central depression	6	500	1.17	-0.07	31	bimodal
		14	537	1.12	-0.07	38	bimodal
		17	325	0.97	-0.48	13	unimodal
		25	799	1.04	0.41	34	bimodal
BC12	Central depression	6	265	0.46	0	11	unimodal
		11	226	0.44	-0.08	12	unimodal
		13	270	0.55	-0.04	16	bimodal
		20	250	0.59	0.01	19	bimodal
BC15	Central depression	3	253	0.52	-1.04	14	unimodal
		12	318	0.68	-0.14	9	unimodal
		17	284	0.60	-0.11	15	bimodal
		20	385	0.83	-0.20	27	bimodal
		28	353	0.71	-0.10	8	
BC13	Gentle slope	4	282	0.47	0.15	1	unimodal
		12	276	0.47	0.1	7	unimodal
		23	310	0.63	-0.1	11	unimodal

Journal of Coastal Research	SI	51	77-86	West Palm Beach, Florida	Summer 2010

Morphological Evolution of the Kwinte Bank Central Depression Before and After the Cessation of Aggregate Extraction

Koen Degrendele[1], Marc Roche[1], Patrik Schotte[1], Vera Van Lancker[2*], Valerie Bellec[2] and Wendy Bonne[3***]**

[1] Federal Public Service Economy, SMEs, Self-employed and Energy –
Continental Shelf - Fund for Sand Extraction
Simon Bolivarlaan 30, WTCIII
1000 Brussel, Belgium
Koen.Degrendele@mineco.fgov.be

[2] Ghent University, Renard Centre of Marine Geology
Krijgslaan 281, S8, 9000 Gent, Belgium

* Present address: Royal Belgian Institute of Natural Sciences. Management Unit of the North Sea Mathematical Models
Gulledelle 100, B-1200 Brussels, Belgium

** Present address: Geological Survey of Norway
Leiv Eirikssons vei 39
7040 Trondheim, Norway

[3] AZTI - Tecnalia / Marine Research Division
Herrera kaia portualdea z/g
20110 Pasaia (Gipuzkoa), Spain

*** Present address: Federal Public Service Health, Food Chain Safety and Environment, Belgian Federal Government
Victor Hortaplein 40 box 10
1060 Brussels, Belgium

ABSTRACT

Analyses of the records of ships registers and Electronic Monitoring Systems, of the trailer suction hopper dredgers, operating on the Belgian Continental Shelf, reveal that since the beginning of extraction in 1976, 75% of the total extracted volume originates from only one sandbank, the Kwinte Bank. At present, two morphologically-distinguished depressions are observed along the two most dredged areas of this sandbank: one in the central; and one in the northern part of the bank. In order to limit the impact of sand extraction on the bathymetry, the central depression of the Kwinte Bank was closed for exploitation, in February 2003.

An understanding of the morphological evolution of this central depression is based upon data obtained: (a) from November 1999, until the closure for extraction in February 2003; and (b) on the subsequent post-dredging evolution, until June 2005. During this 5-year period, a total of 17 surveys were carried out with a multibeam echosounder over the area of the central depression (KBMA) and over a reference zone on an adjacent non-exploited sandbank. The resulting time-series of bathymetrical digital terrain models, together with backscatter strength maps, permit a detailed comparison of the bathy-morphological and sedimentary evolution of both of the monitored areas.

Since the commencement of multibeam monitoring in 1999, an overall deepening (by 0.5m) of the entire KBMA monitoring zone is observed, until the cessation of dredging, in February 2003. Subsequently, the deepening slowed down and the variation in sediment volumes became similar to that of the adjacent non-exploited sandbank. From this, marine aggregate extraction appears to have only a local impact.

ADDITIONAL INDEX WORDS: *North Sea; sandbank; dredging; multibeam echosounder; bathymetry; morphology; seabed imagery; monitoring; marine sand extraction; aggregate extraction.*

INTRODUCTION

Numerous tidal sandbanks characterise the sediment deposits of the Belgian Continental Shelf. From an economical perspective, these sandbanks represent an important resource of sandy aggregates (Van Lancker *et al.,* this volume). Gravel occurs in some of the swales, but its exploitation is limited, due to the low industrial quality of the gravel deposits.

Within Belgium, sand exploitation commenced in 1976, with an annual volume extracted of around 29,000m^3. This volume increased to 220,000m^3 in 1977; it has increased, steadily, to reach 1,700,000m^3 in the middle of the 1990's. In 2001, production exceeded 1,900,000m^3 (or nearly 3,000,000 tonnes, at a mean density of sand of 1.55tonnes/m^3). Since 2002, the production has stabilised at around 1,600,000m^3.

The exploitation of marine aggregates (MA) on the Belgian Continental Shelf is confined to three seabed areas. These areas were defined by the Royal Decree of September 1, 2004 related to the requirements, the geographical delimitation and the appropriation procedures for concessions for the exploration and exploitation of mineral and other non-living resources in the territorial sea and on the continental shelf (see Degrendele *et al.*, 2005; and Radzevicius *et al.*, this volume).

Extraction activities have been subjected to a monitoring programme, almost from the commencement of exploitation in 1976. The monitoring undertaken is two-fold: (1) the activity of the extraction vessels is followed (volume dredged, location and time), using extraction registers and, since 1996, Electronic Monitoring Systems (EMS or 'black-boxes'); and (2) the physical impact of the extraction on the environment (since 1999, studied with a multibeam echosounder).

DOI: 10.2112 / SI51-007.1 received 15 January 2007; accepted in revision 26 February 2008.

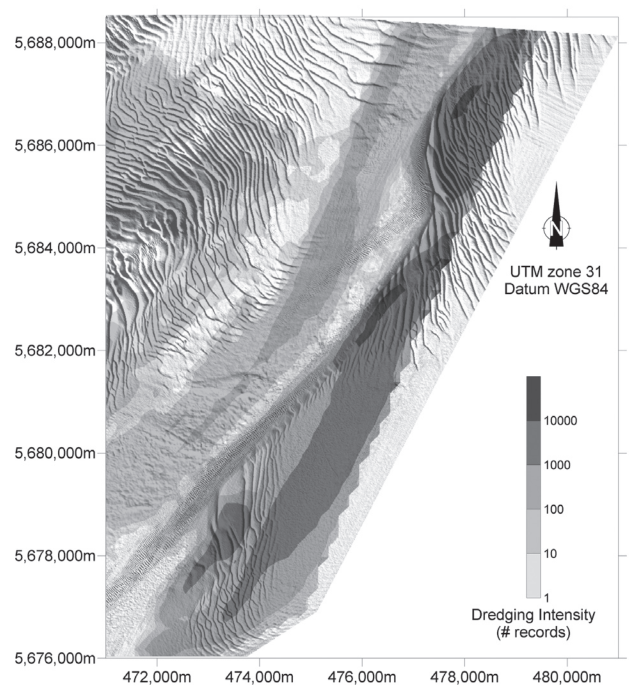


Figure 1. Superposition of extraction intensity on a shaded relief map of the Kwinte Bank (number of dredging records, from 05/11/1996 to 30/03/2005; each record represents 30s of operation of a trailer suction hopper dredger).

According to the ships registers database and the EMS records, the extraction is concentrated mainly on one particular sandbank: 75% (11,620,000m^3, of a total of 15,570,000m^3, from 1997 until 2004) is extracted on the Kwinte Bank. The superposition of the dredging intensity on the general digital terrain model (DTM) of the Kwinte Bank reveals the spatial coincidence between areas, which are most dredged, together with two morphological depressions in the central and northern parts of this sandbank (Figure 1.).

According to the Federal Legislation, the extraction level is limited to a maximum of 5m below the seabed, as defined by the most recent hydrographic chart. As the hydrographic charts are updated regularly and incorporate potential depressions, this would imply that the limit of 5m is never reached. However, when comparing the oldest reliable single-beam profiles and the recent multibeam data, such a difference has been observed along the central depression. These findings led to the closure of this zone, in 2003 (Degrendele, Roche, and Schotte, 2002).

The Kwinte Bank central area is impacted upon regularly by trailer hopper dredgers, but is subjected also to the natural dynamics of the sandbank. As such, it is an ideal case to study the effect of MA extraction from a tidal sandbank; likewise, to evaluate the potential of restoration of the sandbank, following the cessation of MA extraction. This contribution focuses upon the bathy-geomorphological and sedimentary evolution of the sandbank, during and after sediment extraction in the central depression; similarly, the relationship between this evolution and the extraction activities.

ENVIRONMENTAL SETTING

The Kwinte Bank is part of the Flemish sandbank system (Figure 2.), a group of Quaternary sand bodies deposited on Tertiary (Ypresian) units (mainly clays) (Le Bot *et al.*, 2005, for an overview). The sandbank, NE-SW aligned, is about 15km in length, 10-20m in height, and 1 to 2km in width (i.e. about 400 Mm^3 in volume); it shows an asymmetric profile, being steeper towards the NW. Water depths are around 5 to 25m MLLWS (Mean Lowest Low Water at Spring). Macrotidal (4-5m), semi-diurnal tides characterise the area. The tidal currents rotate counter-clockwise, with maximum currents (1 m/s) observed generally during the flood, towards the NE (Van Cauwenberghe, Dekker, and Schuurman, 1993). Waves of 0.50–1m in height (period of 3.5 – 4.5s) are most common; waves of more than 3m originate from the W to WNW (Ministerie Van De Vlaamse Gemeenschap, 1993). Large to very-large dunes (*sensu* Ashley, 1990; with heights of respectively >0.75m and >5m) cover the sandbank extensively. The Kwinte Bank is characterized by fine to medium-sized sand. The grain-size coarsens from south to north; 180 to 240 µm is found over the southern part, whilst coarser sediment (of up to about 400 µm) characterises the middle and northern part (Verfaillie, Van Lancker, and Van Meirvenne, 2006). The specific morphological and sedimentological characteristics are discussed in Bellec *et al.* (this volume); the hydrodynamics are particularly dealt with in Garel (this volume) and Van den Eynde *et al.* (this volume).

METHODOLOGY

Monitoring of the Extraction Activities

The activities of the extraction vessels are monitored using two approaches: the registers; and, since 1996, an EMS system. For each trip, a register is completed and provides the general location (which sandbank) of the extraction, the date and the volume extracted. This volume is obtained by multiplying the weight of the aggregate load, by 1.55tonnes/m^3, the average density of compacted sand. Based upon these data, the extraction volumes for each ship and for each sandbank are calculated. In addition, the rate at which each ship dredges, together with the average dredging speed are obtained. Because of the absence of any detailed positions in the registers, only the overall quantities for the entire sandbanks can be evaluated. In contrast, the EMS records all relevant parameters (e.g. ship ID, trip number, date, time, GPS position), at an acquisition rate of 30sec, during the dredging operations. These data are collected, analysed and stored in a single GIS database. The average dredging speed of each vessel is multiplied by the frequency (number of 30sec records), to obtain the extracted volumes within specific time intervals and for delimited areas; these can be shown on maps and in data Tables, in a GIS.

Multibeam Echosounder

Within the framework of the MA extraction 'follow-up', the Fund for Sand Extraction acquired a Kongsberg Simrad EM1002 multibeam echosounder. This system is installed aboard *RV Belgica*. The system has 111 beams of 2° (athwart) x 3.3° (fore-aft) width, working at a nominal frequency of 95kHz, with a ping-rate of around 4 to 6Hz. The data are corrected in real-time, for roll and heave, using a Seatex MRU5 motion sensor and, for heading, using an Anschütz Standard 20 gyrocompas. A Sercel NR103 (from 1999 until January

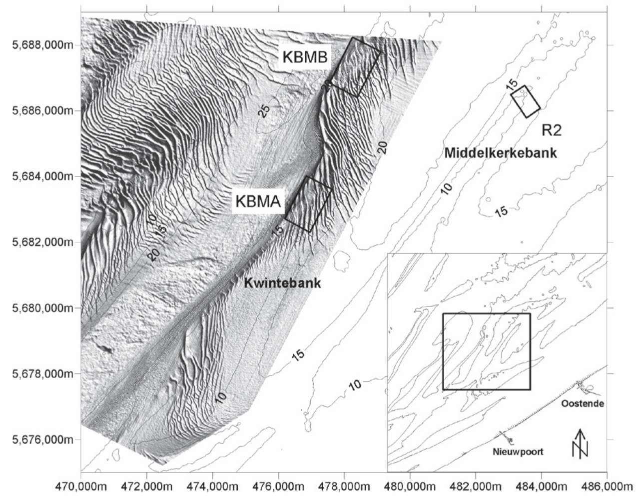


Figure 2. Location of the monitoring areas, KBMA, KBMB and R2.

2003) and a Thales Aquarius 02 (since January 2003) are used as GPS positioning systems; these have a theoretical precision of <5 m and 10mm, respectively. The datum used is WGS84.

The depth measurement accuracy of the EM1002 is up to 10cm RMS, or 0.2% of the depth (KONGSBERG SIMRAD, 1999-2001), in water depths of less than 30m. According to HAGA, PØHNER and NILSEN (2003), and HAMMERSTAD (2001), the EM1002 is compliant to the IHO S-44 standard.

The soundings have been tidally-corrected using the M2 tidal reduction method for the Belgian coastal zone (VAN CAUWENBERGHE, DEKKER, and SCHUURMAN, 1993). The water level is measured continuously at three reference stations (tide gauges) along the Belgian Coast. These values are used to calculate the water level, during the measurements. The depths are corrected during post-processing and referenced to the level of mean lowest low water, at spring tide (MLLWS). The swath width of a multibeam system allows 'full coverage' data to be obtained from the seafloor; from these, to construct highly accurate terrain models. A global bathymetric error (2σ) of 0.35% of the depth has been estimated, on the basis of the variance between bathymetrical digital terrain models of 4 successive surveys of the same area within a single tidal cycle (Fund for Sand Extraction, unpublished results). This global error on the final product, the terrain model, is the combination of the independent errors of the EM1002 multibeam echosounder, the auxiliary sensors, the draught and the tide correction.

The backscattered acoustic signal was processed using Poseidon (KONGSBERG SIMRAD, 1999-2001) for seabed image mosaicing. This involves merging of data from overlapping survey lines, applying systematic corrections which are required, filtering and interpolation. Poseidon normalises the backscatter using Lamberts Law. This is an optic approximation, and does therefore not take into account volume scattering or attenuation. Since multibeam echosounders receive most of the data in the domain where both volume and surface scattering contribute to the overall scattering strength; Lamberts Law can be used only as an approximation where scattering is caused by surface scatter (i.e. harder sediments) (HUGHES CLARKE, DANFORTH, and VALENTINE,1997). In order to eliminate the influence of bedform morphology, when comparing results from successive surveys, the mean backscatter strength over large areas is calculated. The resolution of the measured backscatter strength values, due to the variation in transducer sensitivities, is estimated to be typically ±1dB (HAMMERSTAD, 1994 and HAMMERSTAD, 2000).

Monitoring of the Bathymetry and Nature of the Seabed

Three small zones (total surface area around 1km^2) are surveyed several times a year: the central (KBMA) and northern

Table 1. *Overview of the surveys on the KBMA and R2 monitoring areas.*

Survey	Month Year	KBMA	R2	Month	Interval months
9925	November 1999	16/11/1999	18/11/1999	0	
0023	September 2000	28-29/09/2000	29/09/2000	10	10
0104	February 2001	21/02/2001	22/02/2001	15	5
0131	November 2001	27/11/2001	30/11/2001	24	9
0203	February 2002	12-13/02/2002	13/02/2003	27	3
0219	September 2002	04-05/09/2002	06/09/2002	34	7
0229	December 2002	12/12/2002	12/12/2002	37	3
0306	March 2003	03-04/03/2003	04/03/2003	40	3
0315	June 2003	10-11/06/2003	11/06/2003	43	3
0324	October 2003	01-02/10/2003	02-03/10/2003	47	4
0406	March 2004	18-19/03/2004	19-22/03/2004	52	5
0415	July 2004	09/07/2004	08-09/07/2004	56	4
0420	September 2004	15-16/09/2004	16-17/09/2004	58	2
0423	October 2004	12/10/2004		59	1
0429	December 2004	07/12/2004	07/12/2004	61	2
0504	March 2005	08-09/03/2005	09/03/2005	64	3
0514	June 2005	15-16/06/2005	14-15/06/2005	67	3

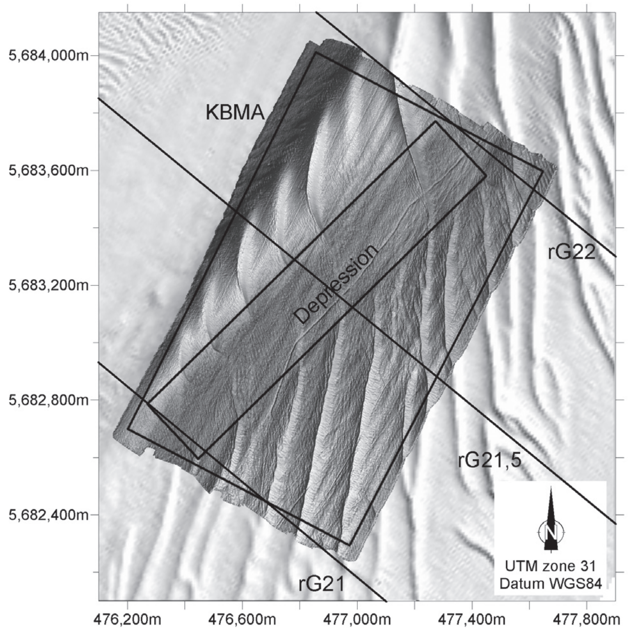


Figure 3. Detail of the monitoring area KBMA, with delineation of the central depression and the location of the single-beam tracks (rG21, rG21.5 and rG22).

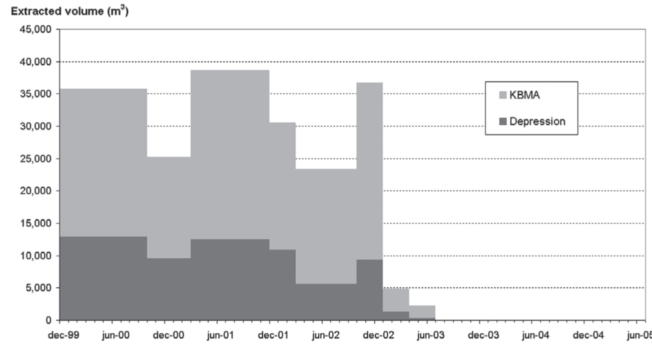


Figure 4. Extracted sediment volume inside the KBMA monitoring area and in the depression. In February 2003, the depression was closed for extraction; any values after this date are due to the infringements of some vessels.

parts (KBMB) of the Kwinte Bank; and a reference area, outside the extraction zone (Figure 2.). The latter area, defined as R2 (Flemish Authorities, Maritime Services, Van Cauwenberghe, 1996), is situated on the northern part of the Middelkerke Bank; it is a sandbank with a similar morphology as the Kwinte Bank. This particular sandbank is not exploited, permitting the study of the bathy-geomorphological evolution of a relatively natural environment. In this paper, only results from the KBMA and the R2 monitoring zones will be presented.

From November 1999 until June 2005, a total of 17 multibeam surveys were carried out on the KBMA monitoring area and 15 surveys on the R2 monitoring area (Table 1). Both areas were surveyed within the same week. The application of a standardised operating and processing procedure, for all surveys, allows comparison of the bathymetrical and backscatter strength models.

For each survey, a high resolution DTM of 1x1m is computed, using an inverse distance interpolation algorithm. Comparison of the successive DTM's permits the evaluation of the mobility of the morphological structures and the bathymetrical evolution. From comparison of some cross-sections from each DTM, the shifts from large to very-large dunes can be quantified. Histograms and statistical analyses undertaken of the depth values, of each DTM, provide additional information on the bathymetrical evolution. Similarly, the mapping and the statistical analysis of backscatter strength, recorded during successive surveys, are used to evaluate any changes in the sedimentary nature of the seabed. Based upon the morphology of the monitoring area KBMA, a distinction was made within KBMA, between the depression *sensu stricto* and the remainder of the zone (Figure 3.).

Until 1999, the morphology and topography of the sandbanks were monitored using a single-beam echosounder, along track lines perpendicular to the bank (Figure 3.). At that time, the evaluation of the bathymetrical changes was restricted to individual profiles and was limited by the need of accurate navigation, to permit comparison between successive recordings. Such profiles were surveyed up to 4 times a year and their evolution was studied by calculating and comparing the sandbank volume, beneath each profile (De Moor, 1985; De Moor*et al.*, 1994; and Vernemmen and Degrendele, 2002). Since 1992, the profiles were recorded digitally and corrected in real-time for the heave of the ship, with a depth accuracy of 12cm (Vandewiele, 2000; and Hartsuiker, 1992 *In*: Vernemmen and Degrendele, 2002). The accuracy of the position fixing was comparable to the present GPS standards (Vanzieleghem, 1998 and Vernemmen and Degrendele, 2002). In the present study, the evolution of the bathymetry along a reference line, crossing the central depression (rG21, Figure 3.), is investigated for the period 1992-1998. For each of the profiles, the depth values are compared to the corresponding depths, extracted from the multibeam model of the Kwinte Bank. As the exact position of the soundings is respected, errors, based on the navigation deviation during the recordings, are eliminated.

RESULTS

Extraction Activity

Based upon EMS data from November 1999, an average MA extraction rate of $0.64m^3/m^2$ ($825.10^3m^3/1290.10^3m^2$) can be calculated for the KBMA monitoring zone (Figure 4.). In the depression, this rate increases to $1.08m^3/m^2$ (394.10^3m^3 (48 % of KBMA) for a surface area of only 366.10^3m^2 (i.e. 28 % of the total surface); for the remainder of KBMA, $0.47m^3/m^2$ is derived.

Bathymetrical Evolution

Based upon the bathymetrical evolution in the depression (period 1992 until 1999), a gradual deepening is observed (Figure 5.). In 1992, the depression is barely visible and exists only as a trough between the larger bedforms. In 1995, the trough became broader and, by 1998, it evolved into a small depres-

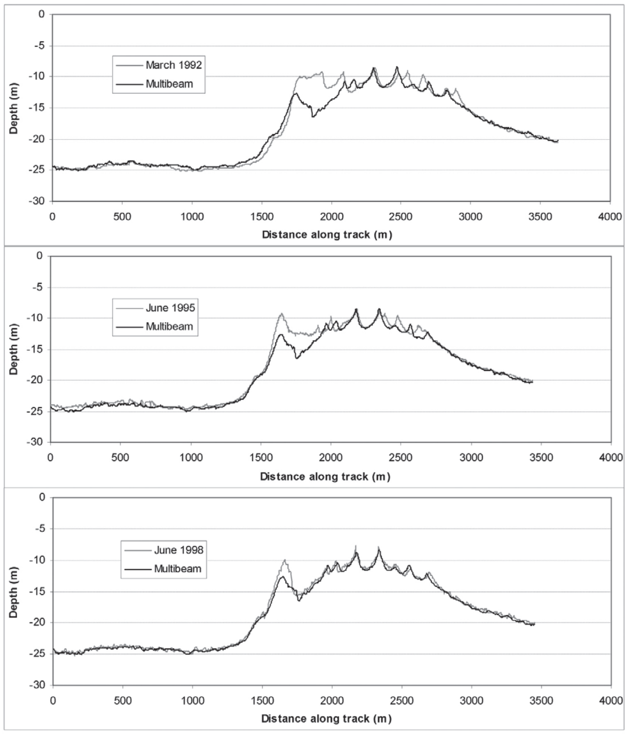


Figure 5. Comparison of single-beam profiles along reference line rG21 across the KBMA monitoring area against the multibeam data of December 1999 (depths referenced to MLLWS).

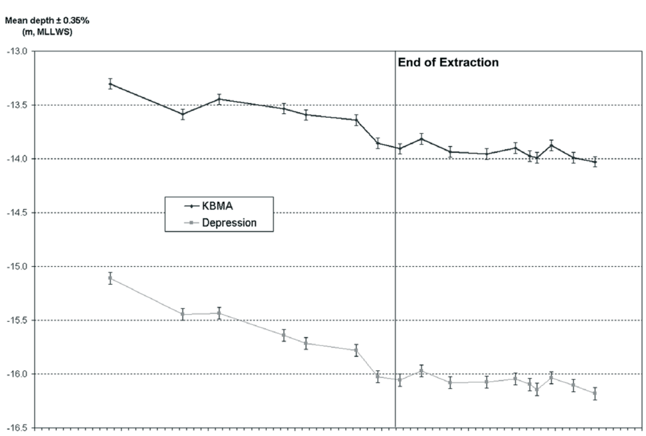


Figure 7. Evolution of the mean depth in the KBMA monitoring area and within its depression.

sion. Only small changes, due probably to bedform movement, are observed outside this depression.

The bathymetrical evolution from 1999 until 2005 shows an overall deepening of the entire KBMA, with a depth increase of 0.5m between November 1999 and March 2003 (Figure 6.).

Figure 7 shows the overall increase in mean depth. After the closure of the site for further dredging, the mean depth

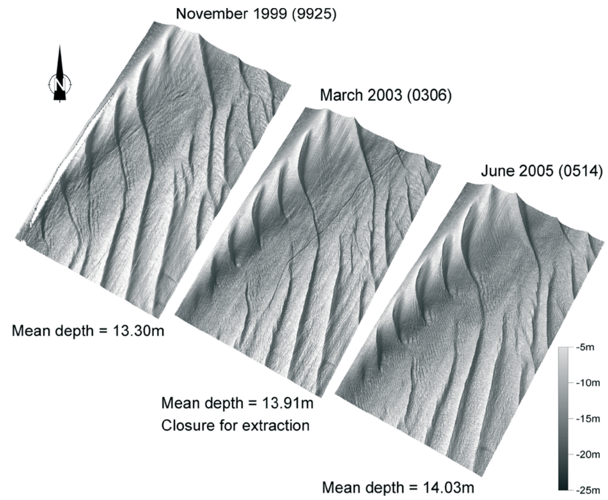


Figure 6. Successive terrain models of the KBMA monitoring area (depth in negative values and referenced to MLLWS). Notice the trailer-dredged furrow marks within the depression, in November 1999 and March 2003.

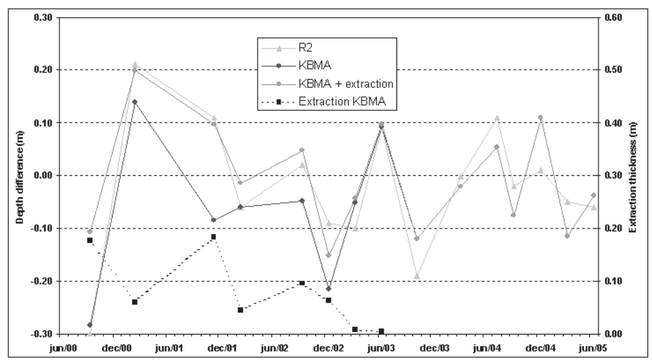


Figure 8. Depth evolution of the monitoring areas KBMA and R2, the evolution of the extracted thickness on KBMA and the depth evolution of KBMA, together with the extracted thickness.

variation becomes relatively stable. For the central depression, the deepening is more pronounced (0.9m), than for the KBMA monitoring area. The evolution of both the KBMA and R2 monitoring areas is shown in Figure 8 and listed in Table 2.

Similar trends are observed, but the erosion is higher for KBMA, at least until February 2003. After the cessation of dredging, there is still a deepening of the depression (0.12m from March 2003, until June 2005); in the same period, a similar deepening is observed over the R2 (0.11m) and KBMB monitoring areas (0.10m) (for locations, see Figure 2.). The dredged volumes in KBMA can be converted into a dredged volume per surface unit, or thickness of the extracted volume (Table 2.). Adding these values to the depth differences, provides the evolution of KBMA, without the extracted quantities. Compared

Table 2. *Bathymetric and extraction evolution over the KBMA and R2 monitoring areas. Depths given relate to MLLWS.*

SURVEY ID	KBMA					R2	
	mean depth (m)	depth difference (m)	extracted volume (m^3)	Thickness of extraction (m)	depth difference + thickness extraction (m)	mean depth (m)	depth difference (m)
9925	-13.30					-10.88	
0023	-13.59	-0.28	228640	0.18	-0.11	-11.18	-0.30
0104	-13.45	0.14	78085	0.06	0.20	-10.97	0.21
0131	-13.53	-0.09	236126	0.18	0.10	-10.86	0.11
0203	-13.59	-0.06	59093	0.05	-0.01	-10.92	-0.06
0219	-13.64	-0.05	124389	0.10	0.05	-10.90	0.02
0229	-13.86	-0.22	82168	0.06	-0.15	-10.99	-0.09
0306	-13.91	-0.05	10533	0.01	-0.04	-11.09	-0.10
0315	-13.82	0.09	5838	0.00	0.10	-11.00	0.09
0324	-13.94	-0.12	0	0	-0.12	-11.19	-0.19
0406	-13.96	-0.02	0	0	-0.02	-11.19	0.00
0415	-13.90	0.05	0	0	0.05	-11.08	0.11
0420	-13.98	-0.08	0	0	-0.08	-11.10	-0.02
0429	-13.88	0.11	0	0	0.11	-11.09	0.01
0504	-13.99	-0.11	0	0	-0.11	-11.14	-0.05
0514	-14.03	-0.04	0	0	-0.04	-11.20	-0.06

to the "natural" evolution of R2, the differences, observed before February 2003, are now reduced (Table 2. and Figure 8.).

The linear correlation coefficient between the 'corrected' KBMA and R2 values (Figure 9.) is highly significant (R=0.83). Hence, by correcting the bathymetric evolution, with the extracted sediment volume, a close to natural evolution is obtained. This result, together with the limited decrease in depth, since the closure, suggests that the extraction is the main cause of the deepening of the depression. Also, the time-series do not indicate a further cumulative effect on the bathymetry, after the closure of the depression.

The difference in evolution inside KBMA was studied in more detail: clearly, more erosion is observed within the depression, than outside of it (Figure 10.). After correction of the extracted sediment volumes inside both areas, the depth differences became (once again) very similar. Apparently, the higher extraction in the depression has had no additional effect on the surrounding area, where the extraction is less important. This observation suggests a rather localised impact of the extraction activities.

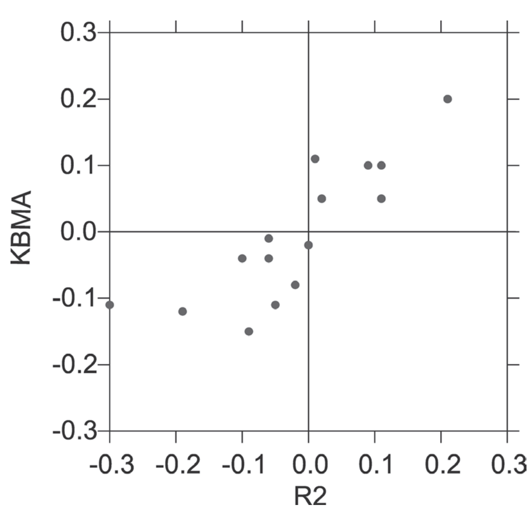


Figure 9. Scatter plot of the depth difference between successive surveys of the monitoring areas KBMA (corrected for extracted volume) and R2. The linear correlation coefficient (r) =0.83 is highly significant.

Morphological Evolution

The heights of the large to very-large dunes are consistently smaller in the depression; they decreased slowly whilst extraction took place (Cross-Section 2, Figure 11.). Within the depression, the dunes are clearly asymmetric towards the NE and have a migration rate of 20m/year. To the west of the depression, the dunes move in the same direction, at a rate of 10m/year; to the east of the depression, the dunes become more symmetrical and the migration rate reduces to 5m/year (Cross-Sections 1 and 3, Figure 11.). In the depression, medium dunes are observed as being abundant; together with the higher migration rate of the larger bedforms, this reflects the stronger dynamic character of the central part of KBMA, compared to the peripheral area. After the closure, the migration rate did not change, however, the slow decrease in the dune heights, in the depression ceased. Dredging furrows are observed, with their depths varying from 10 to 50cm (Figure 6.).

Evolution of the nature of the seabed

The nature of the seabed is derived indirectly from spatial variability in backscatter strength values. On this ba-

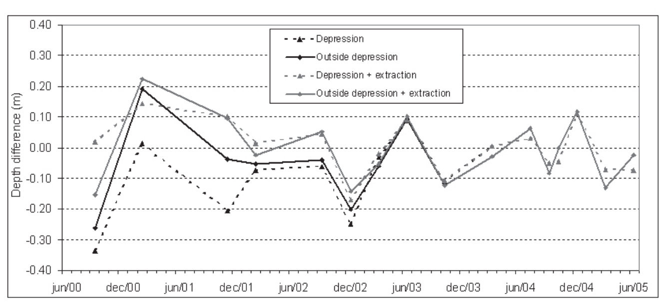


Figure 10. Depth evolution of the depression and its surroundings; the depth evolution plus the extracted thickness is indicated also.

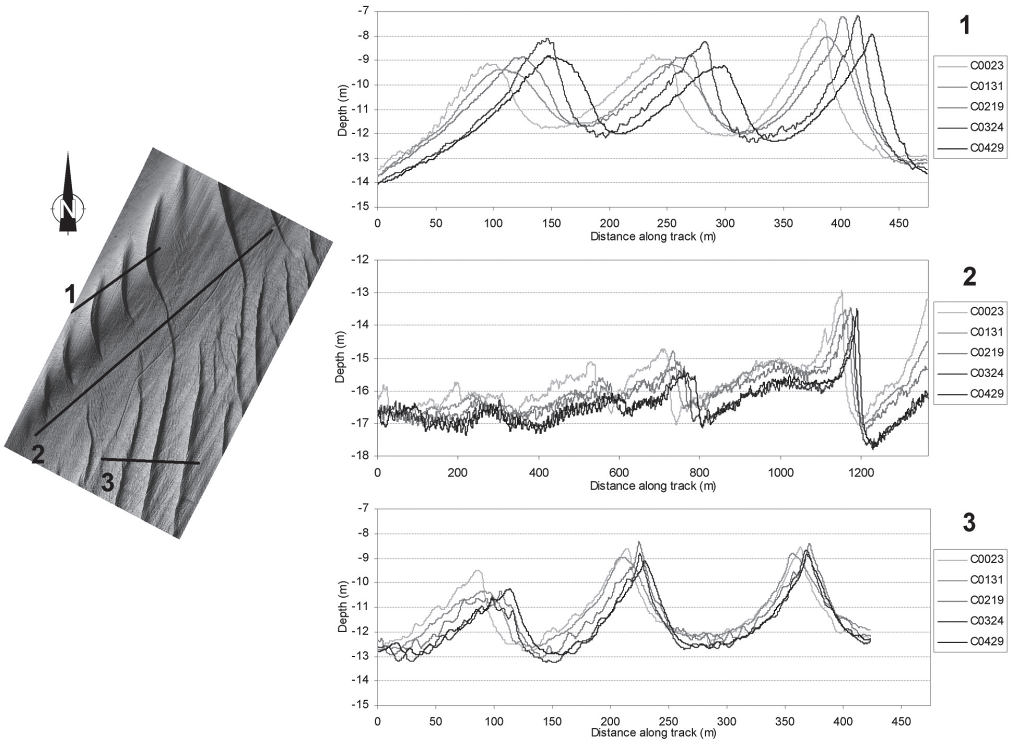


Figure 11. Evolution of bedform position across the KBMA monitoring area. Locations of Cross-Sections shown on the inset. The identification of the different surveys is given.

sis, the surficial sediments in the depression appear to differ clearly from those outside of the depression (Figure 12.). The central depression has a mean backscatter strength value of –24dB, which, compared to data presented in the literature, corresponds to medium- to coarse-grained sand (De Moustier, 2001). The mean backscatter strength values, along the eastern side of the KBMA area, extends up to –27dB, suggesting the dominance of very-fine sand. To the west, more intermediate backscatter strength values are observed; these correspond with medium to coarse sand, as validated by the grab samples obtained (see Bellec *et al.*, this volume). The backscatter strength values are fairly stable and do not show a clear evolution, before or after the cessation of dredging (Figure 13.). Similar results are obtained for the R2 monitoring area.

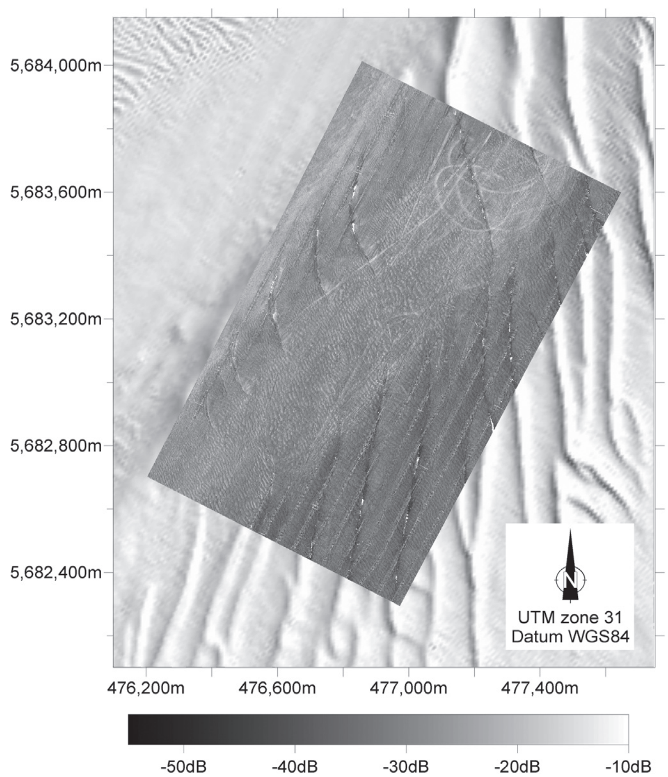


Figure 12. Backscatter strength image of the KBMA monitoring area (September 2002).

DISCUSSION

Local versus regional impact of MA extraction

The spatial relationship between the extraction intensity data and the depression, along the crest of the Kwinte Bank, suggests a local impact of the MA extraction. This conclusion is consistent with the findings of Brière *et al.*; Garel, and Van den Eynde *et al.* (this volume), based, respectively, on hydrodynamic measurements, numerical model output and stability analyses. In the short-term, these results show reveal erosional behaviour of the depression; in the long-term, regeneration of the sediment volumes is predicted. This interpretation contrasts to the findings of De Moor *et al.* (1994) and Norro *et al.* (2006), studying the sediment volume changes along fixed

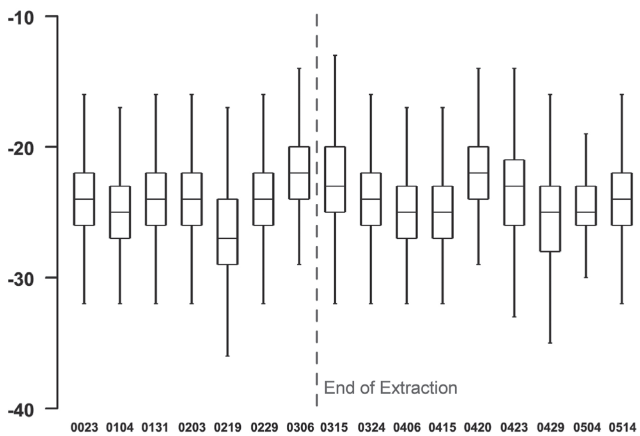


Figure 13. Box plot of the backscatter strength values derived from DTMs from successive surveys (x-axis, also Table 2.) undertaken on the KBMA monitoring area (the values are in dB; the central line is the median; the box represent the interquartile 25 % and 75 %; the 'whiskers' show the range of values, falling within the quartiles ± 1.5 interquartile; outside values are not represented).

tracklines covering entire sandbank areas (see Van Lancker *et al.* (this volume), for an overall discussion). On the basis of single-beam data obtained during the period 1987-2000, Norro *et al.* (2006) calculated, for the Kwinte Bank, a statistically significant, annual decline of +/- 1.5%, which questioned the long-term sustainability of the MA extraction. However, it must be highlighted that only limited knowledge is available on the natural evolution of the seabed, whilst the balance against the anthropogenically-induced dynamics is not clear – here and elsewhere. Furthermore, the EMS records obtained, within the KBMA monitoring area, represent only 18% of the total number of records on the Kwinte Bank obtained during the period November 1996 to March 2005; as such, only a limited part of the extraction activities are considered in this study. Future research should focus both upon a detailed, as well as on a regional, approach to clarify the real impact of MA extraction.

Natural Evolution

When the sediment volume variation is considered, without the extraction-induced changes, there is an overall similarity between the KBMA and R2 monitoring areas (i.e. a slight decrease of +/- 0.05m^3/m^2/year). On the basis of this observation, a simple model for the sedimentary balance inside the KBMA area was suggested; with the total sediment volume variation being the sum of the natural component and the amount of sediments extracted. However, it might be questioned whether the R2 area, located on the Middelkerke Bank, is representative of 'natural' regional sedimentary conditions, unaffected by the nearby intensive extraction on the Kwinte Bank. Indeed, the volume differences per surface unit, for both the KBMA and R2 areas, fluctuate considerably during the extraction period: for both areas, the differences stabilise after cessation of the dredging. Likewise for the R2 area, the results show very high variability, of 0.3m/year, between the two first surveys (November 1999 and September 2000) (Table 2.). Analysis of coincident hydro-meteorological datasets could not explain this variance. This study has proposed an average sediment volume variation of 0.05m^3/m^2/year; this would be the result of only naturally-driven processes. On the Belgian Continental Shelf, only limited studies are available to validate these findings: trend analyses undertaken are based upon the comparison of widely-spaced single-beam profiles, from which the results are difficult to compare to those based upon multibeam echosounder data, covering the full extent of an area. More detailed information is available (e.g. Houthuys, Trentesaux, and De Wolf , 1994), but the temporal spread of the surveys is much too broad (once or twice a year), inhibiting the study of the natural evolution of a sandbank area. However, closer to the coast, a small sandbank area has been monitored intensively (Van Lancker, 1999). From 12 DTM's, based upon closely-spaced single-beam measurements (1996-1998), a mean sediment volume variation of 0.05m^3/m^2 was deduced, with a maximum of +/- 0.1m^3/m^2. These values are comparable to the evolution observed on the R2 monitoring area located on the northern part of the Middelkerke Bank. In the same investigation, sediment volume changes were studied over the southern part of the Middelkerke Bank; these were subtle and varied around zero. Vincent, Stolk, and Porter (1998) have shown previously a difference in sediment transport along the southern and central part of the NW flank of the Middelkerke Bank. Over a 49-day period, the sediment flux was different over both areas, with values of 0.05 and 0.9tonnes/m/day (at 0-0.3m above the bed), respectively. Similarly, the analyses of De Moor *et al.* (1994) have identified a higher sediment flux, to the north of the Flemish Banks.

Morphological Changes

Based upon successive DTM's (Figure 6.), cross-lines (Figure 11.) and backscatter strength images (Figure 12.), the evolution of dunes and dredging furrows was investigated. The data show the impact of the extraction activities, on the height of the large dunes inside the depression; outside of it, the height differences are much less. Following cessation of the dredging, the decrease in dune height ceased: two years afterwards, the height of these dunes was stable and no trend of restoration of the dune height, in the depression, was observed. The migration rate of the dunes in the KBMA and R2 areas agree well with values reported previously for the Kwinte Bank and the Middelkerke Bank; in the short- to medium-term, this is dependent upon the dominant tidal currents and meteorological events (e.g. Degrendele, Roche, and Schotte , 2004; Houthuys, Trentesaux, and De Wolf, 1994; Lanckneus and De Moor, 1994;, andLanckneus *et al.,* 1992, 2001). However, the higher migration rates of the dunes in the central depression is related to the higher current speeds in the depression, due to canalisation of the flood flow (Garel, this volume).

The longevity of trailer dredging marks in the medium sands on the Kwinte Bank has been studied. The furrows on the borders of the central and northern depressions, on the Kwinte Bank, remain visible for a maximum of 6 months; this is based upon the results of the bathymetric models and on the backscatter strength images. Within the central depression, the MA extraction is too intense to deduce any life span of the furrows. A reduced ship speed during the MA extraction explains, probably, the large variability in the depth of the furrows (10 to 50cm). The infill of the furrows could result from local sedimentation, combined with (or activated by) the MA extraction itself. However, the time-scales of regeneration of the dredge furrows will vary according to substrate, water depth, currents and wave climate. HITCHCOCK, NEWELL, and SEIDERER (1998) reported on the disappearance of the dredged furrows on sandbanks, over 2-3 tidal cycles whereas, in areas with low sediment mobility, dredge furrows may be visible for up to a decade. In the fine to medium sands of the Graal-Müritz area in the Baltic Sea, similar furrows, in 8-10m water depths, refilled rapidly within months (MANSO *et al.*, this volume).

Sedimentary Stability

Despite short-term hydrodynamic measurements, indicating erosional behaviour in the depression (GAREL, this volume), evolution of the backscatter strength did not show a significant change in the inferred nature of the seabed, before or after the cessation of dredging. Similar conclusions were reached, based upon 4 successive and detailed sediment sampling campaigns, inside and outside of the depression (VANAVERBEKE *et al.,* 2007). Even on a longer time-scale, several authors have confirmed the general stability of the sediment characteristics over the Kwinte Bank (DE MOOR *et al.*, 1994; and VERNEMMEN and DEGRENDELE, 2002).

CONCLUSIONS

The bathymetrical, morphological and sedimentological impact of marine aggregate extraction on a tidal sandbank has been evaluated, based upon the results of an intensive and detailed monitoring programme. Over the period 1976 to 1999, the monitoring was based upon a follow-up of single-beam profiles, that were widely-spaced. Afterwards, multibeam technology permitted highly accurate digital terrain models to be obtained, of both bathymetry and backscatter strength values. Results from successive surveys, over exploited and non-exploited sandbanks, were evaluated against extraction statistics, derived from ship registers and EMS data.

Over the period 1992-1999, MA extraction on the Kwinte Bank has changed significantly the shape of the sandbank, with the creation of a local depression of 5m. The creation of this depression has led to the closure of the extraction site, permitting the study of the potential regeneration of the morphology and the nature of the seabed. Considering the period from 1999, up to the closure of the site in 2003 (i.e. 4 years), an overall deepening of 0.5m could be observed. The results show that two years after the closure, the site has not undergone sedimentation, nor has there been a significant change in nature of the sediment. The morphological changes, identified during the extraction, ceased, but no significant regeneration took place after cessation of the dredging. If the sediment volume variation, during extraction, is compensated for the amount of extracted sediments, the resulting variation is similar to the natural evolution of a non-exploited sandbank; this would imply that MA extraction has only a local impact.

At present, a new depression is being observed over the northern part of the sandbank, where the MA extraction is still highly concentrated. The monitoring of this new depression, together with the central depression, remain important; this will provide further knowledge on the impact of MA extraction on tidal sandbanks.

ACKNOWLEDGEMENTS

The Management Unit of the Mathematical Model of the North Sea and the Scheldt Estuary (MUMM) provided ship time on board the *RV Belgica*. The Captains and the crew of *RV Belgica* are thanked, for their flexibility and assistance during the campaigns.

LITERATURE CITED

ASHLEY, G.M., 1990. Classification of large-scale subaqueous bedforms: A new look at an old problems. *Journal of Sedimentary Petrology,* 60, 160-172.

BELLEC, V.,;VAN LANCKER, V.; DEGRENDELE, K.; ROCHE, M., and LE BOT, S., this volume. Geo-environmental characterization of the Kwinte Bank. *Journal of Coastal Research*.

BRIÈRE, C.; ROOS, P.; GAREL, E., and HULSCHER, S., this volume. Modeling the morphodynamics of the Kwinte Bank, subject to Sand Extraction. *Journal of Coastal Research*.

DEGRENDELE, K.; ROCHE, M., and SCHOTTE, P., 2002. *Synthèse des données acquises de novembre 1999 à avril 2001 quant à l'incidence des extractions sur le Kwintebank.* Brussels, Belgium: Fonds pour l'extraction de sable. Ministère des affaires économiques de Belgique, 23 p.

DEGRENDELE, K.; ROCHE, M., and SCHOTTE, P., 2004. Three years of bedform evolution on the Flemish banks, based on successive multibeam surveying of 2 monitoring areas. *In*: HULSCHER, S.J.M.H., GARLAN, T. and IDIER, D. (eds.), *Marine Sandwave and River Dune Dynamics II, International Workshop, April 1-2 2004.* Enschede, the Netherlands: Proceedings, pp 48 -54.

DEGRENDELE, K. ; MOINET C. ; ROCHE M. ; SCHOTTE P. ; TROUSSON J.-P., and VANDENREYKEN H., 2005. *Gérer durablement le Plateau continental de la Belgique. Fonds pour l'extraction de sable.* Brussels, Belgium: Ministère des affaires économiques de Belgique, 20 p.

DE MOOR, G., 1985. Shelf bank morphology off the Belgian coast. Recent methodological and scientific developments. *In:* VAN MOLLE, M. (ed.), *Recent trends in physical geography. Liber Amicorum L. Peeters*, Brussels, Belgium: VUB Study Series 20, pp 47-90.

DE MOOR, G.; LANCKNEUS, J.; DE SCHAEPMEESTER, G., and DE WINNE, E., 1994. *Project Westbank II – Eindverslag*. Brussels, Belgium: Ministerie van Economische Zaken, Dienst der Mijnen, 168 p.

DE MOUSTIER, C., 2001. Lectures 18 Acoustic seabed interaction theory. *25th UNB Ocean Mapping Group Multibeam Course, Hogeschool van Amsterdam, 15-20 October 2001*, (Amsterdam, Netherlands), pp. 17-18.

GAREL E., this volume. Short-term hydrodynamics and sediment transport on the Kwintebank, Southern North Sea. *Journal of Coastal Research*.

HAGA K. H.; PØHNER F., and NILSEN K., 2003. Testing Multibeam Echo Sounders versus IHO S-44 Requirements. International Hydrographic Review, 4(2), 31-40.

HAMMERSTAD E., 1994. *Backscattering and Sonar Image Reflectivity*. EM 12/950/1000 technical note, Internal Kongsberg Simrad Publication, 10 p.

HAMMERSTAD E., 2000. *Backscattering and Sonar Image Reflectivity*. EM technical note, Internal Kongsberg Simrad Publication, 5 p.

HAMMERSTAD, E., 2001. Multibeam echosounder accuracy. EM technical note, Internal Kongsberg Simrad Publication. 19 p.

HARTSUIKER, F.E.A.P., 1992. Mariene Geodesie: Practische toepassingen. *In: Mariene Geodesie, Meten op zee.* The Hydrographic Society, Benelux Branch, pp35-45.

HITCHCOCK, D.R.; NEWELL, R.C., and SEIDERER, L.J., 1998. Investigation of Benthic and Surface Plumes associated with Marine Aggregate Mining in the United Kingdom. Final Report. *Contract Report for the U.S Department of the Interior. Minerals Management Service* MMS Contract 14-35-0001-30763.

Houthuys, R.; Trentesaux, A., and De Wolf, P., 1994. Storm influences on a tidal sandbank's surface (Middelkerke Bank, southern North Sea). *Marine Geology*, 121, 23-41.

Hughes Clarke, J.E.; Danforth, B.W., and Valentine, P., 1997. Areal seabed classification using backscatter angular response at 95 kHz. *In*: Pace, N.G., Pouliquen, E., Bergem, O., and Lyons, A.P.E. (Eds.), *High Frequency Acoustics in Shallow Water*. Conference proceedings series CP-45, NATO SACLANTCEN, pp. 243-250.

Kongsberg Simrad, 1999-2001. EM1002 Multibeam echo sounder. Horten, Norway: Product Description, 160866, 23 p.

Kongsberg Simrad, 1999-2001. EM1002 Multibeam Echosounder, Operator Manual – Base Version. Horten, Norway: Doc. 850-160977, 423 p.

Kongsberg Simrad, 1999-2001. Neptune Bathymetric post-processing. Horten, Norway: Doc. 850-130021, 481 p.

Kongsberg Simrad, 1999-2001. Poseidon Operator Manual. Horten, Norway: Doc. 850-164063C, 90 p.

Lanckneus, J.; De Moor, G.; De Schaepmeester, G.; De Winne, E., and Meyus, I, 1992. Monitoring of a tidal sandbank: evolution of bedforms, volumetric trends, sedimentological changes. Hydro '92, Eight Biennial International Symposium of the Hydrographic Society, 30 November – 3 December 1992, Copenhagen, 19 p.

Lanckneus, J. and De Moor, G., 1994. Evolution of large dunes. *In*: De Moor, G. and Lanckneus, J. (eds.), *Sediment Mobility and Morphodynamics of the Middelkerke bank*. Univ. Gent, CEC, Brussels, pp. 85-106.

Lanckneus, J.; Van Lancker, V.; Moerkerke, G.; Van Den Eynde, D.; Fettweis, M.; De Batist, M., and Jacobs, P., 2001. *Investigation of natural sand transport on the Belgian continental shelf: BUDGET (Beneficial usage of data and geo-environmental techniques). Final report.* Brussels: Federal Office for Scientific, Technical and Cultural Affairs (OSTC), 191 p.

Le Bot, S.; Van Lancker, V.; Deleu S.; De Batist, M.; Henriet J.P., and Haegeman, W., 2005. Geological and geotechnical properties of Eocene and Quaternary deposits on the Belgian continental shelf: a synthesis. *Netherlands Journal of Geosciences,* 84 (2), 147-160.

Manso, F.; Radzevičius, R.; Blažauskas, N., and Balay, A., this volume. Geo-environmental conditions of a nearshore dredged area: Tromper Wiek, Baltic Sea. *Journal of Coastal research.*

Ministerie Van De Vlaamse Gemeenschap, 1993. *Kust 2002. Deel 1. De zeewerende functie van de kust. Stand van zaken.* Brussel: Administratie Waterinfrastructuur en Zeewezen, AWZ, 82pp.

Norro, A.; Pichot, G.; Pison, V., and Ozer, J., 2006. Bidimensional approach to the volumetric evolution of an exploited sandbank. ICES *Journal of Marine Science* 63(1), 176-186.

Radzevičius R.; Velegrakis A.; Bonne W.; Kortekaas S.; Garel E.; Blažauskas N., and Asariotis, R., this volume. Marine Aggregate Extraction in EU Member States. *Journal of Coastal Research.*

Vanaverbeke, J.;Bellec, V.; Bonne, W.; Deprez, T.; Hostens, K.; Moulaert, I.; Van Lancker, V., and Vincx, M., 2007. *Study of post-extraction ecological effects in the Kwintebank sand dredging area (SPEEK). Final report*. Scientific Support Plan for a Sustainable Development Policy, SPSDII. Part 2 Global Change, Ecosystems and Biodiversity. Brussels: Belgian Science Policy (D/2007/1191/2), 91 p.

Van Cauwenberghe, C., 1996. Multibeam Echosounder Technology: a Time Series Analysis of Sandbank Movement. *The Hydrographic Journal*, 81, 13-18.

Van Cauwenberghe, C; Dekker, L., and Schuurman, A., 1993. M2 tidal reduction method for coastal zones. Oostende, Belgium: Ministerie van openbare werken, Bestuur der waterwegen, Dienst der kust, *Rapport nr. 33 van de Hydrografische Dienst der Kust*, 12 p.

Van den Eynde, D.; Giardino, A.; Portilla, J.; Fettweis, M.; Francken, F., and Monbaliu, J., this volume. Modelling the effects of sand extraction on the sediment transport due to tides on the Kwinte Bank. *Journal of Coastal Research.*

Van Lancker, V. (1999). *Sediment and morphodynamics of a siliciclastic near coastal area, in relation to hydrodynamical and meteorological conditions: Belgian continental shelf*. Ghent University, unpublished PhD thesis, 194 pp.

Van Lancker, V.; Bonne, W.; Velegrakis, A.F., and Collins, M.B., this volume. Aggregate extraction from tidal sandbanks: is dredging with nature an option? An introductory perspective. *Journal of Coastal Research.*

Vanzieleghem, T., 1998. Kwaliteitscontrole van DGPS plaatsbepaling op zee. Gent, Belgium: Universiteit Gent, Master's thesis, 93 p.

Vandewiele, T., 2000. Aspects of Accuracy Analysis for Soundings. *The Hydrographic Journal,* 95, 19-21.

Vincent, C.E.; Stolk, A., and Porter, C.F.C., 1998. Sand suspension and transport on the Middelkerke Bank (southern North Sea) by storms and tidal currents. *Marine Geology*, 150(1-4), 113-129.

Vernemmen, C. and Degrendele, K., 2002. *Project Zandwinningen, Evolutie exploitatie invloed*. Brussels, Belgium: Ministerie van Economische Zaken, 106 p.

Journal of Coastal Research	SI	51	87-94	West Palm Beach, Florida	Summer 2010

Tidally-averaged Currents and Bedload Transport over the Kwinte Bank, Southern North Sea

Erwan Garel [1*]

[1] School of Ocean and Earth Science
National Oceanography Centre
Southampton (NOCS),
European Way
Southampton, SO14 3ZH
United Kingdom

[*] Present address: CIACOMAR
University of Algarve
Avenida 16 de Junho
8700-311 Olhão
Portugal
egarel@ualg.pt

ABSTRACT

The short-term dynamics of a dredged tidal sandbank (the Kwinte Bank, southern North Sea) are examined, on the basis of field measurements and 1D sediment transport modelling. The field measurements include current data from shipborne Acoustic Doppler Current Profiler (ADCP) and from moorings (ADCP and electromagnetic S4), collected across the bank during a nominal (spring) tidal cycle, and during 7 tidal cycles, respectively. The dynamics of the bank are described in terms of tidally-averaged (residual) currents and (net) bedload transport.

The results indicate a predominance of ebb flow during the period of study. Convergence of (net) bedload transport is predicted, from both flanks towards the crest of the bank. The exact location of the sand transport convergence zone varies, in the short-term, according to the prevailing tidal currents. The observation of clockwise veering of the peak ebb and flood currents over the bank indicates that this sediment transport pattern relates, at least partially, to tidal rectification of the flow.

In relation to dredging, the present study suggests that the presence of a (dredged) depression at the crest of the bank influences locally the short-term hydrodynamics. The currents are channelised, and the across-bank peak (near-bed) flow is enhanced towards the crest. Net erosion of the depression is predicted, over the tidal cycle considered. More data are needed to evaluate the morphological evolution of the trough over the long-term.

ADDITIONAL INDEX WORDS: *sandbank, short-term dynamics, dredging.*

INTRODUCTION

Sandbanks are present on continental shelves, in shelf seas and within estuarine environments. They occur in areas characterised by strong currents, capable of moving the sand, and an abundance of sand, supplied from the local seabed or coastal erosion (Dyer and Huntley, 1999). Although many studies have attempted to describe their morphodynamic behaviour (for reviews, see Dyer and Huntley, 1999; Pattiaratchi and Collins, 1987; and Wright, 1995), there is no overall consensus on the processes of sandbank formation and maintenance. Several classifications have been proposed, to account for their diverse morphology, regional setting, formation and development (e.g. Dyer and Huntley, 1999; and Pattiaratchi and Collins, 1987).

This study concerns tidal sandbanks which are defined as open shelf linear ridges (Type I, according to the classification of Dyer and Huntley, 1999). Typically, these sand bodies present an asymmetric cross-section profile, with a main axis oriented at an angle to the peak tidal flow. These features are 13 km wide, on average, tens of metres in height, and up to 80 km in length. Amongst a number of theories to explain the existence of this type of sandbank, the "seabed stability analysis" approach (Huthnance, 1982a, b), is the most promising. The model considers water and sand movements as an interacting system, which is described on the basis of coupled hydrodynamic and sediment dynamic equations. The theory relates the existence of tidal sandbanks to the deflection of flow over the bank (tidal rectification). Such deflection is explained by increasing bottom friction (over the seafloor elevation), resulting in a deceleration of the along-bank component of the flow, together with acceleration of the across-bank component, in order to satisfy continuity. As such, the currents veer as they move on to the bank, resulting in sediment transport towards the crest. On the downstream side of the bank, the current is weaker, due to friction over the bank. Thus, sediment transport takes place mainly on the upstream side, towards the top of the deposit. Consequently, for reversing tidal flow, net convergence of sand occurs over the crest. In addition, the Coriolis force generates vorticity, due to compression of the water column over the bank. This effect tends to enhance the deflection and, hence, the growth of the banks which are aligned cyclonically (anti-clockwise, in the northern hemisphere), relative to the flow (Stride, 1982; and Zimmerman, 1981). The morphology (orientation and wavelength) of numerous tidal sandbanks supports the above concept, at least, qualitatively (Belderson, Johnson, and Kenyon, 1982; Caston, 1972;

DOI: 10.2112 / SI51-008.1 received 15 January 2007; accepted in revision 24 September 2007.

KENYON *et al.*, 1981; LANCKNEUS and DE MOOR, 1995, and PATTIARATCHI and COLLINS, 1987).

This contribution focuses upon the short-term hydro-sediment dynamics over the Kwinte Bank, a tidal sandbank in the southern North Sea (Figure 1.). Intense sand extraction (see below) has created depressions at the crest of the bank. Although of importance to a number of environmental issues (e.g. coastal erosion) and to a sustainable management of the resource, the morphodynamic response of the bank to dredging is largely unknown. In this study, both hull-mounted and moored current-meters are used to examine the tidally-averaged currents over the bank. Residual bedload sediment transport patterns are derived using a one-dimensional (1D) sediment transport model. The aims are to examine maintenance processes associated with the bank, together with the near-field hydro-sediment dynamic impact of dredging.

ENVIRONMENTAL SETTING

The Kwinte Bank is part of the Flemish sandbank system (Figure 1.), a group of Quaternary sand bodies deposited on Tertiary (Ypresian) units (mainly clays) (BERNÉ *et al.*, 1994; LE BOT *et al.*, 2005). These banks are considered to be in, or close to, an equilibrium state, maintained by the present-day flow conditions (STRIDE, 1982). The Kwinte Bank is about 15 km in length, 10-20 m in height, and 1 to 2 km in width (i.e. about 400 Mm^3 in volume). The minimum water depth lies close to 5 m MLLWS (Mean Lowest Low-Water at Spring), over its southern part. The bank is aligned in a NE-SW direction. It shows a strongly asymmetric profile, being steeper towards the NW. The area experiences semi-diurnal progressive tides, macrotidal in range (4-5 m). The average tidal ellipse is elongated along a NE-SW axis, rotated some degrees clockwise from the Kwinte Bank orientation. The tidal currents rotate counter-clockwise, with maximum currents (about 1 m/s) observed generally during the flood, towards the NE (CASTON, 1972; DE MOOR, 1986; HOUBOLT, 1968; and VAN CAUWENBERGHE, 1971). Small to large 3D compound dunes (ASHLEY, 1990) cover extensively the bank (LANCKNEUS and DE MOOR, 1991) (e.g. Figure 2.). On the basis of the direct observation of the asymmetry of small dunes on side-scan sonar imagery, LANCKNEUS *et al.* (1992) consider that the flood and ebb are dominant on the western and eastern part of the bank, respectively, inducing sand transport, from the adjacent swales, towards the crest. Such convergence of sand transport, over a tidal cycle, is considered to play a major role in the build up of the bank. The exact location and extension of the areas over which residual sand transport is either dominated by the peak flood or ebb currents, appears to vary significantly, over time (LANCKNEUS *et al.*, 1992). Vertical growth of the bank is limited probably by wave and storm action, i.e. the stirred sediments are re-distributed over the flanks, where they reintegrate into the maintenance mechanism.

Intense sand extraction has taken place from the Kwinte Bank, since 1979, by trailer suction dredging (DEGRENDELE *et al.*, this volume). This activity has formed two particular depressions, located along the crestline, in the northern and central parts of the bank. The central depression is the area excavated the most, with dimensions of about 700 m in width, 1 km in length and up to 5 m in depth (Figure 2.). Dredging at this location ceased in February 2003, for a 3 year period, to allow monitoring of the evolution (and potential recovery) of the sand extraction zone. To date, no regeneration of the depression has been identified, on the basis of sequential swath bathymetric surveys (DEGRENDELE *et al.*, this volume).

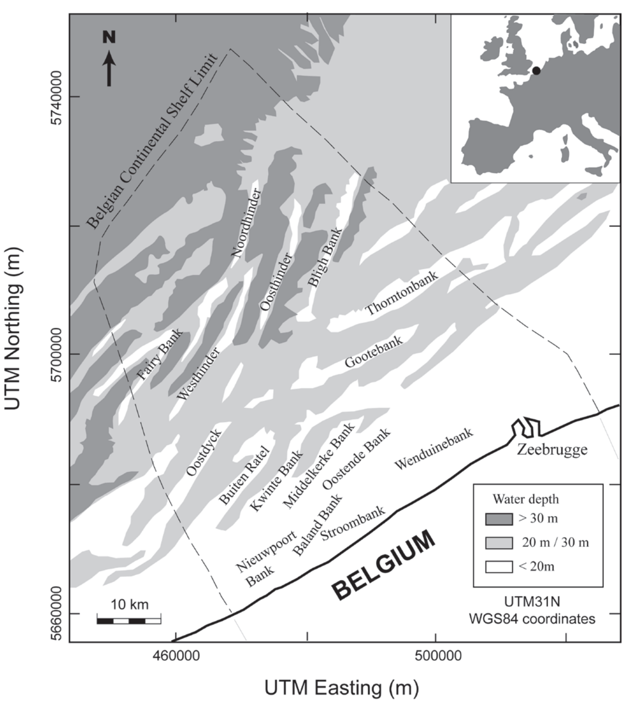


Figure 1. Location map of the sandbanks on the Belgian Continental Shelf (modified from Deleu et al., 2004). Note: bathymetric contours relative to the Mean Lowest Low-Water at Spring (MLLWS).

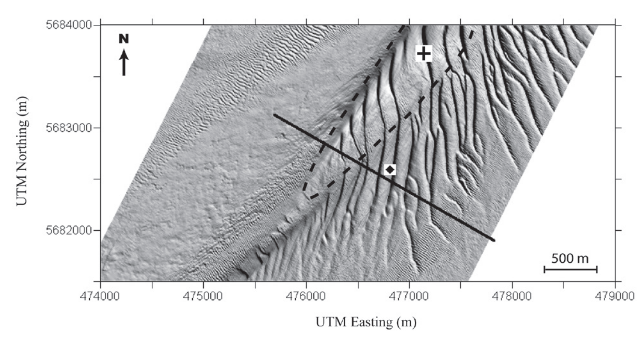


Figure 2. Shaded relief map of the central part of the Kwinte Bank (illuminated from the southwest), based upon swath bathymetry (grid data from the Marine Sand Fund for Extraction). Key: black line- location of the repeated hull-mounted ADCP profiles; diamond- S4 deployment site; cross- bottom-mounted ADCP location; and the dashed line indicates the limits of the central dredged depression (see text).

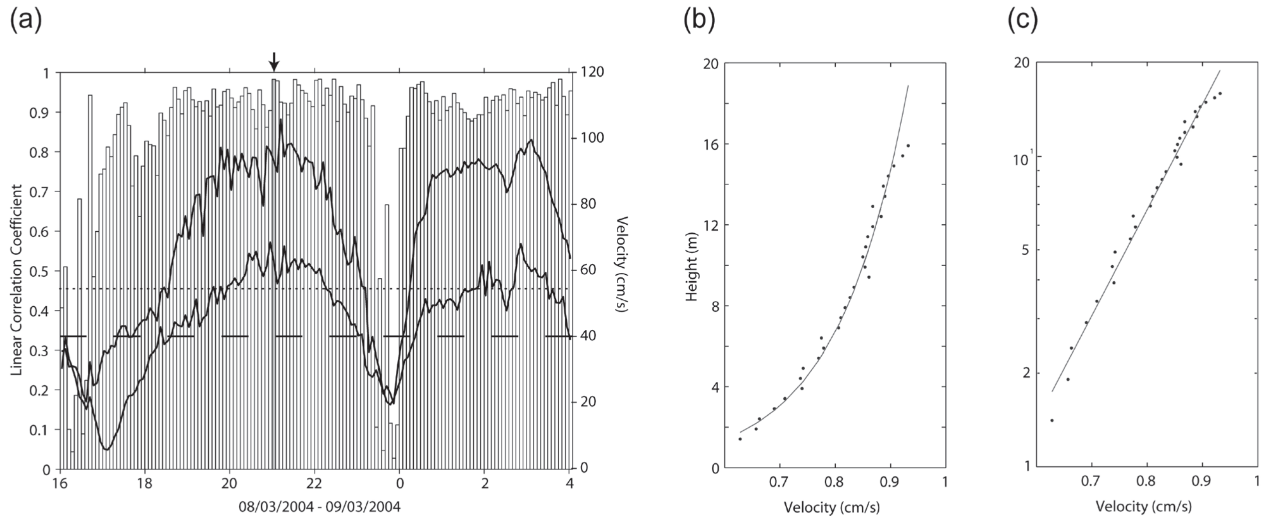


Figure 3. (a) Linear correlation coefficient for the logarithmic velocity distribution throughout the water column (bars), together with the near-surface and near-bed current velocities from the BM-ADCP (solid lines, the near-surface currents being generally faster). Key: dashed line- approximate threshold for significant sand transport by tidal currents; dotted line- critical correlation coefficient, at a 99 % confidence level; the arrow and the grey bar indicate the example shown in (b) and (c). (b) Velocity profile observed at 21h, on 8th March 2004 (measurements (dots) and line of best fit); and (c), as (b), plotted on a logarithmic depth scale.

METHODS

Data Acquisition

Flow velocities were recorded, over the Kwinte Bank, using 3 instruments (Figure 2.): (1) a moored 1200 kHz (RDI) Acoustic Doppler Current Profiler (ADCP), operating at 0.3 Hz, from 1.4 m up to 16.4 m above the seafloor, with a resolution of 0.5 m (hereafter BM-ADCP, for Bottom-Mounted ADCP); (2) a S4 electromagnetic current meter (Model ADW, INTEROCEAN) operating at 2 Hz, at 0.75 m from the seabed (hereafter S4); (3) a 300 kHz ADCP (RDI), mounted in the hull of the R/V *Belgica* (hereafter HM-ADCP, for Hull-Mounted ADCP), operating at 1 Hz, at 1 m intervals, from 7 m below the water surface (due to the vessel draught and the blanking period), to 2-3 m above the sea bed. The latter rejects errors due to contamination of the signal with the reflection from the seabed. Herein, '*near-bed currents*' refers to the ADCP bin lying closest to the sea bottom, and to the S4 records; likewise, '*near-surface currents*' to the ADCP bin closest to the water surface.

The moorings were deployed between the 2nd and 11th March 2004, at the northern extremity of the central dredged depression (BM-ADCP) and at the crest of the bank (S4), at 9 and 11 m MLLWS, respectively (Figure 2.). The present contribution focuses upon measurements undertaken under mild meteorological conditions, between the 7th and 10th March (with W-SW wind < 8 m/s, and insignificant wave action near the sea bed). HM-ADCP data were collected on the 8th and 9th March, during a (nominal) 13 hour cycle on spring tides. Fifteen tracks were repeated along a profile being perpendicular to the bank axis (including the dredged depression), at around 3 knots (1.5 m/s) (Figure 2.). The navigation data were acquired with a Differentially-corrected Geographical Positioning System (DGPS), precise to within ±1 m.

Data Processing

BM-ADCP records were averaged every 100 pings inside the data acquisition system, to reduce measurement uncertainties; this provided an averaged current velocity and direction, every 8 min and 20 s. The HM-ADCP transmitted averaged data to an onboard PC, every 30 pings; these data were processed and averaged to a horizontal sampling interval of 180 m (i.e. 10 averaged values along the profile). The S4 was set up to provide averaged current fluctuations over 9 min, every 15 min.

Sediment transport was computed using the 1D sediment transport model SEDTRANS05 (Neumeier *et al.*, in press), an improved version of SEDTRANS96 (for details, see Li and Amos, 2001). Bottom shear stresses have been derived from the averaged near-bed currents, using the Grant and Madsen (1986) bottom boundary layer approach. Bedload sediment transport, using the skin-friction shear stress, has been computed based upon the algorithm for non-cohesive material of Yalin (1963), for currents alone. The Yalin equation applies to a grain-size of 0.2 mm, or coarser. For a grain-size of 0.45 mm, Gadd, Lavelle, and Swift, (1978) consider that the algorithm yields predictions of transport rates which are in relatively good agreement with flume data, at velocities near the threshold of movement. Sediment transport simulations were carried out using the distribution of the mean grain-size (d50) over the study area, established on the basis of recent sediment sampling campaigns (Bellec *et al.*, this volume). The mean grain size was 0.3 and 0.8 mm at the S4 and BM-ADCP locations, respectively; it ranged from 0.25 to 0.4 mm along the HM-ADCP tracks. The bedform dimension inputs into the model (wavelength = 2.5 m; height = 0.35 m) were derived from side-scan sonar imagery acquired during the survey (Garel, Manso, and Collins, 2005).

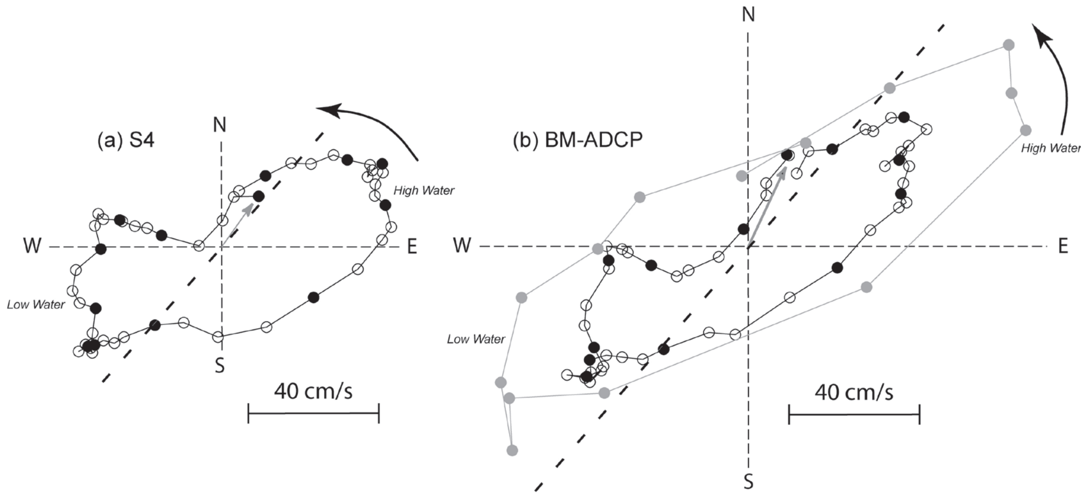


Figure 4. Typical tidal ellipse, as recorded by the S4 (a) and BM-ADCP ((b): black- near-bed currents; grey- near-surface currents). The selected tidal cycle is that shown in Figure 3a. Key: the grey vector denotes currents at the beginning of the experiment; small circles represent 15 min time-steps, for the current vectors (1 hour-time step for the circles filled with black). Arrows outside the ellipse denote the direction of the vector rotation. The dashed line indicates the bank axis.

For the sediment transport calculations, the model considers the velocity profile to be logarithmic within the turbulent boundary layer. This assumption was tested over a single tidal cycle, based upon the BM-ADCP measurements. The correlation coefficient (*r*) for the 'goodness-of-fit' to a logarithmic profile is shown in Figure 3. The trend exists, at a confidence level of 99 %, if *r* is above a critical value of 0.463 (Davis, 2002). The fit of the measurements to the logarithmic profile is very good, with *r* generally about 0.9 (Figure 3a.). Examples of an observed velocity profile are presented in Figures 3b. and 3c. Poor correlation is observed only around the slack waters, when the bed sediment is not mobile (for example, Soulsby (1997) considers that significant sand transport takes place for tidal current in excess of about 40 cm/s). Therefore, the velocity profiles can reasonably be considered as logarithmic, for the sediment transport calculations.

Inherent to the method of data acquisition, the sampling time interval of the HM-ADCP data was not regular at fixed locations along the profile. Thus, in this case, the tidally-averaged currents and sediment transport were obtained by applying a trapezoidal rule. Concerning the Eulerian measurements (i.e. BM-ADCP and S4), the tidally-averaged values correspond to the mean, over the tidal cycle which was considered.

RESULTS

Bottom-mounted instruments

An example of the records from the moored current meters, during the same tidal cycle as Figure 3., is presented in Figure 4. The tidal ellipses display the regional tidal features, i.e. a dominantly (anti-clockwise) progressive tidal wave, with SW-NE trending peak currents rotated 15-25° (clockwise) to the axis of the bank. These observations are consistent with previous data sets available for the area, on the basis of *in-situ* measurements (such as free drifting buoy experiments) and numerical modelling outputs (Van Lancker *et al*., 2004; and Williams *et al*., 2000). In detail, the main axis of the tidal ellipse lies closer to the orientation of the depression at the BM-ADCP location, than at the crest (S4). This observation persists over the (4 day) period of the records. In the selected example (Figure 4.), peak flood currents (towards the NE) are similar in magnitude to the peak on the ebb, with faster currents observed with greater distance from the bed. However, at both locations, the peak currents last longer during the ebb, than the flood. For example, the near-bed currents are > 40 cm/s during approximately 3h45min of the ebb and 3h of the flood (see Figure 3.). Such a difference is important in terms of the tidally-averaged (net) sediment transport. The tidal currents over the 4 day period show high variability in the peak currents patterns, over time and with location (Figure 5a.). Ebb asymmetry is not observed for all the tides, e.g. Tide 7 in Figure 5a., where the flood is prevailing. Furthermore, for any given tide, the ebb or the flood may predominate, depending upon location on the bank (e.g. Tides 2 or 3, where the tidal asymmetry is apparent for one instrument, only). Consequently, the residual current vectors show distinct orientation, depending of the tidal cycle and instrument considered (Figure 5b.). At the crest (S4), the residual currents are constantly towards the southwest. In contrast, the residual currents from the BM-ADCP data are directed either towards the northeast, or the west. Residual current magnitudes are similar at both locations, of up to 8 cm/s (Figure 5c.).

Due to the non-linearity of sediment transport, in response to the prevailing flow conditions, net sand transport patterns do not correspond necessarily to the directions of the residual currents. The net bedload transport directions are either flood- or ebb- dominated, depending upon the tidal cycle considered (Figure 5d.). Tides 6 and 7 are ebb and flood dominated, re-

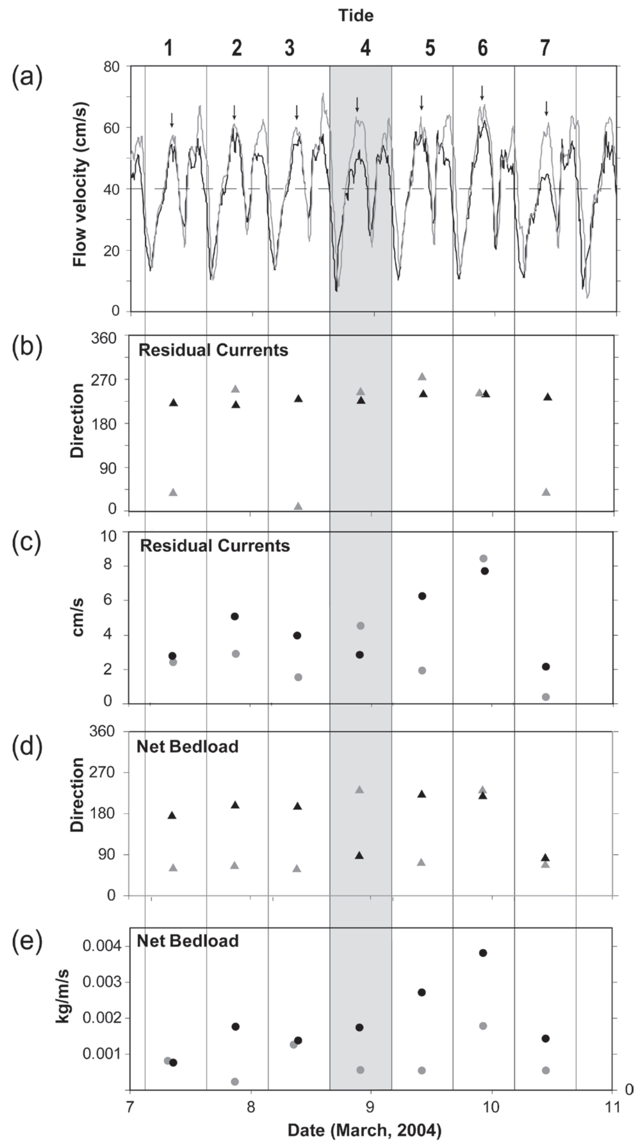


Figure 5. Comparison of the flow, residual currents and net sediment transport, from the S4 (black) and BM-ADCP (grey) data (the vertical grey area indicates the particular tidal cycle corresponding to Figures 3a, 4, and to the HM-ADCP data): (a) near-bed current magnitude (arrows indicate the peak ebb currents); (b) residual near-bed current direction; (c) residual near-bed current magnitude; (d) net bedload transport direction; (e) net bedload transport magnitude.

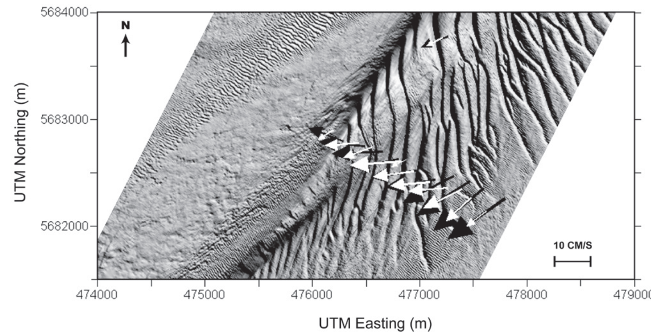


Figure 6. Residual near-bed (white arrows) and near-surface (black arrows) currents, based upon the HM-ADCP data.

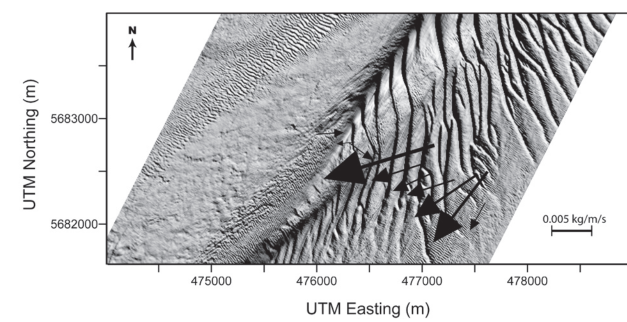


Figure 7. Net bedload transport across the bank, based upon the HM-ADCP data.

spectively. In other cases, the model indicates opposing net sand transport directions at crest and at the depression, i.e. sand convergence between these two sites. Bedload transport rates are slightly greater at crest, with values up to ~0.004 kg/m/s (Figure 5e.).

Hull-mounted ADCP

The residual currents computed from the shipborne ADCP data, over a single tidal cycle (Tide 4, Figure 5.), are consistent with those obtained from the moorings (Figures 5b., 5c. and 6.). The vectors are orientated (mainly) towards the west-southwest. Thus, ebb flows predominate over the study area, during this tidal cycle. In detail, the near-surface and near-bed residuals present similar directions and magnitude over the crest (Figure 6.). Probably, the reduced water depth at this location induces a more uniform behaviour of the currents along the water column than elsewhere across the bank. The near-surface residual current directions are deviated progressively clockwise, towards the western flank of the bank; this is associated with a decrease in magnitude (from 20 cm/s, in the East, to 10 cm/s, in the West). In contrast, the near-bed currents are deflected (clockwise) only over the upper lee slope and crest, associated with the strongest residuals (up to 14 cm/s).

The net bedload transport predictions are shown in Figure 7. Overall, transport is towards the SW, i.e. the general direction of the residual currents (Figure 6.). In detail, the potential net transport lies sub-parallel to the bathymetric contour at the foot of the eastern flank and veers progressively 45° clockwise, towards the crest of the bank. In contrast, the transport is towards the E-NE over the western flank. Further, divergent transport pathways are predicted inside the depression. The highest transport rates (up to 0.014 kg/m/s) are at the crest and over the eastern flank of the bank, which compare with the residual currents.

DISCUSSION

Hydrodynamic numerical modelling of the tidal flow, over the Kwinte Bank area, was integrated over an 11 day period (Brière *et al*., this volume) and over a complete spring-neap tidal cycle (14.8 days) (Van Lancker *et al*., 2004; Van den Eynde *et al*., this volume). These models describe anti-clockwise gyres, centred over the adjacent swales, whose position or scale varies with the tidal flow conditions. The near-bed tidally-averaged flow magnitudes and directions described here are in good agreement with the outputs of these models, averaged over several tidal cycles (e.g. Brière *et al*., this volume). Thus, the records of the present study are considered to be typical of tidal flow conditions over the bank, i.e. rather than being generated by exceptional (non-tidal) conditions. Ebb predominance over the bank appears to be more important than was considered previously.

Repeated seafloor mapping surveys undertaken over the Kwinte Bank, during 4 years, indicate a slow and constant propagation rate (of up to 10 m/yr) for the large dunes, towards the NE (Degrendele *et al*., this volume); this is in agreement with their asymmetry (Bellec *et al.,* this volume). However, net sand transport directions towards the SW are (often) proposed in the present study (Figure 7.; Figure 5d.). These striking differences relate to the time-scale of the observations. From side-scan sonar data, Garel, Manso, and Collins. (2005) reported elsewhere the complete reversal of small dunes, on the western rim of the depression, during a single tidal cycle. In contrast, the asymmetry of the larger bedforms is indicative of net sediment transport over a longer time scale (Berné *et al.*, 1993; Lanckneus and de Moor, 1995). In this case, the bedform dynamics is governed by the dominant tidal flow and, probably, (shorter term) storm events. For example, based upon numerical modelling, Van den Eynde *et al.* (this volume) consider that the influence of waves over the Kwinte Bank may alter drastically the direction of the residual sediment transport.

In the short-term, the present data indicate prevailing ebb and flood sand transport pathways, on each flank of the bank, respectively; as such, sand convergence up to the crest (Figure 7.; Figure 5d.). This pattern is consistent with the modelling results of Brière, Roos, and Garel. (this volume) and Van den Eynde *et al.* (this volume). Previously, Lanckneus *et al.* (1992), and, more recently, Bellec *et al.* (this volume), arrived at the same interpretation, based upon bedform asymmetries. Lanckneus *et al.* (1992) consider that areas in which the net sand transport direction is controlled, either by the flood or the ebb phase of the tide, varies significantly with time. Such variations are consistent with fluctuations in the net transport directions, observed at the mooring sites, over various tidal cycles (Figure 5d.).

The stability model proposed by Huthnance (1982a, b) depicts sand convergence up to a bank crest, in response to tidal rectification of the flow. At the Kwinte Bank, the angle observed (sometimes) between the crest of the large and (superimposed) small bedforms, suggests veering in the sand transport pathways, towards the crest (e.g. Figure 6. in Bellec *et al.*, this volume). However, as noted by Dyer and Huntley (1999), acceleration and refraction of tidal flows over sandbanks have proved to be difficult to identify in the field. Difficulties arise from the highly localised nature of the flow refraction. Good examples of tidal rectification originate from Ocean Surface Current Radar measurements over the Middelkerke Bank, which lies adjacent to the Kwinte Bank (Figure 1.) (Williams *et al*., 2000), and from shipborne ADCP measurements obtained across the Shambles Bank, in the English Channel (Bastos, Paphitis, and Collins, 2004). Following the approach of Bastos, Paphitis, and Collins. (2004), HM-ADCP data were used to identify deflection of the flow over the bank. Peak ebb and flood current velocities throughout the water column were transformed into perpendicular along-bank (positive towards the NE) and across-bank (positive towards the NW) components, and displayed in a 50 m horizontal- and 1 m vertical-resolution grid (Figure 8.). Acceleration of the across-bank component, together with retardation of the along-bank component over the bank, can be observed along some of the tracks. This flow pattern is consistent with tidal rectification over the bank, providing a mechanism for the convergence of sand towards the crest. Thus, a part of the maintenance processes of the bank can be described successfully by the sea bed stability model.

The (dredged) depression has been found to affect the short-term near-field hydro-sediment dynamics. The distinct orientation of the main axis of the tidal ellipses, over the depression (BM-ADCP) and at the crest (S4), suggests a channelisation of the peak (tidal) currents over the depression (Figure 4.). The veering of the crest of the very large dunes, inside the depression, is indicative of a persistent pattern, predominantly in the flood direction, in the long-term. Bellec *et al.* (this volume) support this interpretation, based upon morphological and sedimentological considerations. However, the differences in the observed tidal ellipses might relate to site effects, e.g. the position of the instrument with respect to the very large dunes; additional measurements, including moored current-meters together with swath bathymetry, are required to investigate this point. Besides, near-bed peak currents show, on occasions, specific flow patterns inside the depression; these are restricted to the depression, suggesting a local effect, as proposed by Degrendele *et al.* (this volume). For example, the across-bank component of the flood flow within the depression (Figure 8a.), is stronger near the bed than in the overlying cells. Moreover, the across-bank components of the peak ebb flow, inside and above the depression are in opposite directions (Figure 8c.). In both examples, the near-bed across-bank flow is enhanced towards the crest, in the trough. In this way, localised sediment transport may be significantly affected. Such flow patterns are not observed systematically in the records. Their significance in terms of net sediment transport and morphological evolution of the depression should be considered on the basis of a data set with a higher vertical resolution (i.e. < 1 m). Nonetheless, divergent net sand transport directions are predicted inside the depression (Figure 7.), indicating net erosion, over the tidal cycle studied. Since the depression has not recovered since extraction ceased (Degrendele *et al*., this volume), erosion induced by divergent net sand transport may be a persistent active process, inside the depression.

CONCLUSIONS

The processes which govern sandbank dynamics in the long-term are difficult to identify, on the basis of short-term hydrodynamic measurements. In the present study, tidally-averaged currents and residual sediment transport patterns are computed, for the Kwinte Bank, by using moored and shipborne current meter data. The results contribute to understanding the maintenance processes of the bank, and the near-field hydro-sediment dynamic impact of sand extraction, at this particular location.

The tidally-induced, short-term, sand transport pattern over the Kwinte Bank is characterised by sand convergence towards the crest of the bank. The location of the convergence zone varies, in the short-term, according to the prevailing tidal flow characteristics. Sediment transport over each flank of the bank is governed by a distinct phase of the tide. During peak flood and ebb flows, tidal rectification, in response to enhanced bed friction, provides a mechanism for the veering of sand towards the crest of the bank. As such, the sea bed stability model described by HUTHNANCE (1982a, b) accounts, at least partially, for the bank maintenance process.

The presence of the dredged depression affects, on a local basis, the short-term hydrodynamics and sediment transport patterns. The collected data support the concept of channelisation of peak tidal flows, at this particular location. In addition, within the depression, the cross-bank components of the peak near-bed currents are enhanced towards the crest of the bank. Divergent net sand transport is induced within the trough. Hence, the depression experienced net erosion over the tidal cycle considered. More data are needed to detail the structure of the flow within the trough, and to investigate the morphodynamic evolution of this feature over the long-term.

ACKNOWLEDGEMENTS

This study was undertaken as part of the EUMARSAND Research Training Network (European Sand and Gravel Resources: Evaluation and Environmental Impact of Extraction, HPRN-CT-2002-00222). The assistance of the officers and crew of the research vessel R/V *Belgica*, in collecting the data, is gratefully acknowledged. Thanks are extended to Dries Van den Eynde, for providing the meteorological data and to the Management Unit of the North Sea Mathematical Models (MUMM), for assistance during the field campaign and the use of the hull-mounted and bottom-mounted ADCP data. The University of Dunkerque is acknowledged for the deployment of the S4 current meter. Professor Michael Collins (NOCS, Southampton, U.K, and AZTI-Technalia, Spain) is thanked for his comments on early draft of the manuscript.

LITERATURE CITED

ASHLEY, G.M., 1990. Classification of large-scale subaqueous bedforms: a new look at an old problem, *Journal of Sedimentary Petrology*, 60(1), 60-172.

BASTOS, A.C.; PAPHITIS, D., and COLLINS, M.B., 2004. Short-term dynamics and maintenance processes of headland-associated sandbanks: Shambles Bank, English Channel, UK, *Estuarine Coastal and Shelf Science,* 59, 33-47.

BELDERSON, R.H.; JOHNSON, M.A., and KENYON, N.H., 1982. Bedforms. *In*: STRIDE, A.H. (ed.), *Offshore Tidal Sands: Processes and Deposits*. London: Chapman & Hall, 27-57.

BELLEC, V.; VAN LANCKER, V.; DEGRENDELE, K.; ROCHE, M., and LE BOT, S., this volume. Geo-environmental characterization of the Kwinte Bank. *Journal of Coastal Research*.

BERNÉ, S.; CASTAING, P.; LE DREZEN, E., and LERICOLAS, G., 1993. Morphology, internal structure and reversal of asymmetry of large subtidal dunes in the entrance to Gironde Estuary (France), *Journal of Sedimentary Research,* 65(5), 780-793.

BERNÉ, S.; TRENTESAUX, A.; STOLK, A.; MISSIAEN, T., and DE BAPTIST, M., 1994. Architecture and long-term evolution of a tidal sand-bank: the Middelkerke Bank (southern North Sea). *Marine Geology*, 121, 57-72.

BRIÈRE, C.; ROOS, P., and GAREL E., this volume. Modeling the morphodynamic effects of sand extraction on the Kwinte Bank. *Journal of Coastal Research*.

CASTON, V.N.D., 1972. Linear sand banks in the southern North Sea. *Sedimentology*, 18, 63-78.

DAVIS, J.C., 2002. *Statistics and data analysis in Geology, 3rd Edition*. New York: John Wiley & Sons, 646 p.

DELEU, S.; VAN LANCKER, V.; VAN DEN EYNDE, D., and MOERKERKE, G., 2004. Morphodynamic evolution of the kink of an offshore tidal sandbank: the Westhinder Bank (Southern North Sea). *Continental Shelf Research*, 24, 1587-1610.

DEGRENDELE, K.; ROCHE, M.; SCHOTTE, P.; VAN LANCKER, V.; BELLEC, V., and BONNE, W., this volume. Morphological evolution of the Kwinte Bank central depression before and after cessation of aggregate extraction. *Journal of Coastal Research*.

DE MOOR, G., 1986. Geomorfologisch onderzoek op het Belgisch Continental Plat. *Tijdschrift van de Belg. Ver. Aarddr. Studies BEVAS 2*, 133-174.

DYER, K.R. and HUNTLEY, D.A., 1999. The origin, classification and modeling of sand banks and ridges. *Continental Shelf Research*, 19, 1285-1330.

GADD, P.E.; LAVELLE, J.W., and SWIFT, D.J.P., 1978. Estimates of sand transport on the New York shelf using near-bottom current-meter observations. *Jour. Sed. Pet.*, 48(1), 239-252.

GAREL, E.; MANSO, F., and COLLINS, M.B., 2005. Hydrodynamics and sediment transport during a tidal cycle on the Kwinte Bank (Southern North Sea), *Proceedings of the 5th Conference of Coastal Dynamics* (Barcelona, Spain, ASCE), 135-136.

GRANT, W.D. and MADSEN, O.S., 1986. The continental shelf bottom boundary layer. *Ann. Rev. Fluid Mech.*, 18, 265-305.

HOUBOLT, J.J.H.C., 1968. Recent sediments in the Southern Bight of the North Sea. *Geologie & Mijnbouw*, 47(4), 245-273.

HUTHNANCE, J.M., 1982a. On one mechanism forming linear sandbanks, *Estuarine, Coastal and Shelf Science*, 14, 79-99.

HUTHNANCE, J.M., 1982b. On the formation of sandbanks of finite extent, *Estuarine, Coastal and Shelf Science*, 15, 277-299.

KENYON, N.H.; BELDERSON, R.H.; STRIDE, A.H., and JOHNSON, M.A., 1981. Offshore tidal sandbanks as indicator of net sand transport and as potential deposits. *In*: *Holocene Marine Sedimentation in the North Sea Basin 5*, (ed. Nio, S.D., Shuttenhelm, R.T.E., Van Weering, TC.E.), Blackwell Science, 257-268.

LANCKNEUS, J. and DE MOOR, G., 1991. Present-day day evolution of sandwaves on a sandy shelf bank in the southern Bigh, *Oceanologica Acta*, Vol. Sp. 11, 123-127.

LANCKNEUS, J.; DE MOOR, G.; DE SCHAEPMEESTER, G., and DE WINNE, E., 1992. Monitoring of a tidal sandbank: Evolution of bedforms, volumetric trends, sedimentological changes. *Hydro '92, Eight Biennial International Symposium of the Hydrographic Society* (Copenhagen, Denmark), 19 p.

LANCKNEUS, J. and DE MOOR, G., 1995. Bedforms on the Middelkerke bank, southern North Sea, *In*: *Tidal Signatures in Modern and Ancient Sediments* (ed. Flemming, B.W., Bartholoma, A.), Blackwell Science, 35-51.

LE BOT, S.; VAN LANCKER, V.; DELEU S.; DE BATIST, M.; HENRIET J.P., and HAEGEMAN, W., 2005. Geological and geotechnical properties of

Eocene and Quaternary deposits on the Belgian continental shelf: a synthesis. *Netherlands Journal of Geosciences*, 84(2), 147-160.

Li, M. Z. and Amos, C. L., 2001. SEDTRANS96: the upgraded and better calibrated sediment-transport model for continental shelves, *Computers & Geosciences*, 27, 619-645.

Neumeier, U.; Ferrarin, C.; Amos, C.L.; Umgiesser, G., and Li, M.Z. (in press). Sedtrans05: An improved sediment-transport model for continental shelf and coastal waters, including a new algorithm for cohesive sediments, *Computer & Geosciences*.

Pattiaratchi, C.B. and Collins, M.B., 1987. Mechanisms for linear sandbank formation and maintenance in relation to dynamical oceanographic observations. *Progress in Oceanography*, 19, 117-176.

Soulsby, R L., 1997. Dynamics of Marine Sands. London : Thomas Telford Publications, 249 p.

Stride, A.H., 1982. Offshore Tidal Sands. Process and Deposition. London: Chapman & Hall, 222 p.

Van Cauwenberghe, C., 1971. Hydrografische analyse van de Vlaamse banken langs de Belgische-Frans kust. *Ingenieurdtijdingen Blatt*, 20, 141-149.

Van den Eynde, D.; Giardino, A.; Portilla, J.; Fettweis, M.; Francken, F., and Monbaliu, J., this volume. Modelling the effects of sand extraction on the sediment transport due to tides on the Kwinte Bank. *Journal of Coastal Research*.

Van Lancker, V.; Deleu, S.; Bellec, V.; Le Bot, S.; Verfaillie, E.; Fettweis, M.; Van Den Eynde, D.; Francken, F.; Pison, V.; WartelL, S.; Monballiu, J.; Portilla, J.; Lanckneus, J.; Moerkerke, G., and Degraer, S., 2004. Management, research and budgeting of aggregates in shelf seas related to end-users (Marebasse), *Scientific Report Year 2*, Belgian Science Policy, 144 p.

Williams, J.J.; MacDonald, N.J.; O'Connor, B.A., and Pan, S., 2000. Offshore sand bank dynamics, *Journal of Marine Systems,* 24, 153-173.

Wright, L.D., 1995. Morphodynamics of Inner-Continental shelves. Boca Raton: Marine Science Series, CRC Press, 233 p.

Yalin, M.S., 1963. An expression for bedload transportation. *Jour. Hydraul. Div. Proc.* ASCE, 89, HY3, 221-250.

Zimmerman, J.T.F., 1981. Dynamics, diffusion and geomorphological significance of tidal residual eddies. *Nature*, 290, 549-555.

Journal of Coastal Research	SI	51	95-100	West Palm Beach, Florida	Summer 2010

Grain-Size Trend Analysis for the Determination of Non-Biogenic Sediment Transport Pathways on the Kwinte Bank (southern North Sea), in Relation to Sand Dredging

Serafim E. Poulos[1*] and Arnaud Ballay[1]**

[1] Department of Geography and Climatology
Faculty of Geology and Geoenvironment
National and Kapodistrian University of Athens
Panepistimioupolis, Zografou
15784 Athens, Greece
[*]poulos@geol.uoa.gr

[**] EcoPlage
100 route de Clisson F44200
Nantes. France

ABSTRACT

Grain-size trend analysis is applied to the determination of sediment transport pathways over the Kwinte Bank, southern North Sea; which had been subjected to intensive dredging, within the context of the environmental impact of dredging activities. On the basis of the results of grain-size trend analysis, focused mainly upon the transportation of the non-biogenic sedimentary material (<2 mm), it appears that: (i) there is a main sediment pathway over the western (bank crest) and central (dredged area) part of the bank directed toward the NE; whilst a secondary pathway is established over its eastern gently-sloping flank, having a SE direction. Further, the present analysis shows that the area of the central (dredged) depression acts more as a 'by-passing' zone rather than as a depo-centre for the non-biogenic sediments. Comparison undertaken with the results of an earlier investigation, for a non-dredged area at the northern end of the same bank, reveals that the depression due to dredging modifies significantly the sediment transport pathways; this may be attributed to a change in the seabed morphology which, in turn, modifies the near-bed hydrodynamics (related to tide and/or storm events).

ADDITIONAL INDEX WORDS: *linear sandbank, dredging effects, grain-size trend analysis, southern North Sea.*

INTRODUCTION

The establishments of sediment transport direction is one of the major concerns in the study of sedimentary systems within the marine environment. The analysis of spatial changes in grain-size parameters (mean, sorting and skewness) is one of the methods used for the identification of net sediment transport pathways. The initial studies undertaken focused upon variations of an individual parameter, such as mean grain-size (e.g. Pettijohn, Potter, and Siever, 1972). However, the use of a single parameter is not always diagnostic for sediment movement because, depending on the type of environment under consideration, grain-size parameters may increase or decrease down-drift. A major improvement in grain-size trend analysis was presented by McLaren (1981), who used a combination of the three main grain-size parameters: mean size, sorting and skewness. Subsequently, McLaren and Bowles (1985) developed a statistical treatment of the grain-size data, which provided a 1-D model of net sediment transport, as pathways. According to the McLaren model, although there are theoretically 8 possible combinations of the above-mentioned statistical parameters, only 2 combinations have a higher possibility of existing in natural environments, where sediment transport occurs in a downstream direction: (1) finer, better sorted and more negatively skewed; or (2) coarser, better sorted and more positively skewed. Subsequently, McLaren's method has been used with satisfactory results as in the case of the Severn Estuary (UK) (McLaren *et al.*, 1993), in a fjord of British Columbia (McLaren, Cretney, and Powys, 1993); this approach was eventually standarised, i.e. patented (McLaren, 2001).

Gao and Collins (1992) re-examined the basic assumptions of the grain-size trend analysis; they argued that, although the two cases described previously may be the dominant ones, the presence of other factors can cause a high level of noise using the 1-D approach. These investigators have shown further that some trends occur in the transport direction, with a higher frequency of occurrence than in any other direction. For comparison, in the McLaren method, it is assumed that in the transport direction only certain types of trends can occur, whilst others do not occur. Thus, these latter authors developed an analytical procedure for grain-size data, based on a semi-quantitative filtering technique; this incorporates an adequate significance test and uses the combined trend of the two main cases (Gao and Collins, 1991, 1992 and 1994a). This procedure results in the calculation of a 2-D residual pattern of transport vectors.

The present contribution presents a grain-size trend analysis, following the Gao and Collins (1992) procedure, for the Kwinte Bank in the Belgian part of the North Sea. This method was adopted, primarily, as it is widely-accepted and has produced good results in tidal environments; and, secondarily, due to the fact that it has also been applied previously and successfully in the case of the Kwinte Bank (Gao *et al.*, 1994). Within the context of the environmental impact of dredging activities, the present trend analysis is focused mainly upon

DOI: 10.2112 / SI51-009.1 received 17 January 2007; accepted in revision 5 October 2007.

the transportation of the non-biogenic sedimentary material, whose grain-sizes have been deduced from their settling velocities. The findings of the present study are discussed further, within the context of the existing knowledge of the hydrodynamics, whilst the effect of dredging is examined through comparison with earlier investigations undertaken on the Kwinte Bank (e.g. BELLEC *et al.*, this volume; GAREL, this volume; GAO *et al.*, 1994; LANCKNEUS, 1989; and VAN DEN EYNDE *et al.*, this volume).

THE STUDY AREA

The present investigation concerns one of the sandbanks located off the Belgian coast, i.e. the Kwinte Bank (Figure 1.); this is one of a series of NE-SW trending linear sandbanks. These banks are some 10-20 m in height, overlain by water depths of less than 10 m, over their shallowest parts. Superimposed upon these banks are N-NW / S-SE trending dunes (widths of several tens of metres and heights of up to 7 m) and megaripples, with spatially-variable asymmetric patterns. Such linear sandbanks are formed in an environment associated with strong currents. High-resolution reflection seismic surveys have revealed that the banks consist mainly of Holocene deposits, with the sands being supplied by the reworking of Tertiary and/or Pleistocene deposits (LIU, MISSIAEN, and HENRIET, 1992). The deposits lie on an erosional surface of Tertiary strata, whose upper layer is comprised mostly of gravely material. The formation of these sandbanks is related strongly to the existing hydrodynamic regime and, in particular, to the tidal currents and storm waves; the former reach mean surface speeds of between 0.9 ms^{-1} and 1.2 ms^{-1} offshore of the Belgian coast (HOWARTH and PROCTOR, 1992), whilst the latter can reach significant wave heights up to 5 m, with significant periods of 7 s (HOUTHUYS, TRENTESAUX, and DE WOLF, 1994). Thus, storm waves restrict the vertical growth of the Flemish Banks to water depths of less than 5 m (MLLWS).

The present investigation is focused upon the central part of the Kwinte Bank (Figure 2.), which includes an elongated depression (5 m deep, 700 m wide and 1 km long); this is the morphological result of intensive dredging identified in 1999, which subsequently lead to the decision of the Belgian Government, in 2003, to stop dredging for a period of at least 3 years, hoping to the regeneration of the bank.

The bank itself has an asymmetric morphology; its crest lies along its western flank, which deepens to the WSW, with slopes of up to 5%. The crest itself lowers from the SW to NE, with water depths on both sides being deeper than 10 m. The eastern flank of the bank slopes are more gently (1.5-3%), towards the SE. Over this area, bedforms, such as sand waves and megaripples, are present extensively; they are of various wavelengths, heights, orientations and asymmetrical patterns. These bedforms consist mainly of well-sorted sands (200-400 μm), with a very small gravel fraction (LANCKNEUS, 1989). A detailed morpho-sedimentological analysis of the study area is presented elsewhere (BELLEC *et al.*, this volume).

Some former studies undertaken into sediment transport pathways over the region have been undertaken; however, they were located over the northern part of this particular bank and did not include the central depression (GAO *et al.*, 1994; LANCKNEUS, DE MOOR, and STOLK, 1994; and VANWESENBEECK and LANCKNEUS, 2000). Analysis of the bed morphology indicates a general NE direction of sediment transport, coinciding with the direction of the flood currents (VANWESENBEECK and LANCKNEUS, 2000). The grain-size trend analysis, applied to the northern part of the Kwinte Bank, showed a similar direction for the western flank of the bank, whilst its eastern flank has a NW direction; this becomes SW, at water depths

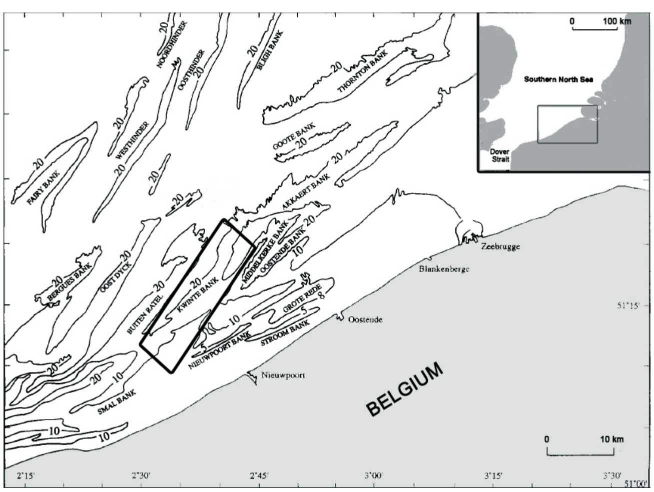


Figure 1. Geographical location of the Kwinte Bank, in relation to the North Sea (inset) and the Belgian Continental Shelf.

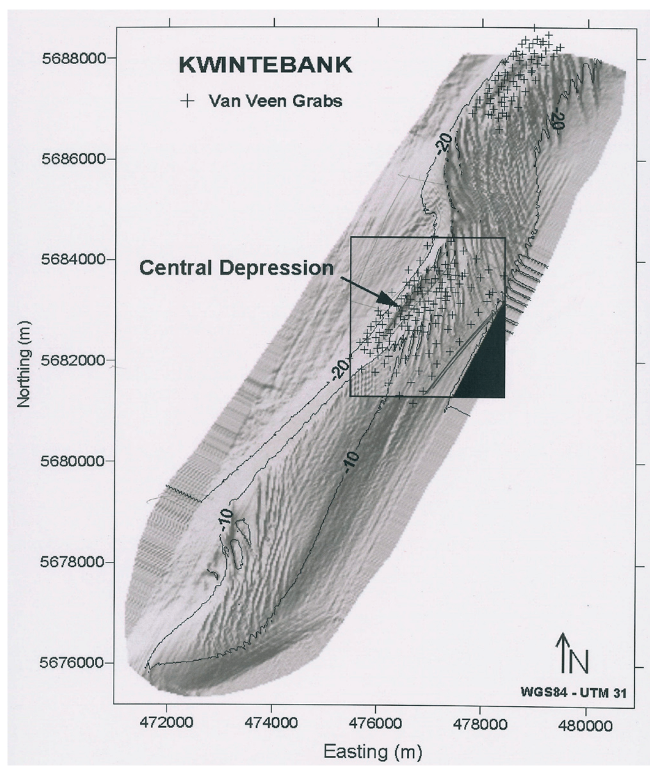


Figure 2. Morphological characteristics and sampling positions (for details, see text) of the Kwinte Bank.

of more than 20 m (Gao *et al.*, 1994). Differences between sediment transport directions given by the grain-size trend analyses, with those indicated by bedform morphometry (e.g. megaripples), may be attributed to their different spatial- and time-scales of operation. The former are influenced often by other local structural (geological) characteristics and, being the result of extreme events, occurred over a much longer period of time (tens to hundreds of years).

DATA COLLECTION AND METHODOLOGY

In September 2003 and February 2004, 120 samples (from the same locations) were collected with the use of a van Veen grab, during MAREBASSE / EUMARSAND campaigns (*R/V Zeeleeuw*). The interval between successive stations was 300 m on the edges of the grid and 150 m over the central dredged depression (Figure 2.).

The samples have been sub-sampled and analysed, following decarbonising with an HCl solution, in order to estimate and remove the biogenic fraction (the shell content), as the present investigation focuses upon the transport pathways of the non-biogenic sediment component. Moreover, the biogenic fraction of the sediment was removed for analytical reasons, i.e. to improve the accuracy of the grain-size trend analysis. The shell content incorporates usually a bimodal grain-size distribution, resulting in inaccuracy in the grain-size determination using settling velocities; its abundance on the sea floor is variable, depending upon localised benthic environmental conditions.

In addition, shell fragments are somewhat different from the quartz grains, in terms of their density and morphology; as such, they differ in terms of their settling, transport and sorting characteristics. Besides, shell fragments are not usually uniformely distributed over the seabed; they are more abundant in some areas, being rare in other; they follow not exclusively near-bed hydrodynamics, but also the local biologic production (benthic and/or neritic). Hence, the use of the bulk sediment would have introduced some additional differences into the sediment texture, related to sediment transport.

Following decarbonising, sediment samples were analysed, by means of a settling tower, to determine the settling velocities (Ws) of the individual particles; these, in turn, have been converted into equivalent sieve diameters, according to the Soulsby (1997) equations. Sediment grain-size fractions were identified according to the Wentworth classification (1922); their statistical parameters needed for the trend analysis method, i.e. mean grain-size, sorting, skewness, were calculated using statistical moment theory (Riviere, 1977).

For the determination of sediment transport pathways, using the statistical parameters of the grain-size analyses, the procedure described by Gao and Collins (1992) has been adopted. This method is based upon the relationship between spatial changes in grain-size trends and the residual transport directions. Thus, grain-size parameters are compared between pairs of sampling sites, considering the increase or decrease in three parameters: mean grain-size *(Mz),* sorting (σ_1) and skewness (S_k). Consequently, 8 cases are theoretically possible; of these, only 2 are representative of physical reality in non-extreme marine conditions (Gao and Collins, 1992; Gao and Collins, 1994a; and McLaren and Bowles, 1985). If transport takes place from Site 1 to Site 2, 2 cases can be valid, either *Case* 1: $\sigma_1 2 \leq \sigma_1 1$, $M_z 1 > M_z 2$, and $S_k 2 \leq S_k 1$ (in a downstream direction, sediment becomes finer, better sorted and more negatively skewed); or *Case* 2: $\sigma_1 2 \leq \sigma_1 1$, $M_z 2 > M_z 1$, and $S_k 2 \geq S_k 1$ (sediment becomes coarser, better sorted and more positively skewed). Notably, these two cases do not represent extreme environments, in which, for example, sediment is trapped or reworked intensively, or transport agents are not selective. For this reason, a three-step approach has been followed: the first step, as proposed by Gao and Collins (1992), consists of the verification that the two aforementioned cases are indeed valid for a study area (see below); the second step refers to the calculation of the three grain-size parameters (according to Folk, 1974), by means of the equations issued from the statistical moment theory (Riviere, 1977); and, finally, the third step incorporates the application of the computerised analytical procedure developed by Gao (1996), to the calculation of the transport vectors.

The Kwinte Bank is under the influence of tidal currents and oscillatory flows related to wave activity, which are selective transport agents; this means that the particle sorting, in all cases, increases in the downstream direction. Furthermore no sediment accumulation has been observed over the study area between 1992-1997 (Degrendele *et al.*, this volume), which is consistent with the relatively "homogeneous" grain-size distribution pattern. Therefore, the two aforementioned cases are expected to be representative of the local non-biogenic sediment transport, in the case of the Kwinte Bank area. Realising step 3 (see above), initially, a critical maximum distance *(Dcr)* has to be selected between two neighbouring sampling sites, whose grain-size parameters are compared. Thus, with the use of all sampling locations, contour maps for the grain-size statistical parameters of the area under investigation has been created; then, common data points have been re-sampled every 300 m, in order to produce a grid with even Dcr.

Subsequently, dimensionless "trend vectors" are drawn between every two sites (separated by Dcr), following the Gao and Collins (1992) procedure; this is based, for a single analysis, upon the consideration of the two types of transport occurring at the same time, i.e. a combination of Case 1 and Case 2. Finally, the following calculations are undertaken for each site: (1) the "resultant vector", which is the sum of the trend vectors; and (2) the "transport vector", calculated with the filtering procedure developed by Gao and Collins (1992, 1994a). This approach allows the resultant vectors from the neighbouring sites (e.g. within the Dcr), to be taken into account; this in turn, leads to the calculation of a weighted-average. Subsequently, these produce all the transport vectors of the pattern of the residual transport, which enables recognition of the main transport directions.

It should be noted that it is impossible to attribute any quantitative significance to the length of these composite transport vectors, without introducing a bias towards one of the grain-size parameters (Le Roux, 1994). Hence, with the use of the Gao and Collins (1992) method only the sediment transport pathways are determined and not the associated transport rates.

RESULTS AND DISCUSSION

The results of the application of the Gao and Collins (1992) procedure, applied to the results of both the sampling campaigns of September 2003 and February 2004, are presented in Figure 3. The analyses of the two series of samples generate generally similar results, which indicates the dominance of

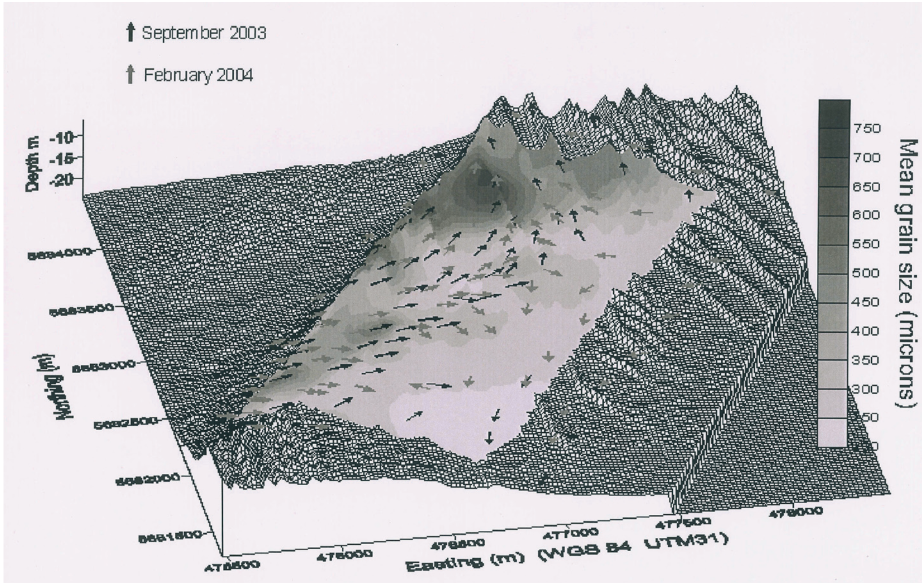


Figure 3. Transport patterns: September 2003 (black arrows) and February 2004 (grey arrows), shown in relation to the grain-size distribution over the sampled area (see Figure 2.).

relatively similar prevailing hydrodynamic conditions, either for a short period of time prior to the (two) campaigns and/or for the whole of the period between them.

Over the western part of the bank and, more specifically along its crest area and the western flank of its central depression (formed by dredging), the transport vectors have a NE orientation, indicating sediment transport towards the depression. Here, the bed material is composed of heterogeneous medium to coarse shelly sand (shell content 40-55%) (Bellec *et al.*, this volume). On the other hand, this vector direction is in accordance with the main axis of the observed large bed forms, i.e. the elongated subaqueous dunes. Further, it should be noted that the direction of the vectors become progressively NNE towards the northern part of the study area; finally, they are directed northwestwards, at its northern limit. Here, the crest of the bank is higher and the bank itself bends, with its elongated axis being directed towards the North.

Within the lower (southern) and middle part of the dredged area, the sediment transport vectors derived from both campaigns indicate a general NE direction of sediment transport; at its northern part, the sediment transport pathways are directed towards the NNE. Once again, this change may be associated with the orientation of the existing mega-bedforms (e.g. sand waves) and the morphology of the Kwinte Bank. Nevertheless, the artificially-made depression appears to act as a sediment transport pathway, rather than being a depo-centre. Here, the sediment are more homogeneous (Mz≈400 μm and 10-40% shell fraction; Bellec *et al.*, this volume). This interpretation is in accordance with the findings of Degrendele *et al.* (this volume), who state that over a period of 8 years (1992-1999), no significant morphological changes can be identified. Furthermore, this pattern is in accordance with the observed currents acting over the area (Van den Eynde *et al.*, this volume), which permit the transport of these coarse and shelly sediments. Overall, it appears that sediment is transported from the crest, towards the eastern flank of the bank, despite the presence of the dredged depression.

The gently-sloping eastern flank of the bank, characterised by homogeneous fine to medium sand with a shell fraction generally <20% (Bellec *et al.*, this volume), presents a transport pattern that could be distinguished into two sub-regions: (a) a northern one, where the vectors are directed towards the NNW; and, (b) a central/southern one, where vectors are more or less directed southerly.

Some vectors located at the boundary of the study area may show various orientations and directions; however, they have not been incorporated into the analysis, having been attributed to the 'edge effect'. Transport vectors on the edge of the grid use less neighbour points, for their calculation (Gao and Collins, 2001). The latter limitation would explain also some differences in direction along the east boundary of the study area, between the September 2003 and February 2004 results.

In terms of the prevailing tidal regime, the sediment transport pathways of the surficial non-biogenic (<2 mm) material of the western side (crest and depression) of the bank appear to be controlled by the flood phase of the tide, whilst its eastern flank by the ebb tide; this is in accordance to the residual flows identified by Garel *(this volume)*. Moreover, the derived transport pathways do not coincide with the mean flood/ebb directions, as they are influenced also by the presence of bedforms and, more specifically, by the presence of asymmetrical dunes (wavelengths >30 m) and megaripples (wavelength of 5-10 m) (Lanckneus *et al.*, 1993). Furthermore, the influence of wave activity, under storm conditions and, particularly for the crest region of the bank, could not be excluded. For example, in the case of similar sandbanks in the Bristol Channel (UK), it has been established that the height of the banks is controlled by the storm conditions (Britton and Britton, 1980). The latter observation is a matter for further investigation, relating to the combined effect of storms and tides.

Finally, if the findings of the present investigation are compared to those produced previously by Gao *et al* (1994), for the northern end of the Kwinte Bank (where sediment pathways are directed towards its crest, having an E-ESE direction along its steep western flank and NW along its eastern more gentle flank), on the assumption that the whole body of the bank is subjected to the same hydrodynamic (tidal) regime, then it may be concluded that the presence of the depression (due to dredging) has modified significantly the near-bed hydraulic regime (Garel, this volume). This regime now favours the transport of sediment from the crest over the bank, towards its eastern flank. The pattern is in accordance with the observations made by Degrendele *et al.* (this volume), where an overall lowering of the height of the bank (by ca. 0.5 m) has been identified, between 1992 and 1999.

CONCLUSIONS

On the basis of grain-size trend analysis, the residual transportation pattern reveals that, on the western steeper slope and within the central depression of the bank, the principal transport pathway of the non-biogenic sandy material is directed towards the northeast. Further, it can be assumed that the relatively coarse (>500 μm) and less well-sorted (>1.2) sediment, within these two sedimentary provinces, are associated with erosion (and/or transportation) during the flood phase of the tide. However, wave action should not be excluded from the analysis. Over the eastern gently sloping part of the bank, characterised by medium sized (250-500 μm) sediments, an overall southerly transport pathway is identified; this is induced, most probably, by the ebb currents; although these are weaker, they last longer and, as such, provides improved sorting (<1.0) of the sediments. In addition, the presence of the bedforms and the overall size of the bank appear to control the sediment transport pathways. Finally, the presence of the central depression appears to act as a 'by-passing' zone, rather than as a depo-centre for sediments.

ACKNOWLEDGEMENTS

This study has been undertaken in accordance with the research objectives of the project EUMARSAND ("European Marine Sand and Gravel Resources: Evaluation and Environmental Impact of Extraction", Contract No. HPRN-CT-2002-00222). The authors thank Sophie Le Bot and Wendy Bonne for organising and performing the sampling campaigns, with the assistance of Samuel Deleu, Els Verfaillie, Andrew Symonds and Déborah Idier. The authors thank Michael Collins, Xaris Plomaritis and Erwan Garel for their help during the grain-size analyses, at the School of Ocean and Earth Science in the University of Southampton. Thanks are extended also to Vera Van Lancker and Valérie Bellec, for the information provided and their constructive comments.

LITERATURE CITED

Bellec, V.; Van Lancker V.; Degrendele K.; Roche R.; Schotte P., and Le Bot S., this volume. Geo-environmental characterisation of the Kwinte Bank. *Journal of Coastal Research*,

Britton R.C. and Britton S.R., 1980. Sedimentary bed forms and linear banks. *In*: Collins, M.B.; Banner, F.T.; Tyler, P.A.; Wakefield, S.J., and James, A.E. (eds.), *Industrialised Embaymants and their Environmental Problems. A case study for Swansea Bay*. Pergamon Press, 177-191

Degrendele, K.; Roche, M.; Schotte, P.; Bellec, V., and Van Lancker, V., this volume. Morphological evolution of the Kwinte Bank central depression after its closure. *Journal of Coastal Research*,

Folk, P.L., 1974. *Petrology of Sedimentary Rocks*. Austin, Texas: Hemphill Publishing Company, 183 p.

Garel, E., this volume. Hydrodynamics and bedload transport, during a tidal cycle (derived from ADCP measurements), across the Kwinte Bank. *Journal of Coastal Research*,

Gao, S. and Collins, M., 1991. A critique of the "McLaren Method" for defining sediment transport paths. *Journal of Sedimentary Petrology*, 61, 143-146.

Gao, S. and Collins M., 1992. Net Sediment transport patterns inferred from grain-size trends, based upon definition of transport vectors. *Sedimentary Geology*, 81(1/2), 47-60

Gao, S. and Collins, M., 1994a. Analysis of grain-size trends, for defining sediment transport pathways in marine environments. *Journal of Coastal Research*, 10(1), 75-78.

Gao, S. and Collins, M., 1994b. Net sediment transport patterns inferred from grain-size trends, based upon definition of "transport Vectors" reply. *Sedimentary Geology*, 90, 171-185.

Gao, S.; Collins M.; Lanckneus J.; De Moor G., and Van Lancker V., 1994. Grain-size trends associated with net sediment transport patterns: An example from the Belgian continental shelf. *Marine Geology*, 121, 171-185

Gao, S., 1996. A fortran program for grain size trend analysis to define net sediment transport pathways. *Computers & Geosciences*, 22(4), 449-452.

Gao, S. and Collins M., 2001. The use of grain-size trends in marine sediment dynamics: a review. *Chinese Journal of Oceanology and Limnology*, 19(3), 265-271.

Howarth, M.J. and Proctor, R., 1992. Ship ADCP measurementsand tidal models of the North Sea. *Continental Shelf Research*, 12, 601-623

Houthuys, R.; Trentesaux, A., and De Wolf, P., 1994. Storm influences on a tidal sandbank's surface (Middelkerke Bank, southern North Sea). *Marine Geology*, 121, 23-41

Lanckneus, J., 1989. A comparative study of some characteristics of superficial sediments on the Flemish Banks. Int. Coll. Quat. Tert. Geology Southern Bight, North Sea, May 1984. *Ministry of Economic Affairs-Belgian Geological Survey*, 29-241.

Lanckneus, J.; De Moor, G.; De Schaepmeester, G.; Meyus, I., and Spiers, V., 1992. Residual sediment transport directions on a tidal sandbank. *In*: *Comparison of the "McLaren Model" with bedform analysis*. Bull. Belg. Ver. Aardr. Stud. (BEVAS) 2, pp. 425–446.

Lanckneus, J.; De Moor, G.; Van Lancker, V., and De Schaepmeester, G., 1993. The use of the McLaren model for the determination of residual transport directions on the Gootebank, southern North Sea: *Progress in Belgian Oceanographic Research*. Institute of Marine Research and Air Sea Interaction (IRMA), Vol. 1, pp. 75–94.

Lanckneus, J.; De Moor, G., and Stolk, A., 1994. Environmental setting, morphology and volumetric evolution of the Middelkerke Bank (southern North Sea). *Marine Geology*, 121(1-2), 1-21.

Le Roux, J.P., 1994. An alternative approach to the identification of net sediment transport paths based on grain-size trends. *Sedimentary Geology*, 94, 97-107.

Liu, A.C.; Missiaen, T., and Henriet, J.P., 1992. The morphology of the top-Tertiary erosion surface in the Belgian sector of the North Sea. *Marine Geology*, 105, 275-284.

McLaren, P.A., 1981. Interpretation of trends in grain-size measurements. *Journal of Sedimentary Petrology*, 51, 611-624.

McLaren, P.A. and Bowles, D., 1985. The effects of sediment transport on grain-size distributions. *Journal of Sedimentary Petrology*, 55(4), 457-470.

McLaren, P., 2001. Sediment Trend Analysis (Sta (R)). *Sea Technology*, 42(3): 10-14.

McLaren, P. and Bowles, D., 1991. A Critique of the Mclaren Method for Defining Sediment Transport Paths - Reply. *Journal of Sedimentary Petrology*, 61(1), 147.

McLaren, P.; Collins, M.B.; Gao, S., and Powys, R.I.L., 1993. Sediment Dynamics of the Severn Estuary and Inner Bristol Channel. *Journal of the Geological Society*, 150, 589-603.

McLaren, P.; Cretney, W.J., and Powys, R.I., 1993. Sediment Pathways in a British-Columbia Fjord and Their Relationship with Particle-Associated Contaminants. *Journal of Coastal Research*, 9(4), 1026-1043.

Pettijohn, F.G.; Potter P.D., and Siever, R., 1972. *Sand and Sandstone*. New York: Springer, 618 p.

Riviere, A., 1977. Methodes Granulometriques; Techniques et Interpritations. *In*: Masson, N. Paris (1977), 170p.

Soulsby, R., 1997. *Dynamics of marine sands: a manual for practical applications*. London: Thomas Telford, 249 p.

Van den Eynde, D.; Giardino, A.; Portilla, J.; Fettweis, M.: Francken, F., and Monbaliu, J., this volume. Modelling the effects of sand extraction on the sediment transport due to tides on the Kwinte Bank. *Journal of Coastal Research*,

Vanwesenbeeck, V. and Lanckneus, J., 2000. Sediment transport paths on a tidal sand bank: a comparison between the modified McLaren model and bedform analysis. *Journal of Sedimentary Research*, 70(3), 470-477.

Journal of Coastal Research	SI	51	101-116	West Palm Beach, Florida	Summer 2010

Modelling the Effects of Sand Extraction, on Sediment Transport due to Tides, on the Kwinte Bank

Dries Van den Eynde[1], Alessio Giardino[2*], Jesùs Portilla[2], Michael Fettweis[1], Frederic Francken[1] and Jaak Monbaliu[2]

[1] Royal Belgian Institute of Natural Sciences
Management Unit of the North Sea
Mathematical Models
Gulledelle 100
B-1200 Brussels
Belgium
D.VandenEynde@mumm.ac.be

[2] Katholieke Universiteit Leuven
Faculty of Engineering – Civil Engineering Department
Hydraulics Laboratory
Kasteelpark Arenberg 40
K.U.Leuven Postbus 2448
B-3001 Heverlee
Belgium

[*] Present address: Deltares
Unit Marine and Coastal Systems
Department of Morphology and Coastal Systems,
Rotterdamseweg 185, 2600 MH, Delft
The Netherlands.

ABSTRACT

In recent years, the exploitation of marine aggregates is increasing. As an example, on the Belgian continental shelf, one particular sandbank (the Kwinte Bank) is exploited extensively; this has led to the creation of a 5 m deep depression along its central part. In the present contribution, the influence of these bathymetric changes, on erosion and sedimentation patterns are studied, using numerical modelling, in order to obtain an initial impression of the effect of such intense sand extraction on the stability of the sandbank. Different numerical models are utilised. Two-dimensional and three-dimensional hydrodynamic models have been used to derive currents, whilst third generation wave models have been used to simulate the waves. Two different models are presented, which calculate the total load sediment transport as a function of the local currents and waves. These models have been used to investigate the erosional and depositional patterns. The use of two different sediment transport models has some advantages, since the results of sediment transport models are still subject to some important uncertainties. The hydrodynamic model results are validated using ADCP current data, confirming the good performance of the models. Likewise the wave models provide good results, comparing their results with data from a buoy. The sediment transport model results were compared to the residual transport patterns, derived from the asymmetry of dunes. The results obtained seem to be in general agreement with these observations. The numerical models are used to simulate the response of the sediment transport to extensive sand extraction from the sandbank. One 'worst-case' scenario and two more realistic scenarios were simulated, whilst the effect of these bathymetric changes on sediment transport was studied. The results show that the intense sand extraction does not seem to influence extensively the stability of the sandbank, but that, as a consequence, there is less erosion and deposition. The model results show, for all of the scenarios, a small amount of deposition on the top of the sandbank; this could be an indication of a regeneration mechanism. A trench, created perpendicular to the crest of the sandbank, could be slowly refilled again. The time-scale of this regeneration and the influence of storms remain uncertain. Although the main emphasis of the paper relates to tidal forcing, a brief discussion is included on the influence of wave action, on sediment transport.

ADDITIONAL INDEX WORDS: *Sandbank, sand extraction, morphological evolution, numerical modelling, Southern North Sea*

INTRODUCTION

The demand for marine sand in Europe is increasing. In 2004, Europe produced around 53 million m^3 sand and gravel of marine origin (ICES, 2005). Since 1980, the winning of marine aggregates under the Belgian jurisdiction has almost quadrupled, to about 3 million tonnes (or 1.9 million m^3) each year. Up until September 2004, the extraction was undertaken in two large exploitation zones: (a) around the Thornton Bank and the Goote Bank; and (b) around the Kwinte Bank, Buitenratel and Oostdyck. More than 80 % of the extraction takes place on the Kwinte Bank, concentrated upon a small section along the northwestern and central part of the sandbank. Over the central part of the bank, this has resulted in the formation of a depression lying about 5 m below the original sea floor, about 700 m wide and 1 km long: this is the so-called Central Depression (Degrendele, Roche and Schotte, 2002).

The effects of this intense extraction of marine aggregates are only poorly known. The extraction has changed significantly the shape, volume and height of the sandbank. However, this altered morphology could also influence the current and wave patterns in the coastal waters, with possible implications on erosion of the coasts. To permit the study of the regeneration potential of the banks and the possible effects of intensive extraction on the sandbank, the depression zone was closed for exploitation (by the Government) in February 2003, for at least three years. The objective was to set-up reliable practical criteria for the maximum quantity of sand that can be extracted, without altering the long-term stability of the sandbank.

Research undertaken by Rijkswaterstaat, within the framework of the PUNAISE project, indicated that the surficial sediment structure and the bottom morphology over the exploitation zone near IJmuiden was rehabilitated after 15 months (Hoogewoning and Boers, 2001). In contrast,

DOI: 10.2112 / SI51-010.1 received 14 January 2007; accepted in revision 15 August 2008.

Rijkswaterstaat showed (within the framework of the SANDPIT project) that in a sand extraction pit near Hoek van Holland, of 10 m in depth, no clear infill was measured over a period of one year (Svašek, 2001). Elsewhere, a project undertaken by CEFAS, on the U.K. continental shelf, showed that the recovery of abandoned exploitation areas extended over 4 years or more. In Area 222 in the southern North Sea, a heavily exploited area, traces of the exploitation were still visible after 9 years (Boyd *et al.*, 2004). However, the CEFAS study is on gravelly areas of the seabed.

In this contribution, numerical models are used to study the influence of sand extraction on sand transport and stability of the bank. Two different sets of models have been used. In relation to sediment transport modelling, it is useful to compare the results of different models, since these can vary over several orders of magnitude, depending upon the transport formulae used. By comparing different model results, a more balanced interpretation can be gained of the actual sediment transport.

Initially, the present situation is modelled, with the results for currents, waves and sediment transport compared to measurements, for validation purposes.

These models have been used then to examine changing patterns of currents, waves and sediment transport, in response to changes in the bathymetry of the Kwinte Bank. Three different scenarios were studied: (a) a 'worst-case', where the bank is removed at 15 m below mean sea level (MSL), *i.e.,* lowering the entire bank by more than 3 m, on average; (b) intensive sand extraction at a particular place, resulting in the generation of a trench; and (c) with the same amount of sand being extracted, but over a larger area of the Kwinte Bank, resulting in a mean deepening of the bathymetry, by almost 30 cm. The latter 2 scenarios can be used to make recommendations regarding the most suitable way to extract sand.

Initially, some general information on the Kwinte Bank is provided. Subsequently, the hydrodynamics on the Kwinte Bank are discussed. Different numerical models are then

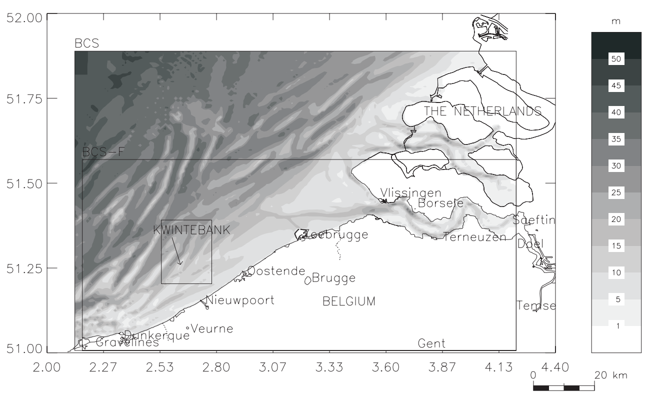


Figure 1. Bathymetry of the Belgian coastal waters. The large rectangle indicates the extension of the coarse BCS model grid, the middle-sized rectangle the extension of the fine BCS-F model grid. The smallest rectangle provides an indication of the location of the Kwinte Bank.

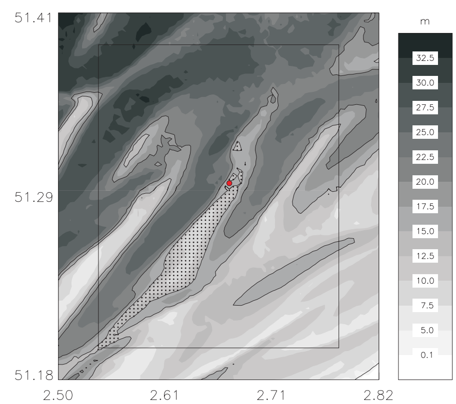


Figure 2. Detailed bathymetry (relative to MSL) of the Kwinte Bank. The rectangle is the area over which the model results are presented. The area shaded with small dots indicate the grid cells that are considered part of the Kwinte Bank and that have a depth less then 15 m with respect to MSL. The larger dot gives the location of the Central Depression (see text). Bathymetric contours are shown for 15 m and 20 m, below MSL.

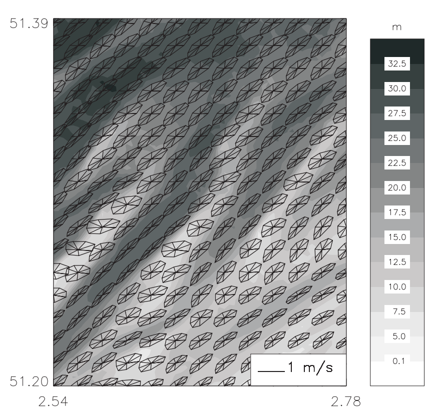


Figure 3. The bathymetry (relative to MSL) and current ellipses along the Kwinte Bank.

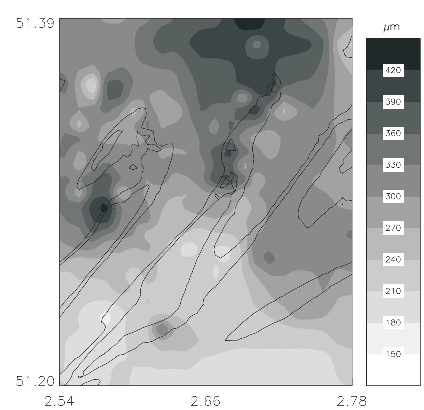


Figure 4. Median grain size of the Kwinte Bank, as used in the MU-SEDIM model. Bathymetric contours are shown for 15 m and 20 m, below MSL.

presented briefly, whilst validation of the model results is discussed. Following a description of 2 sediment transport models, their results (tide-only) are compared in relation to sediment transport pathways, derived from dune asymmetries. Likewise, the results of the numerical models for the three different scenarios are discussed, whilst wave influence on sediment transport is briefly addressed.

BACKGROUND INFORMATION

The Kwinte Bank is one of the Flemish Banks, located on the Belgian continental shelf (Figure 1). The bank is generated by tidal currents off the Belgian coast and is oriented in a SW-NE direction. The bank has a length of about 15 km, with a width varying from 2 km in its southern part, to 1 km in its northern part (Figure 2). The minimum water depth lies close to 7.5 m below MSL. Over the northern part, large dunes are present, with a maximum amplitude of around 8 m. Sand dunes are present also over the middle part of the bank; these can reach 2.5 m in height. The cross-section of the bank is clearly asymmetrical, with the steeper side facing towards the northwest.

The depth-averaged current ellipses over the Kwinte Bank region (Figure 3) typically vary depending upon their location, *i.e.,* in the swale or on the top of the sandbank. The ellipses are more spherical on the sandbanks, than in the deeper swales between the sandbanks. In the swales, the major axes of the ellipses lie nearly in the same direction as the swale/sandbank axis. However, on the sandbank, the major ellipse axes are rotated clockwise, in comparison to the bank axis. The maximum currents are around 0.9 to 1.0 m/s, on the top and the western side of the Kwinte Bank during a spring tide; they are around 0.4 to 0.5 m/s, during a neap tide.

The Kwinte Bank is characterized by fine to medium-sized sand (Figure 4). Over the southern part of the bank, sand of 180 to 240 μm is found; over the middle and the northern part, coarser sediment (of up to about 400 μm) is found. The Figure was derived on the basis of samples collected over the area, acquired by different institutes and obtained from the Belgian Marine Data Centre (BMDC). A method based upon weighted distance was used to interpolate the values for the model grid (Fettweis and Van den Eynde, 2000).

HYDRODYNAMICS

Hydrodynamic Models

Model BCS-F

The three-dimensional hydrodynamic model COHERENS (Luyten *et al.*, 1999) calculates currents and water elevations under the influence of the tides and the prevailing atmospheric conditions. This model was developed, between 1990 and 1998, within the framework of the EU-MAST projects PROFILE, NOMADS and COHERENS. The hydrodynamic model solves the momentum and continuity equations, using the 'mode-splitting' technique. COHERENS has different turbulence schemes, including the two-equation k-ε turbulence model, as used in the present study. The description of turbulence is important, when simulating the vertical current profile.

The model is implemented on the basis of two coupled grids. The coarse grid model BCS has a resolution of 42.86" in longitude (817 – 833 m) and of 25" in latitude (772 m); it has 20 layers, equally spaced over the vertical. This model provides the open sea boundaries for the fine grid BCS-F model, which has a three times higher resolution*, i.e.,* a resolution of about 275 m to 257 m, and 10 equally spaced layers over the vertical. The extension of both of the models is shown in Figure 1. On its open sea boundaries, the BCS model is coupled with two regional models. The CSM model encompasses the Northwest European Continental Shelf and calculates boundary conditions for the North Sea model (NOS). The NOS model generates boundary conditions for the BCS model. The CSM model runs in two dimensions and is driven by the elevation at the open boundaries, governed by four semi-diurnal and four diurnal harmonic constituents (Q_1, O_1, P_1, K_1, N_2, M_2, S_2, K_2). The NOS model runs in all three dimensions. All of the hydrodynamic models can take atmospheric influences into account.

Atmospheric data (wind speed, at 10 m height above sea level, together with atmospheric pressure) were obtained from the United Kingdom Meteorological Office. The data are available at a 6 h interval, on a 1.25° latitude/longitude grid. A spatial interpolation was then performed, to obtain them for the computational mesh. A linear interpolation, over time, was undertaken to calculate wind speed and pressure at each time step (Van den Eynde, Scory, and Malisse, 1995).

The BCS model was validated extensively using about 400 hours of current profiles; these were collected in the Belgian coastal zone, using a bottom-mounted Acoustic Doppler Current Profiler (ADCP), Sentinel 1200 kHz Workhorse type, from RDInstruments (Pison and Ozer, 2005, Van Lancker *et al.*, 2004). Statistical calculations (root-mean-square-error (RMSE), bias, correlation) were carried out in order to establish differences in magnitude and direction of the currents, between the model simulation results and the ADCP measurements. The RMSE of the amplitude of the currents was generally around 0.05 and 0.15 m/s, representing an relative error of about 10 % to 15 %; this varied only slightly, with depth. The error on the current direction was usually less than 20°. Thus, the validation exercise leads to the conclusion that the magnitude and direction of the current profiles are well represented by the three-dimensional hydrodynamic model.

Model TELEMAC-2D

The two-dimensional finite element hydrodynamic model TELEMAC-2D (v. 5.5) (Hervouet and Bates, 2000) was implemented on a mesh which was constructed using four different bathymetries. The large scale topography was taken from the Northeast Atlantic model, developed by Flather (1981) covering the region from 47°50'N to 71°10'N, and from 12°15'W to 12°15'E. Two intermediate bathymetries were extracted from sea-charts and corrected by Yu *et al.* (1990). The high-resolution bathymetry corresponds to the fine model BCS-F (see above). Based upon these data sets, a computational mesh was established with a node distance ranging between 70 km and 150 m on the Kwinte Bank.

At the open boundary, tidal elevation has been used as the only external forcing of the model. The same 8 constituents as for the CSM model (see above) represented the tidal forcing of the modelled region. The same atmospheric forcing was used as for the BCS-F model. A description of the model implementation is given in Giardino and Monbaliu (2004).

Table 1. *Measurements undertaken at the Kwinte Bank, with bottom-mounted ADCP. Key: Lat. - latitude in degrees North; Lon. - longitude in degrees East; Dep. - water depth referred to MSL; Dur. - duration of the measurements; Pres. - mean atmospheric pressure; and Wsp. - mean wind speed.*

Campaign	Lat.	Lon.	Dep.	Start	Dur.	Pres. (mbar)	Wsp. (m/s)
2003/15	51º18.144'	2º40.24'	16.3	11/06/03 16h30	25 h	1020	2.85
2004/04-05	5º18.151'	2º40.245'	16.3	02/03/04 12h45	216 h	1025	5.27

Table 2. *RMSE of the U-component (RMSE U), RMSE of the V-component (RMSE V) and RMSE of the norm of the depth-averaged current (RMSE C) for the BCS-F and the TELEMAC-2D model.*

		BCS-F			TELEMAC-2D		
Campaign	#	RMSE U (m/s)	RMSE V (m/s)	RMSE C (m/s)	RMSE U (m/s)	RMSE V (m/s)	RMSE C (m/s)
2003/15	39	0.140	0.119	0.127	0.279	0.145	0.215
2004/04-05	421	0.069	0.083	0.072	0.173	0.089	0.154

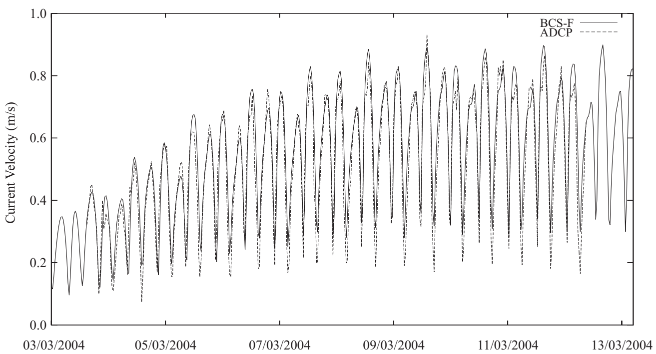


Figure 5. Measured (ADCP) and modelled (BCS-F) depth-averaged currents for the campaign 2004/04-05 on the Kwinte Bank (2°40.245' E, 51°18.151' N).

Validation on the Kwinte Bank

During two R.V. *Belgica* campaigns, measurements were undertaken on the Kwinte Bank with a bottom-mounted Acoustic Doppler Current Profiler (ADCP), Sentinel 1200 kHz Workhorse type, from RDInstruments. The sampling interval was set at 300 s. The profiles were taken with a vertical resolution of 0.5 m, with a maximum of 30 measurements over the profile. The first campaign covered a period of only a single day; however, during the second, measurements were made over a 9 day period. Calm weather conditions occurred during both periods, with mean wind speeds of 2,85 m/s (2 Bft.) and 5.27 m/s (3 Bft.) during the first and second campaigns respectively. More information on the position and timing of the measurements is listed in Table 1.

The two periods have been simulated with the BCS-F and the TELEMAC-2D model and compared with the available ADCP measurements. As an example, the depth-averaged

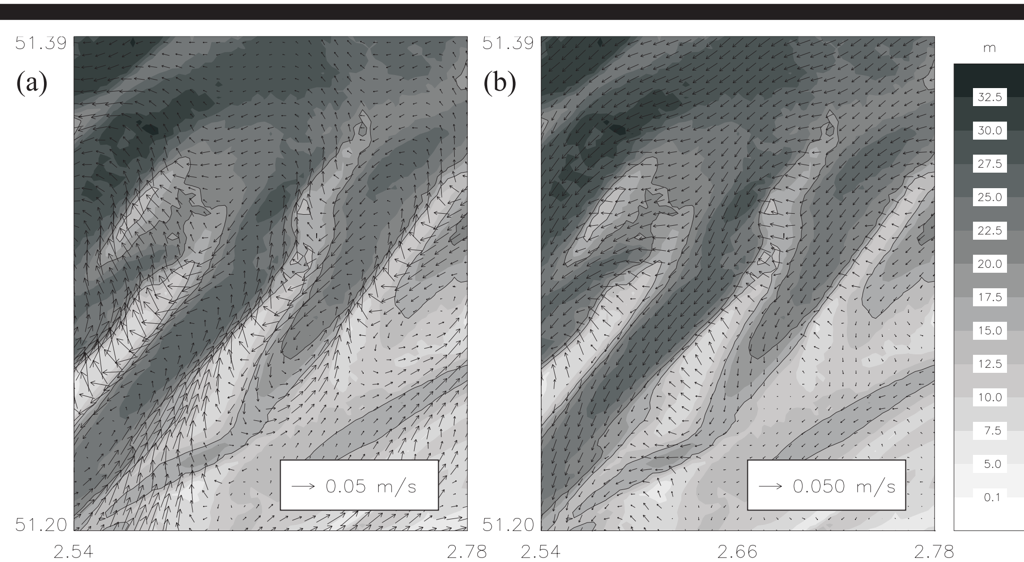


Figure 6. Tidally-induced residual currents on the Kwinte Bank for the period March 2nd 2004 6h30 – March 17th 2004 0h00, *i.e.*, a spring-neap cycle. In the background the bathymetry is shown. (a) Results of BCS-F, with one vector for each four grid points shown. (b) Results of the TELEMAC-2D model, with the results being on the same grid as the BCS-F model. Bathymetric contours are shown for 15 m and 20 m, below MSL.

current speeds for the 2004/04-05 campaigns, as modelled with the BCS-F model, together with the ADCP measurements, are presented in Figure 5.

The root-mean-square-errors (RMSE) are presented in Table 2. For the March 2004 period, the RMSE of the magnitude of the depth-averaged currents calculated by the BCS-F model is around 0.072 m/s, which is clearly satisfying. The higher RMSE for the TELEMAC-2D model are the result of a small time shift in the results, especially for the U-component of the depth-averaged current. When only taking the minima and the maxima of the depth-averaged currents into account, the RMSE for the TELEMAC-2D model are much smaller, around 0.05 m/s for the U- and the V-component for the 2004/04-05 campaigns.

Residual Currents

Both models were used to calculate the depth-averaged residual currents, during a spring-neap tidal cycle (14.8 days). The depth-averaged residual currents are defined as the vectorial mean of the depth-averaged currents at the grid points of the model over a period:

$$\overrightarrow{u_{res}} = \frac{\sum_n \vec{u}}{n} \qquad (1)$$

with $\overrightarrow{u_{res}}$ the depth-averaged residual current, $\vec{u}$ the depth-averaged current and n the number of depth-averaged currents, used in the derivation. The results of the BCS-F and the TELEMAC-2D model are presented in Figure 6.

The residual currents, calculated by the BCS-F model (Figure 6a) show anti-clockwise gyres centred in the swales near the sandbanks. On the western flank of the Kwinte Bank, the residual currents follow the bank towards the northeast (flood-direction); on the eastern flank, they are in the opposite direction, *i.e.*, to the southwest, in the ebb-direction. At the northern crest of the bank and in the Central Depression, the residual currents lie perpendicular to the bank crest and are ebb-dominated, flowing towards the west. The residual currents, calculated by the TELEMAC-2D model (Figure 6b) show a more uniform residual current pattern with residuals, over the bank, to the northwest.

SEDIMENT TRANSPORT DUE TO TIDES

Sediment Transport Models

Model MU-SEDIM

The sediment transport model MU-SEDIM has been implemented on the same grid as the hydrodynamic model BCS-F; it calculates the total sediment load under the influence of the local hydrodynamic conditions.

The current bottom stress, an important driving force, is a function of the depth-averaged current velocity and of the Nikuradse bottom roughness. For the calculation of the Nikuradse bottom roughness, a distinction has to be made between the skin friction and the total friction. The skin friction is the roughness, experienced by the sediments at the bottom. In this model, the expression of Engelund and Hansen (1967) has been used to calculate the skin bottom roughness.

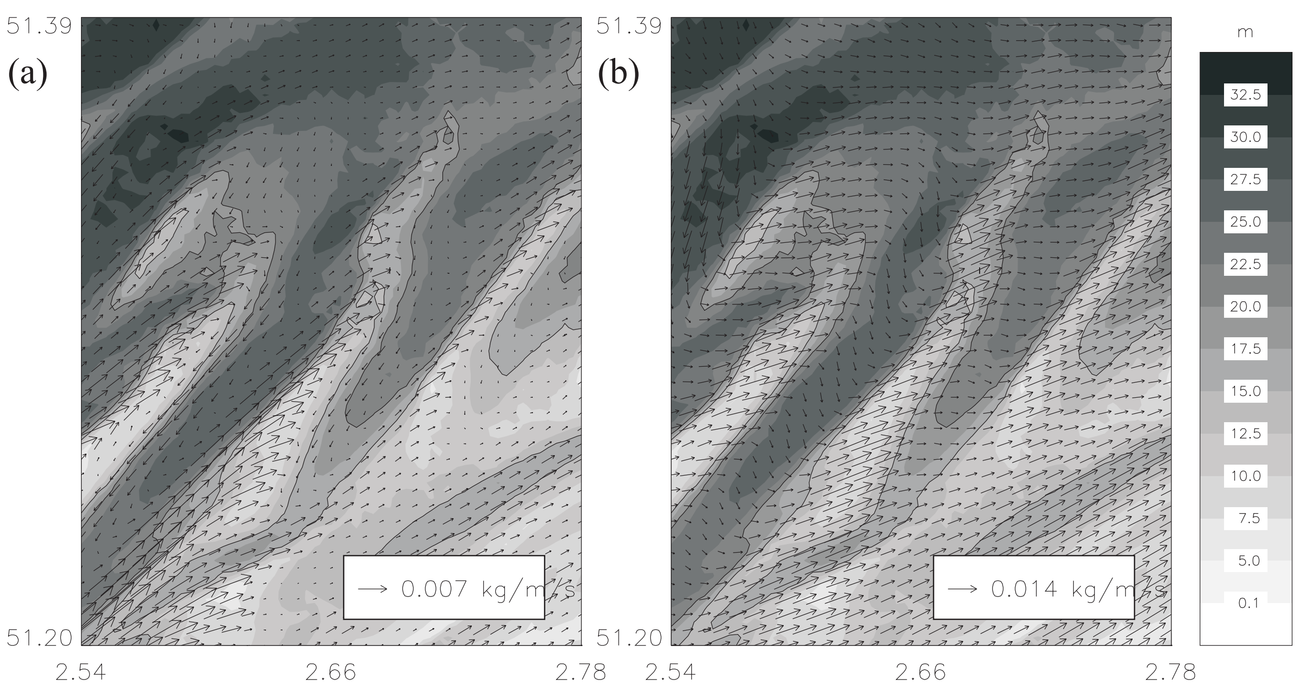


Figure 7. Tidally-induced sediment transport on the Kwinte Bank for the period March 2nd 2004 6h30 – March 17th 2004 0h00. In the background the bathymetry is shown. (a) Results of MU-SEDIM, with one vector for each four grid points shown. (b) Results of the SISYPHE model, with the results being on the same grid as the MU-SEDIM model. Bathymetric contours are shown for 15 m and 20 m, below MSL.

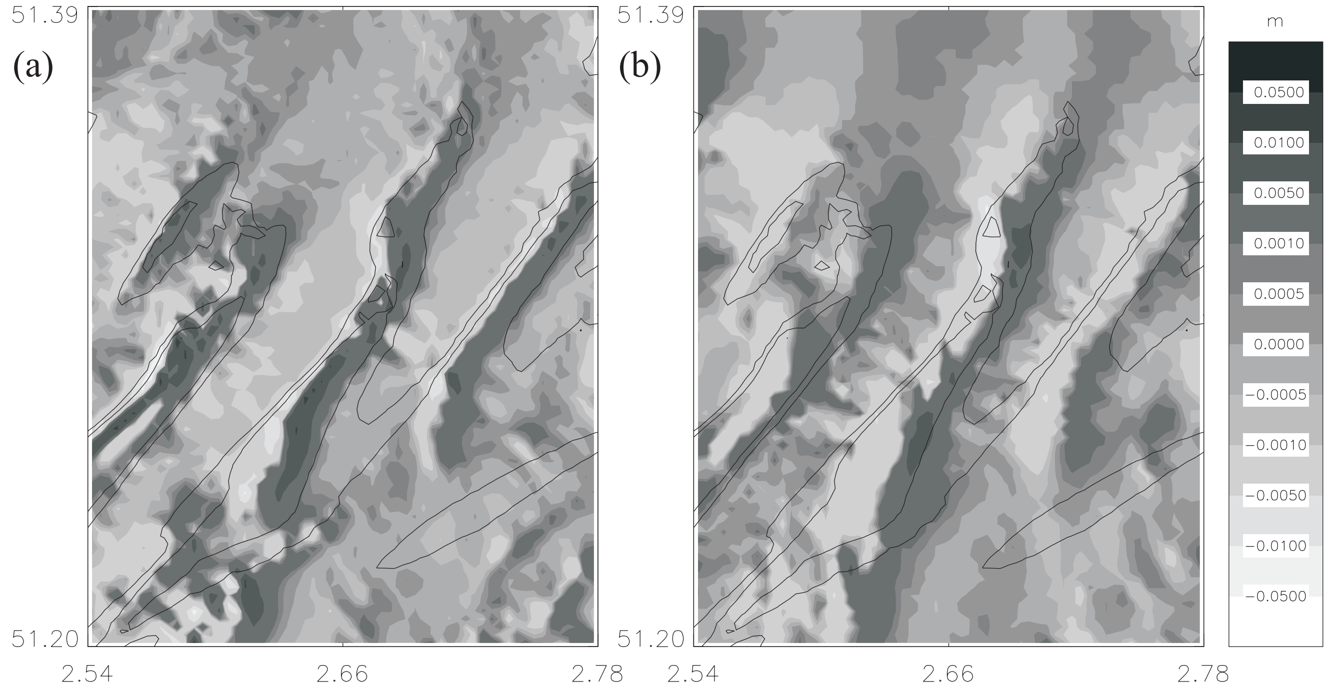


Figure 8. Erosion (light) and sedimentation (dark) patterns on the Kwinte Bank as simulated with tides only and for the period March 2nd 2004 6h30 – March 17th 2004 0h00. (a) Results of the MU-SEDIM model. (b) Results of the SISYPHE model. Bathymetric contours are shown for 15 m and 20 m, below MSL.

The total friction, on the other hand, is the friction felt by the currents and is influenced by the bed load and by the presence of bed forms. The calculation of these influences, including the calculation of the bed form dimensions, is based upon the formulae of Grant and Madsen (1982).

From the different formulae available for the prediction of sediment transport, that of Ackers and White (1973) is used here; this provided the best results, in a comparison carried out by Sleath (1984). This equation can be written as:

$$\overrightarrow{Q_s} = \vec{u} D_{35} \left(\frac{u}{u_*} \right)^n C_1 \left(\frac{F - A}{A} \right)^m \tag{2}$$

$$u_* = \sqrt{\frac{\tau}{\rho}} \tag{3}$$

where $\overrightarrow{Q_s}$ is the total transport, D_{35} the sediment diameter for which 35 % is finer, u_* the friction velocity, τ the bottom stress, ρ the water density, n, m, C_1 dimensionless parameters, F the sediment mobility number and A the critical sediment mobility number, for the commencement of transport. The sediment mobility number F can be determined using:

$$F = \left(\frac{u}{5.66 \log \frac{10h}{D_{35}}} \right)^{1-n} \frac{u_*^n}{\left((s-1) g D_{35} \right)^{1/2}} \tag{4}$$

with h the water depth, s the relative density of sediment and g the acceleration due to gravity. More details on the equations implemented in the MU-SEDIM model can be found in Van den Eynde and Ozer (1993).

The median grain-size, which is an input parameter of the sediment transport model, has been taken from the map presented as Figure 4. The D_{35} was calculated assuming a constant ratio of 0.82 between the D_{35} and the D_{50} (Cooreman *et al.*, 2000). Finally, the model calculates the morphological evolution of the sea bed, using a continuity equation for the bottom sediments (Djenidi and Ronday, 1992):

$$\rho_s (1-p) \frac{\partial \xi}{\partial t} + \nabla \overrightarrow{Q_s} = 0 \tag{5}$$

with ρ_s the sediment density, p the porosity, t time, ξ the position of the bottom, with reference to its original position, and $\nabla \overline{Q_s}$ the divergence of the sediment transport vector.

The MU-SEDIM model has already been applied at the kink of the Westhinder Bank, a sandbank at the Belgian continental shelf, north of the Kwinte Bank (Deleu *et al.*, 2004) and the model results agreed well with the transport pathways, derived from the observations, *e.g.*, from the asymmetry of the sand dunes.

Model SISYPHE

The morphodynamical model SISYPHE (v.5.5) (Villaret, 2004) was set-up on the same computational mesh as used for the TELEMAC-2D computation. The total load sand transport rate was calculated as a function of the hydrodynamic conditions, through internal coupling with the TELEMAC-

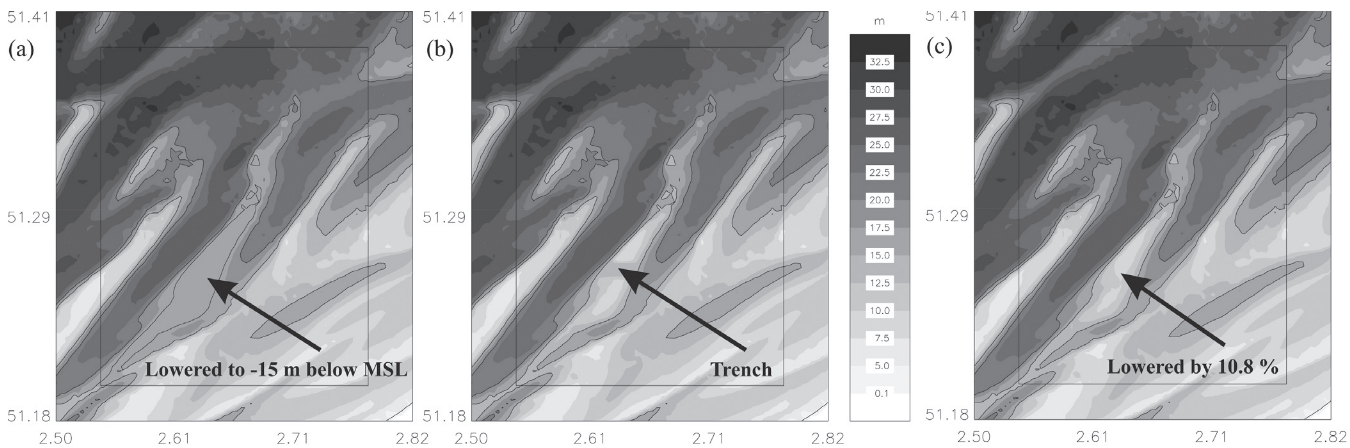


Figure 9. Bathymetry of the Kwinte Bank for the three Scenarios investigated. The lines shown are the 15 and the 20 depth contours of the original bathymetry (Figure 2); (a) Scenario 1, where the complete bank has been deepened up to 15 m below MSL; (b) Scenario 2, where a trench was cut to 13 m below MSL; and (c) Scenario 3, with a decrease in the sandbank height above 15 m below MSL by 10.8 %.

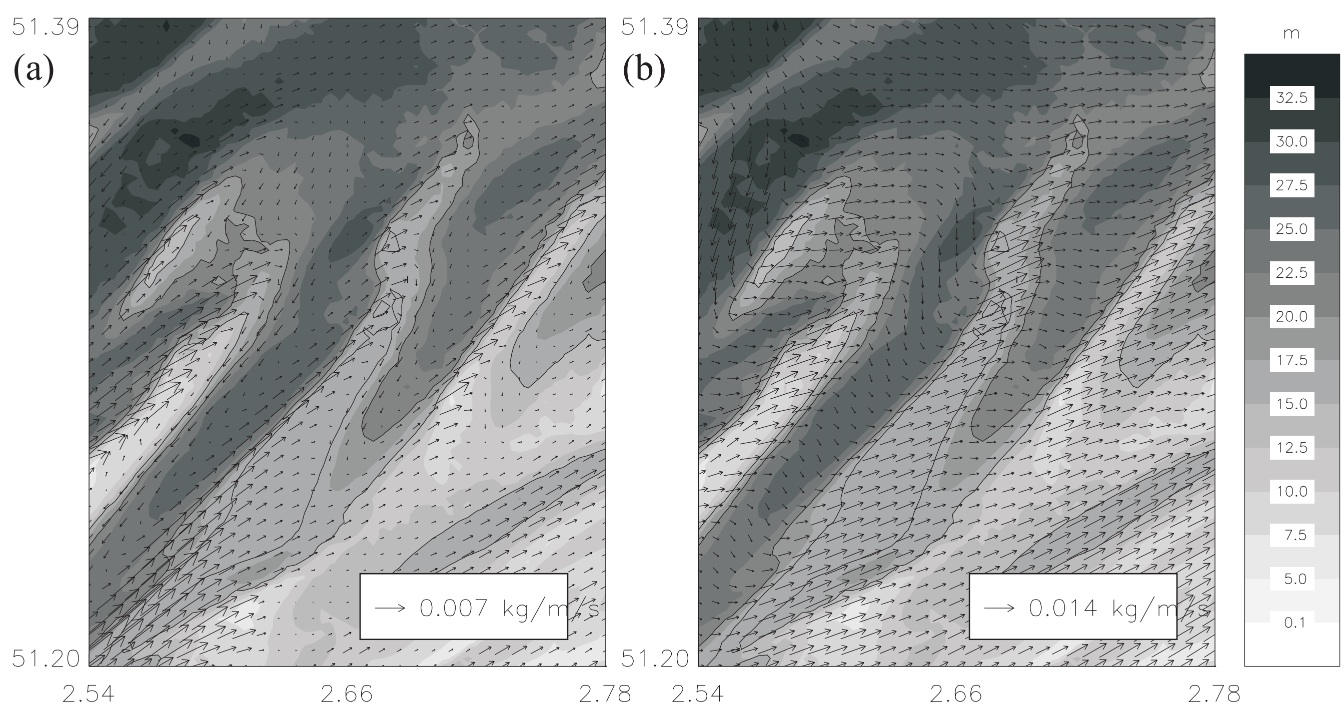


Figure 10. Predicted tidally-induced sediment transport on the Kwinte Bank for the period March 2nd 2004 6h30 – March 17th 2004 0h00 for Scenario 1, where the complete bank has been deepened up to 15 m below MSL. In the background the bathymetry is shown. (a) Results of MU-SEDIM, with one vector for each four grid points shown. (b) Results of the SISYPHE model, with the results being on the same grid as the MU-SEDIM model. Bathymetric contours are the 15 m and the 20 m depth contours, below MSL, of the original bathymetry (Figure 2).

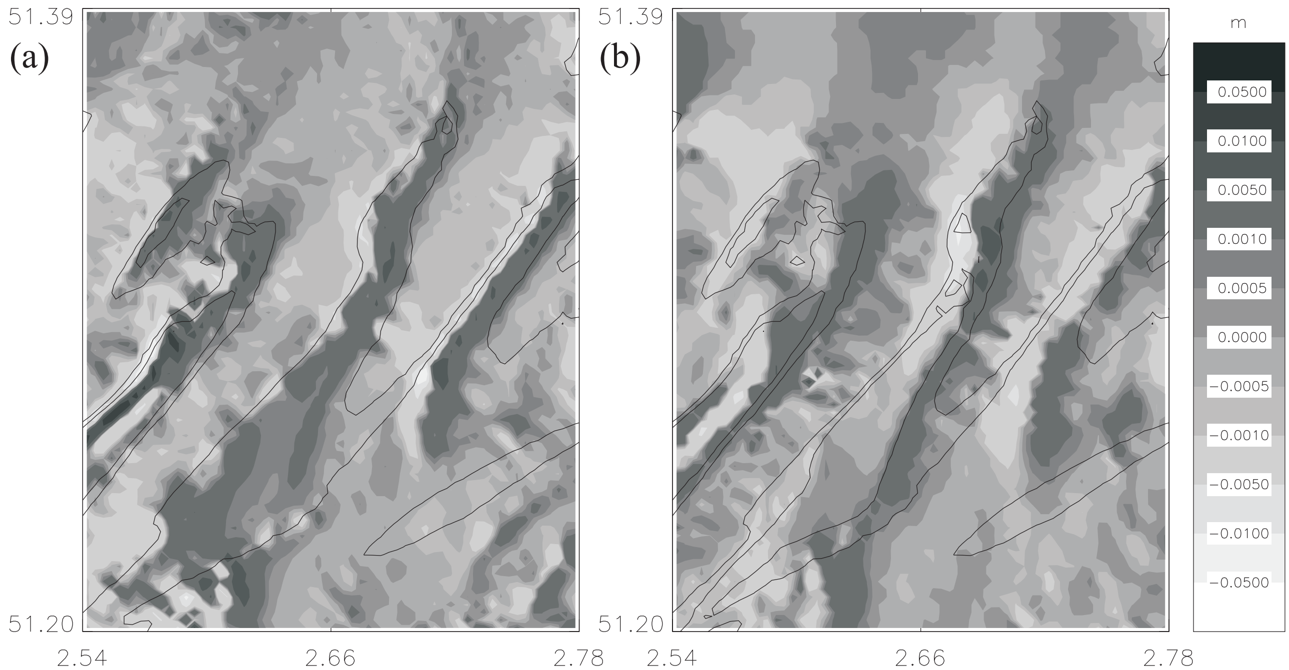


Figure 11. Erosion (light) and sedimentation (dark) patterns on the Kwinte Bank as simulated with tides only, for the period March 2nd 2004 6h30 – March 17th 2004 0h00 and for Scenario 1, where the complete bank has been deepened up to 15 m below MSL. (a) Results of the MU-SEDIM model. (b) Results of the SISYPHE model. Bathymetric contours are shown for 15 m and 20 m below MSL.

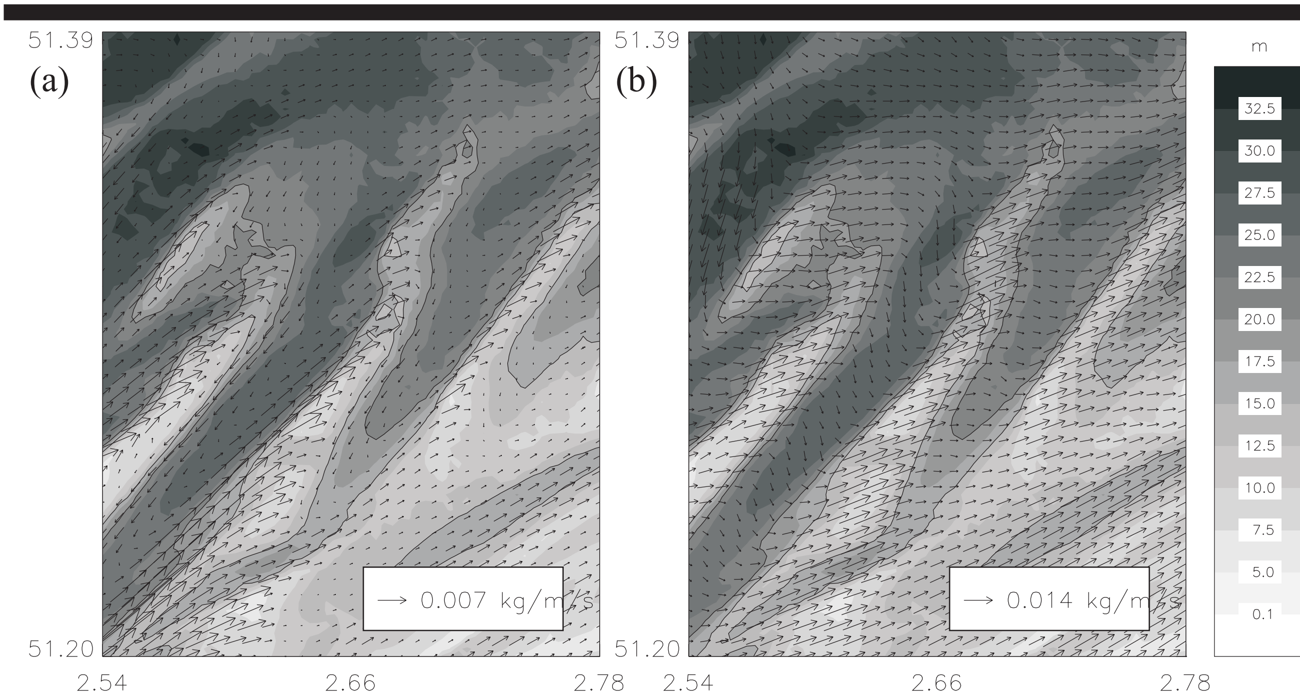


Figure 12. Predicted tidally-induced sediment transport on the Kwinte Bank for the period March 2nd 2004 6h30 – March 17th 2004 0h00 for Scenario 2, where a trench was cut to 13 m below MSL. In the background, the bathymetry is shown. (a) Results of MU-SEDIM, with one vector for each four grid points shown. (b) Results of the SISYPHE model, with the results being on the same grid as the MU-SEDIM model. Bathymetric contours are the 15 m and the 20 m depth contours, below MSL, of the original bathymetry (Figure 2).

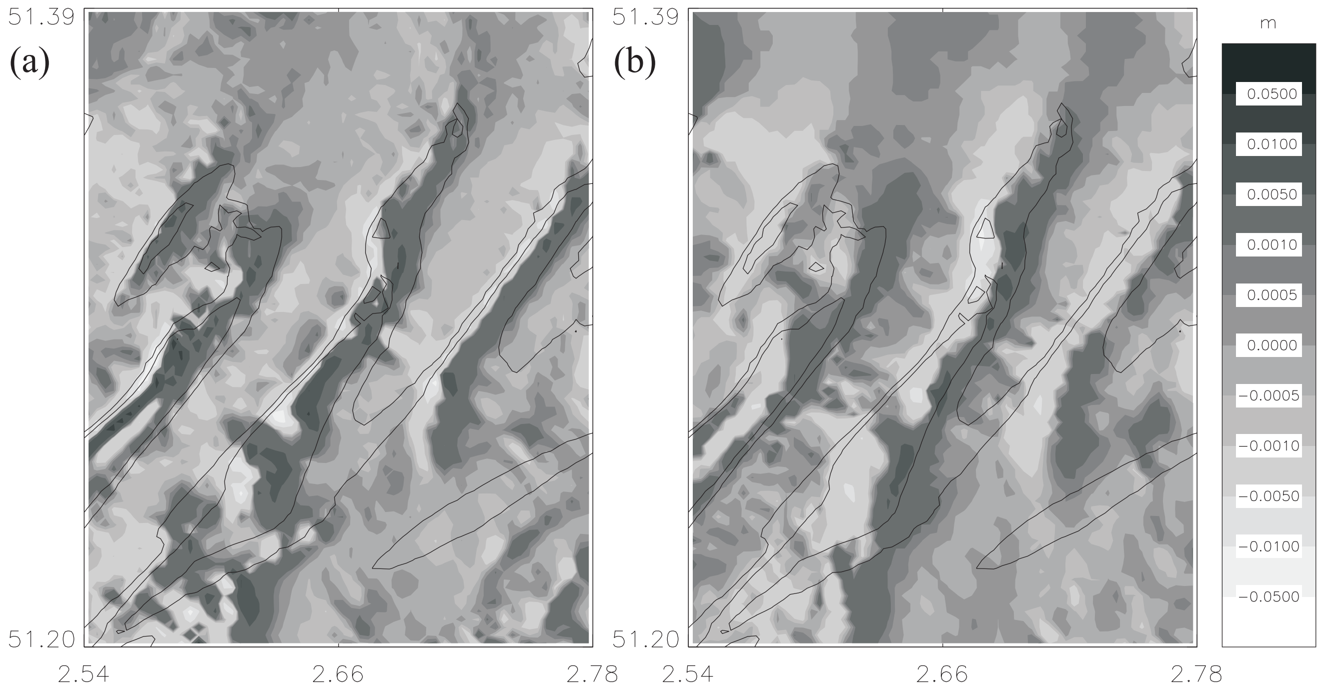


Figure 13. Erosion (light) and sedimentation (dark) patterns over the Kwinte Bank as simulated with tides only, for the period March 2nd 2004 6h30 – March 17th 2004 0h00 and for Scenario 2, where a trench was cut to 13 m below MSL. (a) Results of the MU-SEDIM model. (b) Results of the SISYPHE model. Bathymetric contours are shown for 15 m and 20 m below MSL.

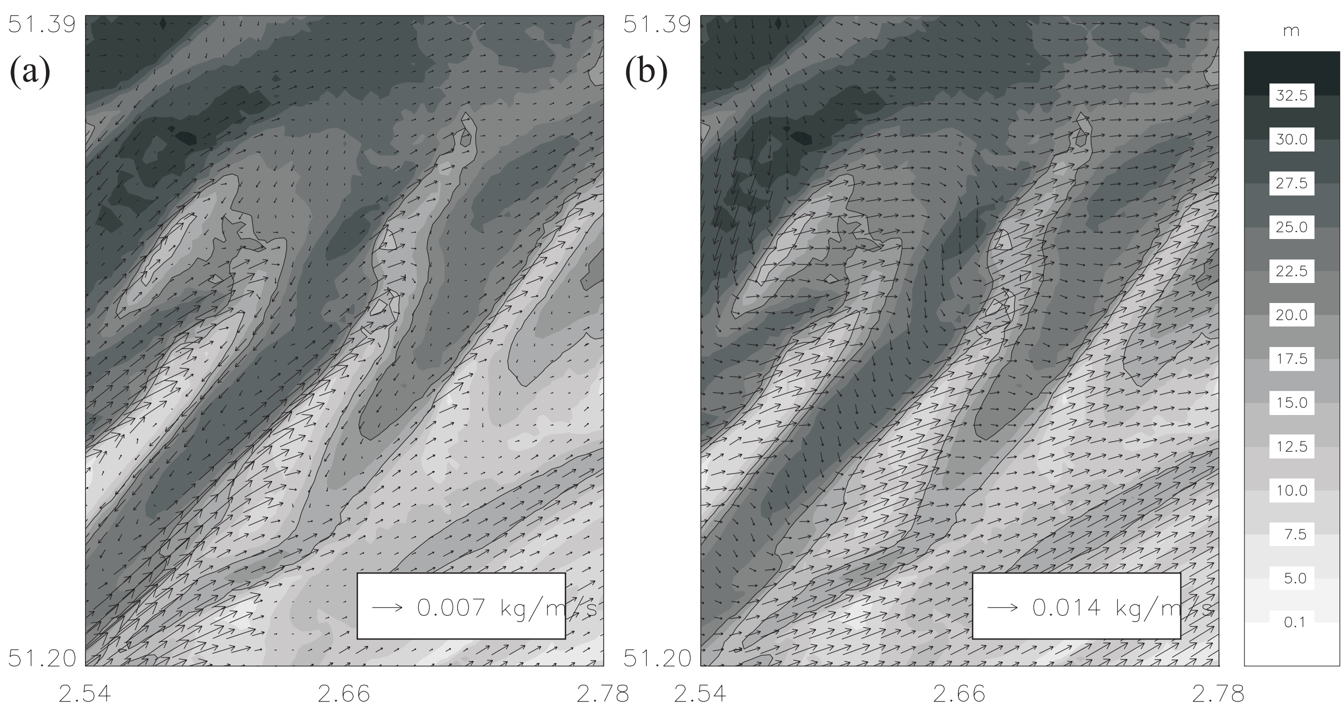


Figure 14. Predicted tidally-induced sediment transport on the Kwinte Bank for the period March 2nd 2004 6h30 – March 17th 2004 0h00 for Scenario 3, decrease of the sandbank height above 15 m below MSL, by 10.8 %. In the background the bathymetry is shown. (a) Results of MU-SEDIM, with one vector for each four grid points shown. (b) Results of the SISYPHE model, with the results being on the same grid as the MU-SEDIM model. Bathymetric contours are the 15 m and the 20 m depth contours, below MSL, of the original bathymetry (Figure 2).

2D model. The model utilised a constant median grain-size of 250 µm.

The total solid transport rate was calculated by means of the Soulsby-Van Rijn formula (Soulsby, 1997), applied to the currents on horizontal and sloping beds:

$$\overrightarrow{Q_s} = \left(A_{sb} + A_{ss}\right)\vec{u}\left[u - u_{\mathrm{cr}}\right]^{2.4}\left(1 - 1.6\tan\beta\right) \quad (6)$$

$$A_{sb} = \frac{0.005h(D_{50}/h)^{1.2}}{\left[(s-1)gD_{50}\right]^{1.2}} \quad (7)$$

$$A_{ss} = \frac{0.012D_{50}D_*^{-0.6}}{\left[(s-1)gD_{50}\right]^{1.2}} \quad (8)$$

$$D_* = \left(\frac{g(s-1)}{\nu^2}\right)^{1/3} D_{50} \quad (9)$$

where A_{sb} is the bed load component, A_{ss} is the suspended load component, u_{cr} the critical entrainment velocity, ß the slope of bed in a streamwise direction (assumed equal to 0), D_* the non-dimensional diameter, z_0 the bed roughness length (assumed equal to 0.006 m) and ν is the kinematic viscosity of the water.

The formula is validated for conditions in which the bed is rippled. Detailed multibeam imagery confirms that this requirement is satisfied (Van Lancker *et al.*, 2004).

Validation under the Influence of Tides Alone

By way of a reference run, a simulation was performed for the period March 2nd 2004 6h30 to March 17th 2004 00h00, comprising an entire spring-neap tidal cycle.

The results for the residual sediment transport under the influence of tides, calculated with the MU-SEDIM model, are presented in Figure 7a. They are comparable with the results of a sediment transport model, based upon a two-dimensional hydrodynamic model, presented in Van Lancker *et al.* (2004). On the steep western side of the bank, sand transport is towards the northeast, whilst on the gently sloping eastern side, transport is in the ebb direction, *i.e.*, towards the southwest. On the western side, the transport directions on the top of the bank veer to an almost perpendicular orientation, with respect to the banks' crest. This pattern is in agreement with the concept presented by Caston and Stride (1970), who described opposing sediment transport directions on either sides of a tidal sandbank; this is caused by an amplification of currents over the sandbank. The sediment transport rate is greatest on the top of the sandbank but much less in the swales. These results are similar to those of Brière *et al.* (this volume).

The results obtained with the SISYPHE model for the same period are presented in Figure 7b. The results show a dominant residual sediment transport, under the influence of tides alone, towards the northeast. Sediment transport over the area is much more uniform (see above) and return transport towards the southwest is not present. In the MU-SEDIM results, sediment transport in the swales, to the west and east of the Kwinte Bank, is towards the southwest. However, in the SISYPHE model results, transport is towards the southeast on the west of the bank; it is towards the east on the east. Furthermore, the rates predicted by the SISYPHE model are a factor of two larger than those of the MU-SEDIM model. Such differences are common in sediment transport modelling; Soulsby (1997) mentions that, in the sea, the total load sediment transport formulae give predictions within a factor of 5 in 70 % of the cases.

In order to validate the results of the models, the sediment transport patterns have been compared with these from dune asymmetries. As Lanckneus, De Moor, and Stolk, 1994, and Lanckneus *et al.* (2001) have shown, both the small to medium dune asymmetries and the large dune asymmetries can be used to derive sediment transport directions. Such asymmetry is, in the first place, defined by the dominant tidal current (Lanckneus *et al.*, 2001). Further, although hydro-meteorological conditions, including the influence of waves, can alter the asymmetry of the bed forms, they return to their original tidally induced asymmetry, once a storm has abated. Therefore, it can be assumed that dune asymmetries, induced by tidal currents, can be used to validate model results for tides. Elsewhere, for the Kwinte Bank, Roche, Degrendele and Schotte, (2004) have presented sediment transport pathways, derived on the basis of dune asymmetries; they showed very similar patterns to those predicted by numerical models, *i.e.*, residual sand transport on the steep western side of the bank in the direction of the flood currents, towards the northeast, whilst on the more gentle sloping eastern side of the bank, where ebb currents are dominant, southwesternly directed sediment transport occurs. Investigations undertaken within the context of the present study also confirm this pattern (Bellec *et al.*, this volume).

Erosion and sedimentation patterns, derived from the simulated sediment transport, are presented in Figure 8a for the MU-SEDIM results. The Figure shows that under calm weather conditions, *i.e.*, without taking into account the meteorological conditions and waves, erosion occurs on the steep western side of the sandbank; on the more gently sloping eastern side, some sand deposition may occur. Also on the top of the sandbank, some sand deposition occurs, tending to make the sandbank shallower. This interpretation is in agreement with the results obtained in the EU-MAST RESECUSED project (De Moor and Lanckneus, 1993). Here, it was shown that under calm weather conditions, the up-slope movement of sand under the influence of near-bed currents caused an accumulation of sand; under stormy conditions, the down-slope dispersion of sand results in a decrease in the volume of the upper part of the bank. The erosion and sedimentation patterns calculated with the SISYPHE model (Figure 8b) are, despite the differences in sediment transport rates, similar to the MU-SEDIM results. However, to the north and to the south of the bank, the area of erosion seems to be more extensive.

SIMULATION OF DIFFERENT SCENARIOS

The effect of large-scale sand extraction on the sediment transport and the morphodynamical evolution of the Kwinte Bank have been investigated using the models described. Three different scenarios have been studied.

In a first scenario, it is assumed that the entire sandbank (the dotted area, Figure 2), an area of 19.4 km², is deepened to 15 m below MSL. This represents an extracted volume of 59.7 10^6 m³, or an averaged deepening of the area by 3.07 m; it is clear that this is an unrealistic 'worst-case' scenario.

The two other scenarios are more realistic, where an extraction volume of 6.4 10^6 m^3 is extracted. Compared with the present level of sand extraction (about 1.9 10^6 m^3 every year), this represents the amount of material that could be extracted in less than 4 years.

In the second scenario, it has been assumed that this amount is extracted in a trench of about 1 km to 2 km in length, located in the area of the sandbank shallower than 13 m below MSL between 51.2604°N and 51.2697°N. A mean deepening of 3.11 m is established, with a maximum deepening of 5.40 m. These values are of the same order of magnitude as the deepening within the Central Depression.

In the last scenario, the same amount of material is extracted, but now over the entire area of the bank shallower than 15 m below MSL (dotted area, Figure 2). In all grid cells of this area, a proportion of material, 10.8 %, is extracted, relative to the sand available above the 15 m below MSL level. As a result, the mean water depth of the area is increased by 0.33 m in this case, with a maximum deepening at the top of the bank of 0.81 m.

Whilst both of the last scenarios are realistic in terms of the amount of material extracted, they represent the two possible ways of extraction: extraction from a specific area; or extraction over a much larger area.

Scenario 1: the 'Worst-Case' Scenario, Removing the Sandbank at 15 m below MSL

The new bathymetry of Scenario 1 is shown in Figure 9a. The effect on the sediment transport is considerable, as is shown by the results of the MU-SEDIM model (Figure 10a). The transport of sediment on the western side of the sandbank is significantly lower. Overall, the magnitude of the tidal-residual sediment transport, in the area where the bathymetry changed, decreased to 72 % of the original size. At the top of the sandbank, the sediment transport rate even decreased to only 28 % of the original transport rate. Furthermore, the returning transport to the southeast of the bank has almost disappeared. Similar results are presented by the SISYPHE model (Figure 10b), where the main effect is a decrease in the sediment transport rates over the Kwinte Bank. In this model, the rate of sediment transport on the top of the bank decreased to 45 % of the original.

The resulting morphodynamical changes are shown in Figure 11a, for the MU-SEDIM model results, and Figure 11b, for the SISYPHE results. It can be observed that for the MU-SEDIM model results, erosion on the western side of the bank decreased. Only on the northwestern side of the bank, near the kink, some erosion still occurs. Overall, on the bank itself, minor deposition is observed.

Minor deposition observed on the top of the sandbank appears to indicate that some regeneration mechanism could exist, to rebuild the sandbank, although the model results are not conclusive. Furthermore, it should be realised that the deposition rate is moderate; as such a regeneration of the sandbank would take a considerable amount of time. Furthermore, it is important to emphasise that, although the model results indicate a potential for regeneration, this does not indicate that the bank will regenerate. Such regeneration depends also upon the possible sources of new sand; this is not taken into account in the model.

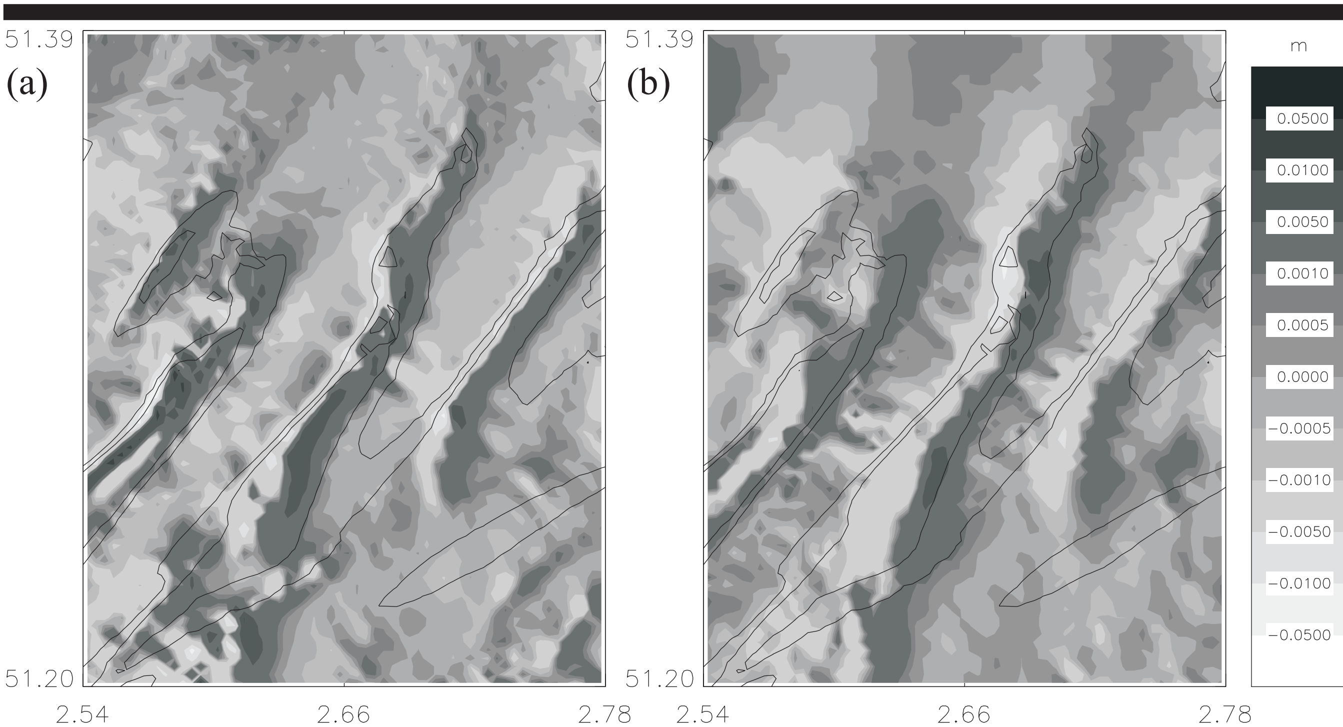


Figure 15. Erosion (light) and sedimentation (dark) patterns on the Kwinte Bank with tides only, for the period March 2nd 2004 6h30 – March 17th 2004 0h00 and for Scenario 3, decrease of the sandbank height above 15 m below MSL by 10.8 %. (a) Results of the MU-SEDIM model. (b) Results of the SISYPHE model. Bathymetric contours are shown for 15 m and 20 m below MSL.

Scenario 2: Moderate extraction from a specific area

In the Scenario 2, a more realistic amount of material is extracted from an area of approximately 1 km by 2 km, resulting in an overall deepening of the area of more than 3 m. The Scenario 2 bathymetry is shown in Figure 9b.

Whilst the main pattern of the sediment transport around the sandbank remains the same (see above), the effect of the trench cut in the sandbank can be identified on a local basis (Figure 12). The sediment transport rate decreases near and over the trench, whilst transport is directed slightly towards the direction of the trench. This decrease in sediment transport rate is reliant upon the combined effect of a decrease of the current over the trench and the increasing water depth; this results in a reduction of bottom stress. In the SISYPHE model, the influence of bathymetry on the sediment transport rate appears to be less pronounced. A reduction in the sediment transport rate over the trench is 78 % of the original. In the MU-SEDIM model results, the transport in the trench is reduced even further, to only 37 % of the original.

The effects on the morphodynamical changes are shown in Figure 13a, for the MU-SEDIM model. Erosion to the western side of the trench disappears, although to the north of the trench a small area of erosion is generated. Over most of the trench, moderate deposition occurs; however, this is smaller than the deposition on the eastern side of the bank. Such simulation appears to indicate that no breakthrough of the bank is developing, *i.e.,* that the trench has the tendency of infilling slowly. Again the SISYPHE model results show a similar trend (Figure 13b). Nevertheless, further research is required to be able to establish the existence of a regeneration mechanism.

Scenario 3: Moderate extraction over a larger area

In the last Scenario, the height of the sandbank, above 15 m below MSL (dotted area, Figure 2) has been decreased by 10.8 %. This results in an overall increase of the water depth over the entire area with only 0.3 m, but causes disturbance to a much larger area. The Scenario 3 bathymetry is shown in Figure 9c.

As could be expected, the sediment transport pattern (Figure 14) and the bottom evolution (Figure 15) are very similar to the situations associated with the original bathymetry. Here, also, clockwise sediment transport is found around the sandbank. Erosion takes place on the steep western side of the bank with deposition on the gently sloping eastern side of the bank. The sediment transport rate decreased on the top of the sandbank slightly to 83 % (95 %) of the original sediment transport for the MU-SEDIM (SISYPHE) model. Likewise erosion and deposition rates are somewhat lower than in the case of the original bathymetry. The simulation appears to indicate that regeneration is more probable, compared to the previous scenario, *i.e.*, with a trench.

DISCUSSION: INFLUENCE OF METEOROLOGICAL CONDITIONS AND WAVES

Introduction

In the previous Section of the paper, sediment transport over the Kwinte Bank was discussed under the influence of the tides alone. Different scenarios were simulated to investigate the influence of bathymetric changes on the sediment transport rates and directions. In this Section, the influence of the meteorological conditions and the waves on the sediment transport is discussed briefly. Firstly, two third-generation wave models are presented. Likewise, the modification to the sediment transport models, to include the wave effects, is discussed. Further, sediment transport under the influence of tides, prevailing meteorological conditions and waves is presented, for the same period as for the tide-only simulations.

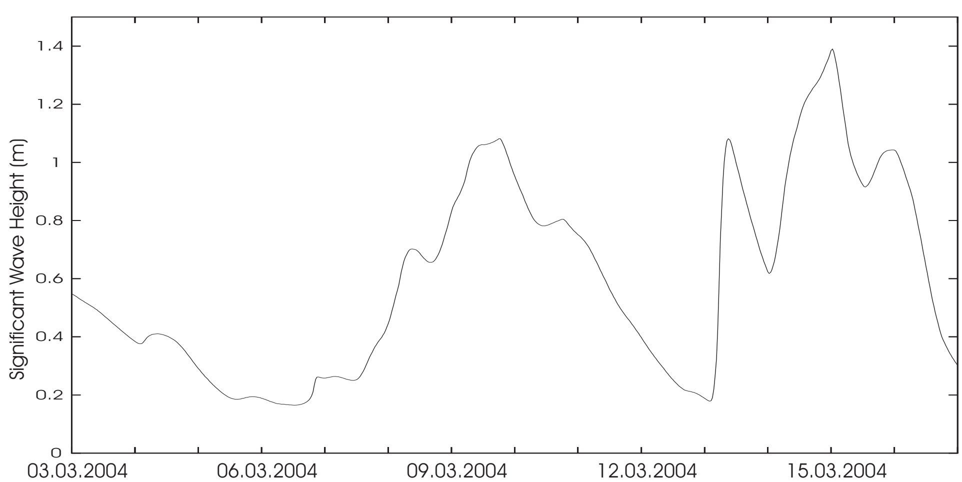


Figure 16. Significant wave height on the Kwinte Bank for the period March 2nd till March 17th 2004, as simulated by the TOMAWAC model.

Wave Models

Wave modelling was carried out using two different third-generation wave models: the WAM model (WAMDI, 1988), adapted for high-spatial resolution applications in shallow waters in the WAM-PRO version (Monbaliu *et al.*, 2000); and the TOMAWAC model (Benoît, Marcos and Becq, 1996).

The WAM model solves the wave transport equation without any assumption in relation to the spectral shape. The physics of the wave evolution are represented for the full set of degrees of freedom, of a two-dimensional wave spectrum. The propagation and source terms are computed with different numerical methods and time-steps. The model was implemented on four nested model grids.

The TOMAWAC model (v.5.5) was implemented on the same mesh used by the hydrodynamic model TELEMAC-2D and the morphodynamical model SISYPHE. The model solves the balance equation of the wave action density spectrum and provides, to the SISYPHE model, the significant wave height, the peak period and the mean wave direction. More information on the TOMAWAC model can be found in Benoît, Marcos and Becq, (1996).

At the open sea boundaries, the wave models use a parametric JONSWAP spectrum for incoming waves, together with a complete wave absorption for outgoing waves.

The two wave models adopt a same spectral discretisation, with 12 directions and 25 frequencies. Source terms include input from the wind, bottom friction dissipation, white-capping and non-linear quadruple interactions (Monbaliu *et al.*, 2000; Benoît, Marcos and Becq, 1996). Comparison of the two model performances, with buoy measurements, provide similar results in terms of significant wave height hindcasting with an average root-mean-square error of 0.25 m (Van Lancker *et al.*, 2005).

Adaptations to the sediment transport models, to include the effect of waves

To account for the influence of the waves on the derivation of sediment transport pathways, using the 'total load' formula of Ackers and White (1973) in the MU-SEDIM model (see above), the friction velocity under the influence of currents and waves u_{*cw} has to be utilised, *i.e.*, instead of the friction velocity under the influence of currents alone. In the MU-SEDIM model, the calculation of the bottom stress and the related friction velocity (Eq. 3), under the influence of currents and waves, is based upon the formula of Bijker (1966). Furthermore, the critical sediment mobility parameter *A* has been adapted by Swart (1976, 1977, *in*: Sleath, 1984), to include the effects of waves on sediment transport.

In order to include the effect of the waves on the total solid transport rate, as calculated by the Soulsby-Van Rijn formula (Soulsby, 1997), which is used in the SISYPHE model, a term is added in the equation, which is dependent upon the RMS orbital velocity of the waves at the bottom U_0 :

$$Q_{bs} = A_s U \left[\left(U^2 + 2 \frac{0.018}{C_D} U_0^2 \right)^{0.5} - U_{cr} \right]^{2.4} (1 - 1.6 \tan \beta) \quad (9)$$

$$C_D = \left[\frac{0.40}{\ln(h / z_o) - 1} \right]^2 \quad (10)$$

with C_D being the drag coefficient due to currents alone.

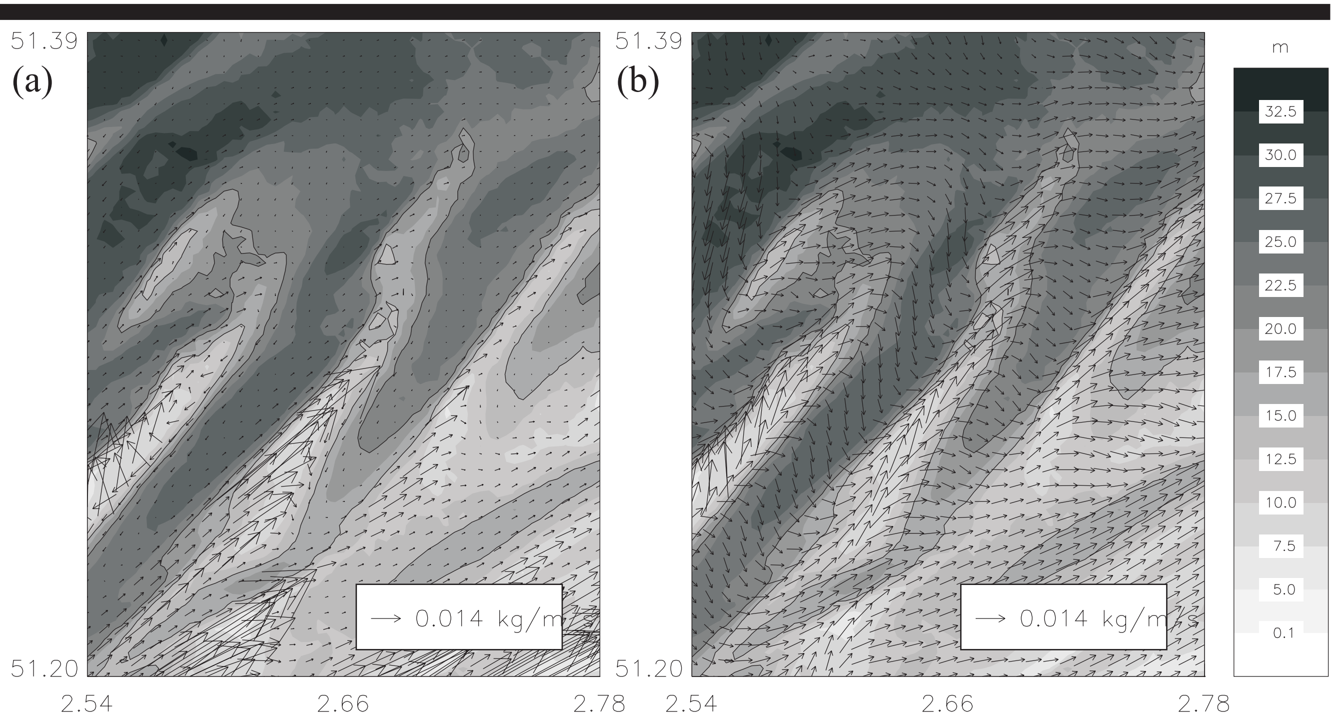


Figure 17. Predicted sediment transport under the influence of tides, meteorological conditions and waves, for the period March 2nd 2004 6h30 – March 17th 2004 0h00. In the background the bathymetry is shown. (a) Results of MU-SEDIM, with one vector for each four grid points shown. (b) Results of the SISYPHE model, with the results being on the same grid as the MU-SEDIM model. Bathymetric contours are the 15 m and the 20 m depth contours, below MSL, of the original bathymetry (Figure 2).

Sediment Transport under the Influence of Tides, Prevailing Meteorological Conditions and Waves

The simulation of sediment transport under the influence of tides, prevailing meteorological conditions and waves has been established for the same period, *i.e.,* from March 2nd 2004 6h30 to March 17th 2004 00h00. Over the selected period, selected waves over the Kwinte Bank reach a maximum of 1.4 m in height. The wave hindcasts from the TOMAWAC model are shown in Figure 16.

As shown in Figure 17a, sediment transport rates, calculated by the MU-SEDIM model, are clearly higher, when the waves are taken into account, especially in the shallower water areas (compare to Figure 7a). In such areas, where the water depth is less than 10 m below MSL, wave effects are important, modifying sediment transport under normal tidal conditions.

The enhancement of the sediment transport rates under the influence of waves, derived using the SISYPHE model (Figure 17b), is clearly smaller than the enhancement in the MU-SEDIM results (compare to Figures 17a and 7b). Whilst the transport of sediment under the influence of the tidally-only situation was mainly towards the northeast, the sediment transport under the influence of tides and waves, for this period, changed the directions to a more northerly direction.

From the above synthesis, it is evident that waves can have an important influence on sediment transport, even under moderate conditions; this will be investigated further in Giardino, Van den Eynde and Monbaliu, (this volume).

CONCLUSIONS

In the present contribution, the influence of bathymetric changes, in response to intense sand extraction, on erosional and depositional patterns on the Kwinte Bank, has been studied using numerical modelling. On the basis of the results obtained, an initial impression of the effect of sand extraction on the stability of the sandbank has been obtained.

Initially, the present situation was simulated, using sediment transport models. Using the MU-SEDIM model, a clockwise sediment transport pattern was found around the sandbank, with sediment transport towards the northeast on the steep western side of the sandbank and to the southwest on its gently sloping eastern side. Overall, this results in erosion on the western side and deposition on the eastern side, associated with a minor increase in height of the sandbank. This pattern is in agreement with the general view of transport around a sandbank under calm weather conditions, with an upslope movement of sand under the influence of tidally-induced near-bed currents causing an up-piling of sand (*e.g.*, De Moor and Lanckneus, 1993). The sediment transport patterns agree well with the directions derived from the asymmetries of the bed forms.

Three different scenarios were investigated, related to the amount and intensity of dredging. In the first scenario, the sandbank was removed at 15 m below MSL, representing a 'worst-case' scenario. A second, more realistic, scenario assumes a trench to be dredged, perpendicular to the crest of the sandbank, where an average deepening of about 3 m is established. In the last scenario, the same amount of material is extracted, but now over a much larger area.

The results of the simulations show that the intense sand extraction does not appear to affect the stability of the sandbank. Whilst there is less erosion and deposition after the sand extraction, a regeneration mechanism seems to be present, potentially allowing the sandbank to rebuild. Likewise, the trench created perpendicular to the crest of the sandbank seems be slowly refilled again. However, further research is needed to be able to make conclusive statements regarding the existence of a regeneration mechanism. In the case of the overall decrease of the sandbank above 15 m below MSL by 10.8 %, the sediment transport pattern is very similar to that obtained with the original bathymetry. Regeneration seems to be more probable for this scenario, compared to that of a trench with the same dredged volume.

These results are in agreement with those of Degrendele, Roche and Schotte, 2005, and Degrendele *et al.* (this volume). On the basis of intensive bathymetric monitoring, these investigations show, at least in the short-term, that, after the cessation of extraction in the Central Depression, the situation remained stable. No further erosion or no regeneration was apparent.

It is clear that deposition on the sandbank is very moderate and that, if regeneration of the sandbank is to occur, this will take a considerable amount of time. Following extensive sand extraction, resulting in significant lowering of the sandbank, the equilibrium height of the sandbank as it is at the present could be reached only again on a very long time-scale. Furthermore, it is important to realise that, although the model results indicate a potential for regeneration, regeneration of the sandbank depends also upon possible sources of new sand. This is not guaranteed.

Some preliminary results on the effects on the morphology of the sandbank are presented here. However, the sediment transport models used are still subject to important uncertainties. Further, it was shown that the effects of waves on the transport patterns and rates could be important; their effects, on the stability of the sandbank, are not investigated here. Nevertheless, some indications are provided that the stability of the sandbanks will not be affected dramatically as a result of the extraction of sand.

ACKNOWLEDGMENTS

This research was supported financially from the fees paid by the holders of licenses, for marine sand exploitation, issued by the Belgian authorities. The study was undertaken within the research objectives of the project MAREBASSE "Management, Research and Budgeting of Aggregates in Shelf Seas, related to End-users", supported by the Belgian Federal Office, PODOII programme (Contract No. EV/02/18A). The Captain and the crew of the R.V. *Belgica* are thanked for their flexibility and assistance, during the various campaigns. Michael Collins, Rik Houthuys and an anonymous reviewer are acknowledged for their constructive remarks.

LITERATURE CITED

Ackers, P. and White, W.R., 1973. Sediment transport: new approach and analysis. *Proceedings of the ASCE Journal of Hydraulics Division*, 99(HY11), 2041-2060.

Bellec, V.; Van Lancker, V.; Degrendele, K.; Roche, M., and Le Bot. S., this volume. Geo-environmental characterization of the Kwinte Bank. *Journal of Coastal Research.*

Benoît, M.; Marcos, F., and Becq, F., 1996. Development of a third generation shallow-water wave model with unstructured spatial meshing. *Proceedings of the 25th International Conference on Coastal Engineering* (Orlando, Florida, USA, American Society of Civil Engineers (ASCE)), pp. 465-478.

Bijker, E.W., 1966. The increase of bed shear in a current due to wave motion. *Proceedings of the 10th Conference on Coastal Engineering* (Tokyo, Japan, American Society of Civil Engineers (ASCE)), pp. 746-765.

Boyd, S.E.; Cooper, K.M.; Limpenny, D.S.; Kilbride, R.; Rees, H.L.; Dearnaley, M.P.; Stevenson, J.; Meadows, W.J., and Morris, C.D., 2004. Assessment of the re-habilitation of the seabed following marine aggregate dredging. Science Series, *Technical Report No. 121*, The Centre for Environment, Fisheries and Aquaculture Science & HR Wallingford, 154 p.

Brière, C.; Roos, P.; Garel, E., and Hulscher, S., this volume. Modeling the morphodynamic effects of sand extraction from the Kwinte Bank. *Journal of Coastal Research.*

Caston, V.N.D. and Stride, A.H., 1970. Tidal sand movement between some linear sandbanks in the North Sea off northeast Norfolk. *Marine Geology*, 9, M38-M42.

Cooreman, K.; Hillewaert, H.; Guns, M., and Van Hoeyweghen, P., 2000. Biological monitoring of dumping of dredged material at the Belgian coast (1997-1999) (in Dutch). Ministerie van Middenstand en Landbouw, Departement Zeevisserij, Oostende*, Report 97060/BAG/5*, 100 pp.

Degrendele, K.; Roche, M., and Schotte, P., 2002. Synthesis of data acquired from November 1999 to April 2001 concerning the extraction activities on the Kwintebank (in French). *Technical Report*, Fund for Sand Extraction, Ministry of Economic Affairs, 23 pp.

Degrendele, K.; Roche, M., and Schotte, P., 2005. Monitoring of the impact of the extraction (in Dutch). *Proceedings of the Workshop "Evaluation of the sustainable development of the sand and gravel extraction on the Belgian Continental Shelf and future perspectives",* (Oostende),1 p.

Degrendele, K.; Roche, M.; Schotte, P.; Van Lancker, V.; Bellec, V., and Bonne, W., this volume. Morphological evolution of the Kwinte Bank central depression before and after cessation of aggregate extraction. *Journal of Coastal Research.*

Deleu, S.; Van Lancker, V.; Van den Eynde, D., and Moerkerke, G., 2004. Morphodynamic evolution of the kink of an offshore tidal sandbank: the Westhinder Bank (Southern North Sea). *Continental Shelf Research*, 24, 1587-1610.

De Moor, G. and Lanckneus, J., (eds.), 1993. Sediment Mobility and Morphodynamics of the Middelkerke Bank. *Final Report MAST Project-0025-C RESECUSED*, Relation between Seafloor Currents and Sediment Mobility in the Southern North Sea. Universiteit Gent, 244 p.

Djenidi, S. and Ronday, F., 1992. Dynamique sédimentaire en mer à marée. *Etude du plateau continental nord-ouest Européen: Structure et mouvement verticaux.* Institut de recherches marines et d'interactions air-mer. Université de Liège, pp. 53-61.

Engelund, F.A. and Hansen, E., 1967. A monograph on sediment transport in alluvial streams. *Teknikal Forlag*, Copenhagen.

Fettweis, M. and Van den Eynde, D., 2000. Assessment of the sediment balance for the Belgian coastal waters: calculation with sediment transport models (in Dutch). Management Unit of the North Sea Mathematical Models*, Report SEBAB/1/MF/200006/NL/AR/2*, 45 pp.

Flather, R.A., 1981. Results From a Model of the North East Atlantic relating to the Norwegian Coastal Current. *In*: Saestre, R. and Mork, M. (eds.), *Proceedings of the Norwegian Coastal Current Symposium*, Geilo, pp.427-458.

Giardino, A. and Monbaliu, J., 2004. Tidal simulation in the North Sea - Code changes to TELEMAC-2D, Hydraulics Department KULeuven, *Internal Report*, 83 p.

Giardino, A.; Van den Eynde, D., and Monbaliu, J., this volume. Wave Effects on the Morphodynamic Evolution of an Offshore Sandbank. *Journal of Coastal Research*.

Grant, W.D. and Madsen, O.S., 1982. Movable bed roughness in unsteady oscillatory flow. *Journal of Geophysical Research*, 87, 469-481.

Hervouet, J.-M. and Bates, P., 2000, The TELEMAC Modelling System. Special Issue, *Hydrological Processes*, 14, Baffins Lane, West Sussex PO19 1UD, United Kingdom, John Wiley & Sons Ltd., 2207-2363.

Hoogewoning, S.E. and Boers, M., 2001. Physical effects of marine sand extraction (in Dutch). *Rapport RIKZ/2001.050*, Rijkswaterstaat, 95 p.

ICES, 2005. WGEXT Report 2003. ICES Marine Habitat Committee, *ICES Report,* CM 2005/E:06.

Lanckneus, J.; De Moor, G., and Stolk, A., 1994. Environmental setting, morphology and volumetric evolution of the Middelkerke Bank (Southern North Sea). *Marine Geology*, 121, 1-21.

Lanckneus, J.; Van Lancker, V.; Moerkerke, G.; Van den Eynde, D.; Fettweis, M.; De Batist, M., and Jacobs, P., 2001. Investigation of the natural sand transport on the Belgian Continental Shelf (BUDGET). *Final Report*. Federal Office for Scientific, Technical and Cultural Affairs (OSTC), 104 p. + 87 p.

Luyten, P.J.; Jones, J.E.; Proctor, R.; Tabor, A.; Tett, P., and Wild-Allen, K., 1999. COHERENS: A Coupled Hydrodynamical-Ecological Model for Regional and Shelf Seas: User Documentation. *Technical Report*, Management Unit of the North Sea Mathematical Models, Brussels, 914 p.

Monbaliu, J.; Padilla-Hernandez, R.; Hargreaves, J.C.; Albiach, J.C.C.; Luo, W.; Sclavo, M., and Günther, H., 2000, The spectral wave model, WAM, adapted for applications with high spatial resolution, *Journal of Coastal Engineering*, 41 (1-3), 41-62.

Pison, V. and Ozer, J., 2003. Operational products and services for Belgian coastal waters. *In:* Dahlin, H.; Flemming, N.C.; Nittis K., and Peterson, S.E. (eds.), *Building the European Capacity in Operational Oceanography. Proceedings of the Third International Conference on EuroGOOS.* Elsevier Oceanography Series, 69, 503-509.

Roche, M.; Degrendele, K., and Schotte, P., 2004. Introduction to the Kwinte Bank from a geomorphological perspective. Fund for Sand Extraction, Ministry of Economic Affairs. *Presentation on the SPEEK Workshop*, Gent.

Sleath, J.F.A., 1984. *Sea Bed Mechanics*. New York: Wiley-Interscience, 335 p.

Soulsby, R.L., 1997. *Dynamic of Marine Sands*. London: Thomas Telford, 272 p.

Svašek, 2001. PUTMOR: field measurements at a temporary sand pit. Part 3: Final Report. *Report 01453/1177 Final*, 27 pp.

Swart, D.H., 1976. Coastal sediment transport. Computation of longshore transport. The Netherlands: Delft Hydraulics Laboratory, *Report R968* (1).

Swart, D.H., 1977. Weighted value of depth of initiation of movement. South Africa: Stellenbosch, *Report NR10.*

Van den Eynde, D. and Ozer, J., 1993. Sediment Trend Analysis: calculation of the sediment transport with a numerical model (in Dutch). Management Unit of the North Sea Mathematical Models, *Rapport BMM/STA/TR01*, 49 pp.

Van den Eynde, D.; Scory, S., and Malisse, J.-P., 1995. Operational modelling of tides and waves in the North Sea on the Convex C230 at MUMM. *Proceedings of the European Convex User's Conference 1995* (Brussels, Belgium).

Van Lancker, V.; Deleu, S.; Bellec, V.; Le Bot, S.; Verfaillie, E.; Fettweis, M.; Van den Eynde, D.; Francken, F.; Pison, V.; Wartel, S.; Monbaliu, J.; Portilla, J.; Lanckneus, J.; Moerkerke, G., and Degraer, S., 2004. Management, research and budgeting of aggregates in shelf seas related to end-users (Marebasse). *Scientific Report*, Year 2. Federal Office of Scientific, Technical and Cultural Affairs (OSTC), 144 p.

Van Lancker, V.; Deleu, S.; Bellec, V.; Du Four, I. ; Verfaillie, E.; Fettweis, M.; Van den Eynde, D.; Francken, F.; Monbaliu, J.; Giardino, A.; Portilla, J.; Lanckneus, J.; Moerkerke, G., and Degraer, S., 2005. Management, research and budgeting of aggregates in shelf seas related to end-users (Marebasse). *Scientific Report*, Year 3. Federal Office of Scientific, Technical and Cultural Affairs (OSTC), 103 pp.

Villaret, C., 2004. SISYPHE release 5.4. *User Manual*. EDF/LNHE, Chateau France. 69p.

WAMDI group., 1988. The WAM model - a third generation ocean wave prediction model, *Journal of Physical Oceanography*, 18, 1775-1810.

Yu, C.S.; Vermunicht, A.; Rosso, M.; Fettweis, M., and Berlamont, J., 1990. Numerical simulation of long waves on the north-west European Continental Shelf. Part 2: Model setup and calibration. Belgium: Katholieke Universiteit Leuven, *Technical Report BH/88/28*.

Journal of Coastal Research | SI | 51 | 117-126 | West Palm Beach, Florida | Summer 2010

Modelling the Morphodynamics of the Kwinte Bank, Subject to Sand Extraction

C. Brière[1*] , P.C. Roos[1], E. Garel[2] and S.J.M.H. Hulscher[1]**

[1] Water Engineering & Management
Universiteit Twente
P.O. Box 217
7500 AE Enschede
The Netherlands

[*] Present address: Deltares
P.O. Box 177
2600 MH Delft
The Netherlands
E-mail: christophe.briere@deltares.nl

[2] National Oceanography Centre, Southampton
European Way, Southampton
SO143ZH, United Kingdom

[**] Present address: CIACOMAR
University of Algarve
Avenida 16 de Junho
8700-311 Olhão
Portugal

ABSTRACT

The North Sea is, to an increasing degree, subject to human activities and interests; a particular example of a user function of this environment is sand extraction. In order to satisfy the demand for sand, tidal sandbanks in some sectors of the North Sea act as a source of sediment, this may lead to the creation of large-scale pits on these bedforms. Sandbanks, which provide protection to adjacent stretches of coastline, are therefore worthy of investigation, especially when their potential as a source of aggregates is taken into account.

To investigate seabed dynamics, in general, and to predict the long-term morphodynamics of tidal sandbanks subject to sand extraction, in particular, process-based modelling is a commonly-used method. Different approaches can be considered: (i) based on complex numerical simulations; (ii) or applying an idealised model, designed specifically to describe sandbank dynamics. Herein, the first approach is applied to a case study of the Kwinte Bank; this is a tidally-maintained sandbank, located on the Belgian continental shelf. The modelling is set up using the complex process-based model Delft 3D – Online, the waves were not taken into account.

Numerical results and experimental data from a field campaign (undertaken in March 2004) are compared and show good agreement. Analysis of residual currents indicates a predominance of ebb flow over the bank. However, the residual sediment transport pattern is flood-dominated. The predicted residual sediment transport pattern shows that the Kwinte Bank should be regarded as part of a system of swales and sandbanks.

Finally, the long-term evolution is discussed, considering complementary approaches that combine the benefits from the complex numerical modelling with the idealised one. The evolution of a tidal sandbank, after removing an amount of sand, is difficult to predict. No clear tendency is evident in the evolution of the depression area on the basis of the long-term full process-based modelling. However, on the basis of idealised modelling, the anticipated long-term trend of an excavated area is the recovery of the depression, resulting in an equilibrium of the sandbank, over a time-span of a few centuries.

ADDITIONAL INDEX WORDS: *sandbank dynamics, numerical modelling, Delft 3D, stability analysis.*

INTRODUCTION

The offshore seabed of shallow shelf seas, like the North Sea, is covered with a wide variety of rhythmic sedimentary features of different length scales. In the potential sand extraction areas, tidal sandbanks and sandwaves, even both are likely to occur (see e.g. Hulscher and Van den Brink, 2001). Tidal sandbanks are the largest of the offshore features; they have lengths of several kilometers, a spacing of up to 10 km and a height of several tens of meters (Dyer and Huntley, 1999). Sand waves are smaller, but are more dynamic and prominently present throughout the North Sea. Tidal sandbanks and sandwaves may act directly as sources of sand, this may lead to the creation of large-scale pits on these bedforms. Typical dimensions of such pits are several kilometers long and wide and several meters deep. Offshore sandbanks affect navigation, but provide protection to adjacent stretches of coastline. These structures, therefore, are worthy of investigation, especially when their potential as a source of aggregates is taken into account.

The formation of tidal sandbanks can be explained in terms of a morphodynamic instability of a flat seabed, subject to tidal flow and sediment transport (Huthnance, 1982). The underlying hydrodynamic mechanism, known as tidal rectification (Zimmerman, 1981), explains the formation and, usually, the counter-clockwise orientation of the bank's crest with respect to the tidal current in the Northern Hemisphere. However, little is known of the morphodynamic processes that shape and maintain tidal sandbanks in equilibrium. Besides, a large-scale intervention such as sand extraction can interfere with the complex hydrodynamic and morphodynamic processes; nonetheless, this impact is largely unknown. In particular, the long-term effects on time-scales of decades to centuries from

DOI: 10.2112 / SI51-011.1 received 14 January 2007; accepted in revision 29 October 2007.

such interaction are of interest to the aggregate industry and to coastal managers.

In order to investigate seabed dynamics, in general, and to predict the long-term evolution of tidal sandbanks subject to sand extraction, in particular, process-based modelling is an approach which has been used commonly. Different approaches can be considered: (i) based upon complex numerical simulations, with a full process-based model such as Delft3D – Online (Lesser *et al.*, 2004); or (ii) applying an idealised model, designed specifically to describe sandbank dynamics (Roos *et al.*, 2004). Although both approaches are based upon the underlying physical processes, they are essentially different; as such, they have different benefits and limitations.

The full process-based models combine different processes (e.g. wind- and wave-driven currents, density gradients, Coriolis force, sediment transport, etc …) within broad classes of problems, over different temporal and spatial scales; they are able to deal with complex geometries. The morphodynamic procedure consists of the coupling of a number of modules that simulate processes such as wave and current propagation, sediment transport and morphodynamic bed updating. In all of these models, the hydrodynamic module is usually the most computationally expensive, explaining why their applications are, in most cases, restricted to initial sedimentation/erosion modelling. This so-called morphostatic approach, which has been extensively and effectively used in comparative impact studies, does not enable the modeling of the long-term evolution of a system. Further disadvantage of these models is related to the uncertainties associated with the boundary conditions and with the inputs, such as wind stress, expressed as explicit forcing terms in the equations.

Alternatively, idealised models have been designed to study rhythmic bed forms (Dodd *et al.*, 2003). These models are based also upon the underlying physical processes and have been developed for particular applications (e.g. sandbank formation in Hulscher, De Swart and De Vriend, 1993; and Huthnance, 1982). Assuming a strongly simplified geometry, inputs and boundary conditions, they are much less computationally expensive. Therefore, they are more appropriate to study the long-term transient behaviour of sandbanks. In particular, they can be used to study the evolution of sandbanks subject to extraction (Roos, 2004). A different example is the study undertaken by De Swart and Calvete (2003), who developed an idealised model to investigate the non-linear response of shoreface-connected ridges, subject to sand extraction.

Comparing and combining the benefits of these two approaches has been the subject of an earlier study on tidal sandbanks (Idier and Astruc, 2003). In this contribution, the objectives are (i) to study the short-term morphodynamics of the Kwinte Bank, and (ii) to discuss the benefits of the idealised and full process-based modelling, to investigate the long-term evolution of the bank subject to sand extraction.

The text is organised as follows. In section 2, the geographical and physical characteristics of the site are presented. Subsequently, section 3 contains the results of the modelling of a field measurement programme. Comparison is undertaken between numerical results and observations, on the basis of statistical analysis. The flow and sediment transport patterns are described next, during the period of interest and focusing upon the depression area. As the long-term effects of sand extraction are of interest to coastal managers and policymakers, the fundamental difficulties of extrapolating short-term

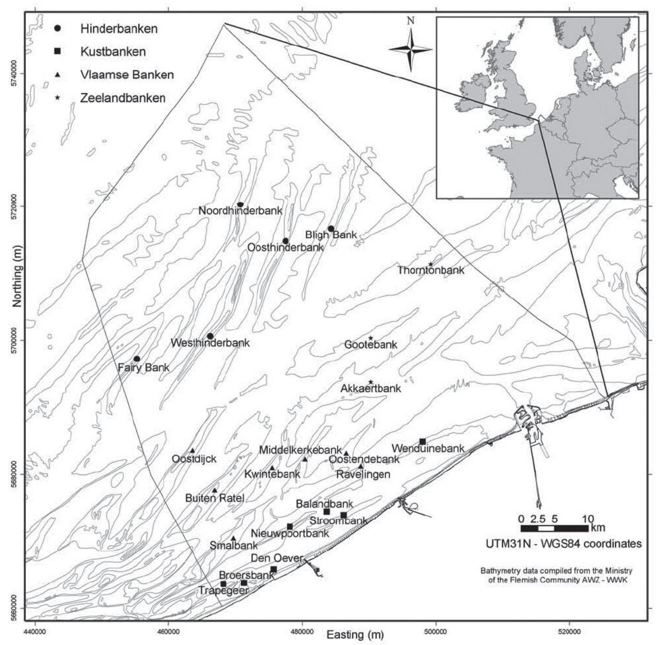


Figure 1. Sandbank patterns in the Belgian continental shelf.

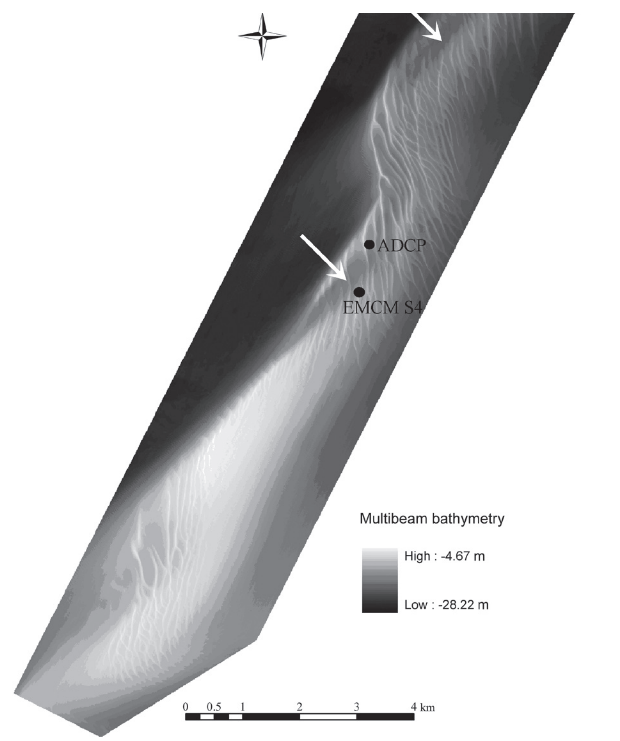


Figure 2. The Kwinte Bank at time of cessation of extraction, showing measurement locations used in the model assessment, and the two main areas of excavation dredging (indicated with arrows).

results to long-term prediction are finally discussed in section 4. Section 5 contains the conclusions.

STUDY AREA

Geographical and Physical Characteristics of the Kwinte Bank

The Kwinte Bank is a Southwest/Northeast oriented tidal sand bank which is located on the Belgian continental shelf and belonging to the Flemish Banks' system (Figure 1.). The sandbank itself has a length of 15 km and a width which varies from 2 km in its southern part, to 1 km in its northern part (Figure 2.). The minimum water depth is about – 5 m MLLWS (Mean Lowest Low Water Springs) in the southern part of the bank. The depth reaches – 22 m MLLWS in the swales around the bank. On the basis of its bathymetry, the estimated volume of the bank represents approximately 400 Mm^3 (Garel, this volume). In the northern part, the bedform is covered by large dunes with maximum height of about 8 m. Sand dunes are also present in the central part of the bank. The cross-section of the sandbank is asymmetrical, with a steeper side facing the northwest and a seabed slope reaching 3° (Van Lancker *et al.*, 2004).

In general, the hydrodynamics of the southern part of the North Sea are characterised by semi-diurnal progressive tides, dominated principally by M2, S2, N2 and M4 harmonic components (Williams *et al.*, 2000). Over the Kwinte Bank, the average tidal ellipse is elongated along a southwest/northeast axis, at about 6 ° in a clockwise direction from the bank's axis. The tidal currents rotate counter-clockwise, over 12 hours 25 mins (Lanckneus *et al.*, 1992), with the strongest peak currents, of about 1 m/s, being during the flood, towards the northeast (Van Cauwenberghe, 1971). Furthermore, numerical modelling and Waverider measurements undertaken on the adjacent Middelkerke Bank (Williams *et al.*, 2000) have shown that significant wave heights less than 3 m are unlikely to have any significant effect on the bed. On the other hand, observed residual currents in the same area were found to be correlated strongly with wind duration, speed and direction. Recent sediment sampling campaigns undertaken over the Kwinte Bank area have established a mean grain-size (d_{50}) distribution ranging from 0.25 to 0.55 mm (Bellec *et al.*, this volume).

Since 1979, sand has been extracted mainly from two distinct areas of the Kwinte Bank, located along the crest in the northern and central parts of the bank (Figures 2.). The latter location is the most excavated, with dimensions of about 700 m wide, 1 km long and 5 m deep, at time of cessation of extraction. Dredging here ceased in February 2003 to allow the monitoring of the evolution of the depression zone, and to improve the knowledge on the biological and physical impacts of aggregate extraction on the state and dynamics of the sandbank.

Field Experiment

Since 2003, field campaigns were carried out by Institutes involved in the MAREBASSE and EUMARSAND projects, focusing mainly upon the central depression (Van Lancker *et al.*, 2004). The objectives were to investigate the mechanisms of sandbank maintenance, as well as the impact of sand extraction on the benthos. Hydrodynamic measurements (Figure 2.) were obtained between the 2nd and 12th March 2004 (Garel, this volume), and are considered here. A 1200 kHz Acoustic Doppler Current Profiler (ADCP Teledyne RDI) was moored during 9 days (2-11/03/2004), at the northern extremity of the central depression; this recorded data every 50 cm, from 1.4 m up to 16.4 m above the seabed. An Electro-Magnetic Current Meter (EMCM S4) was moored at the bank crest during the same period and recorded, at 2 Hz frequency, the horizontal components of the currents at 0.75 m from the seabed.

The measurements obtained by the ADCP showed a good agreement (Garel, this volume) with a parametric velocity profile (Soulsby, 1997), which has been adopted for comparison between the depth-averaged numerical results and the S4 point measurements, near the bed:

$$U(z) = U_{avg}\left(\frac{z}{0.32h}\right)^{1/7} \quad (1)$$

where U_{avg} is the depth-averaged velocity, z the sensor height above the seabed and h is the water depth.

METHODS

The characterisation of the flow and the sediment transport patterns on the Kwinte Bank is based upon the morphodynamic modelling of the field experiment of March 2004, using the complex process-based model Delft 3D – Online (Lesser *et al.*, 2004).

Model Schematisations

The hydrodynamics have been simulated in a depth-averaged 2D model, as a 2DH approach appears sufficient when focussing on the morphodynamics. Moreover, the choice is supported by the pragmatic reason of reducing the computational time.

The model solves the non-linear shallow-water equations using a finite differences formulation. The eddy viscosity included is a property of the flow, varying generally in space and in time. However, a constant viscosity value is used in the modelling undertaken here, as sensitivity tests showed that the model is not strongly sensitive to this particular parameter. Eddy diffusivity in the model is set at 0.5 m^2/s. On the other hand, numerical results are more sensitive to a change in the Chezy coefficient C, which appears in a quadratic bed friction law:

$$\vec{\tau} = \frac{\rho g}{C^2}\|\vec{u}\|\vec{u} \quad (2)$$

where ρ is the density of water, g is the acceleration due to gravity and $\vec{u}$ is the depth-averaged velocity.

The best agreement between the numerical results and observations was obtained using a coefficient, C, of 65 $m^{1/2}/s$. The sediment transport formulation of TRANSPOR1993 (Van Rijn, 1989) is adopted to estimate the sediment transport rates. A constant grain-size is considered over the sandbank, with a mean grain-size (d_{50}) equal to 325 µm.

The bathymetric data were provided by the Ministry of the Flemish Community (Ministerie van de Vlaamse Gemeenschap; Afdeling Kust). The model set-up is based upon a grid covering the Belgian continental shelf, with the highest resolution associated with the Kwinte Bank area. For example, the averaged grid cell length is around 300 m in the area of the depression. The domain, of 4200 grid points, extends from the coastline to some 32 km offshore and over 40 km in the alongshore direction. Model boundaries are located sufficiently far from the Kwinte Bank to ensure that any potential spurious effects are maintained to be outside the area of interest. The hydrodynamic module is forced by time-dependent water levels, generated by the OPTOS-BCZ model (Luyten *et al.*, 1999). Wind stress upon the sea surface is taken into account within the simulations; these data were provided by the UK Met Office, Bracknell. A southwesterly wind component was observed over 35 % of the time, with a speed ranging from 5 to 8 m/s at 10 m above the mean sea water level.

Observations on the adjacent Middelkerke Bank (Williams *et al.*, 2000) demonstrate that no significant changes in the significant wave height and in the wave period occur across the bank when $Hs < 3$ m. Failure to detect significant loss in wave energy across the bank implies that interactions between waves and the bed are weak under "normal" conditions i.e., $Hs < 3$ m. By implication, enhanced mobilisation and suspension of bed sediments and modification to bed topography by wave action is likely to occur only in storm conditions. Therefore, in this study on the Kwinte Bank, the effect of waves on the seabed has not been included due to limited wave activity over the period of the observations (S4 records show significant wave heights of less than 1.3m, during the period 2-9/03/2004)

Model Performance Statistics

Comparing field measurements with numerical results requires the acquisition of a large amount of data, in order to incorporate the wide spectrum of spatial and temporal evolutions. Consequently, field measurements were undertaken over 11 days, the data being recorded at high-frequency. However, the extensive data set makes visual analysis difficult and, as such, statistical methods are used. Information on the statistics adopted for the present comparison, alternative statistics and examples of their use in the EU COAST3D Project, can be found in Sutherland, Peet and Soulsby (2004).

In order to quantify the performance of numerical models, the root-mean-squared error (*RMSE*) is used commonly, defined according to:

$$RMSE = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(Y_n - X_n)^2} \tag{3}$$

where Xn are the observed values, Yn are the computed values and N is the total number of observations.

However, the *RMSE* is appropriate for scalar quantities (e.g. water levels), but not for vector quantities (e.g. flow velocities). To this end, a mean absolute error *MAE* can also be used. Here, for a two-dimensional vector $\vec{X} = (X_1, X_2)$, the *MAE* is defined according to:

$$MAE = \left\langle\left|\vec{Y} - \vec{X}\right|\right\rangle = \frac{1}{N}\sum_{n=1}^{N}\sqrt{(Y_{1n} - X_{1n})^2 + (Y_{2n} - X_{2n})^2} \tag{4}$$

The use of the modulus makes the statistics more difficult to apply, than using a *RMSE* index. However, the *MAE* includes errors of magnitude and direction, in a single statistic. The quality of the modelling may be judged from the value of the mean absolute error, relative to the observations (*RMAE*):

$$RMAE = \frac{MAE}{\left\langle\left|\vec{X}\right|\right\rangle} \tag{5}$$

A *RMAE* value includes the contribution from the measurement error. Van Rijn, Grasmeijer and Ruessink (2000) have discussed the measurement errors associated with the COAST3D Project. They showed that the errors were related to the physical size of the instruments deployed, together with the measurement and conversion principles. On the basis of the equipment used and the conditions prevailing in the present experiment, an average value of the observed error (OE = 5 cm/s) is adopted, for comparison. An adjusted relative mean absolute error (*ARMAE*) is proposed then, reducing the influence of the observational errors (eq. 6):

$$ARMAE = \frac{\left\langle\left|\vec{Y} - \vec{X}\right| - OE\right\rangle}{\left\langle\left|\vec{X}\right|\right\rangle} \tag{6}$$

Statistical Analysis

During the data acquisition, we averaged ADCP records in order to provide values of the current velocity and direction over 5 minutes, every 15 minutes. The S4 was set up to provide an average of pressure and current fluctuations over 9 minutes, every 15 minutes. The depth-averaged values were extrapolated from measurements obtained near the bed, using the velocity profile expression (eq.1). Subsequently, the numerical results were analysed considering 861 and 838 samples at the S4 and ADCP locations, respectively.

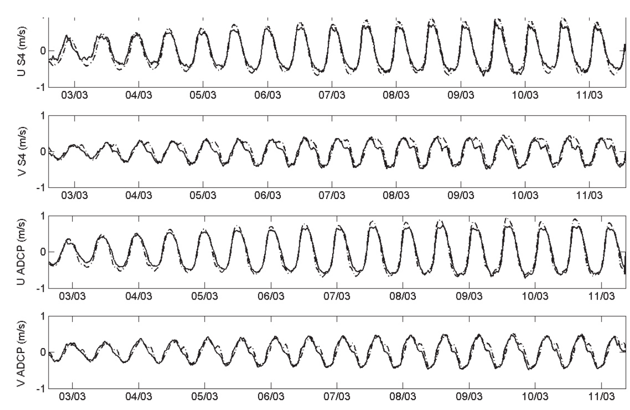


Figure 3. Intercomparison of current speeds at the S4 and ADCP locations, with numerical model outputs. u and v define the easterly and northerly components, respectively. Full and dotted lines display the experimental data and the numerical results, respectively.

Table 1. *Error statistics from DELFT 3D flow module.*

Sensors	Zc (m)	Zc /(h)	$\left\langle \left\| \vec{Y} \right\| \right\rangle$ (cm/s)	$\left\langle \left\| \vec{X} \right\| \right\rangle$ (cm/s)	RMSE (cm/s)	BIAS (cm/s)	STD (cm/s)	MAE (cm/s)	RMAE	ARMAE
S4 point	0.75	0.03	53.0	45.1	12.3	7.8	9.5	14.2	0.31	0.10
ADCP point			53.4	48.5	9.0	4.9	7.7	11.9	0.24	0.08

RESULTS

Validation Results

The water level statistics indicate that inputs at the boundaries are of good quality: data available from the S4 deployment show a *RMSE* error of 15 cm and a bias (numerical results, minus experimental data) of 1.5 cm.

Time-series of the current speeds are presented in Figure 3., in terms of the easterly (u) and northerly (v) components at the S4 and ADCP deployment sites. Good agreement is shown between the observations and the numerical model outputs. At the S4 location, the model reproduces the tidally-induced flow variation along the easterly axis, although a difference in amplitude can be noted. In contrast, the northerly component shows a slight difference in phase. The model overestimates the phenomenon of tidal rectification: the west northwest cross-bank component of the flow is accelerated, by continuity; whereas the along-bank component is decelerated, by the increased effect of bottom friction. Such flow deflection is noticeable particularly during the ebb tide, in the numerical results; in contrast, the experimental velocities are directed mainly towards the west southwest. At the S4 location, the measured maximum and mean (absolute time- averaged) current speeds are 81 cm/s and 45 cm/s, respectively. The numerical predictions are somewhat higher, at 92 cm/s and 53 cm/s, respectively. At the ADCP location, the maximum and mean velocities of the current are, respectively, 87 cm/s and 49 cm/s for the experimental data; the numerical predictions are higher, at 94 cm/s and 53 cm/s, respectively. The major tidal ellipse axes (not presented here for the sake of brevity, see GAREL, this volume; and VAN DEN EYNDE *et al.*, this volume) are rotated about 10° clockwise compared to the bank's axis, due to tidal rectification. The observations show that the mean orientation of the axes is similar at both the S4 and ADCP locations; in contrast, the stronger currents, obtained at the S4 location with the model, are directed more eastward than those obtained at the ADCP point. At both locations, the numerically predicted ellipses are more spherical in shape than the elongated experimental ellipses.

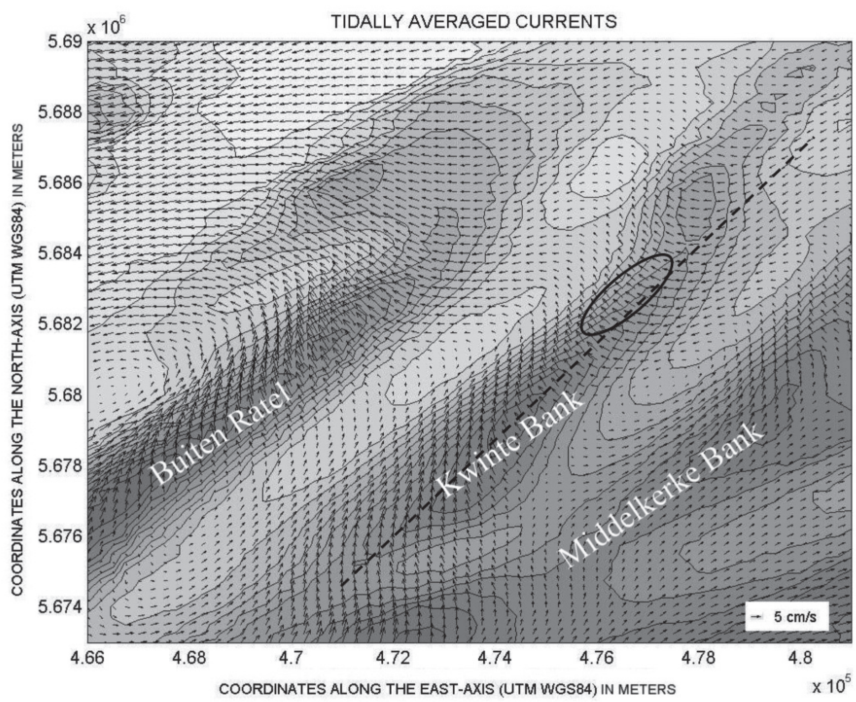


Figure 4. Residual currents over the Kwinte Bank area. Full lines and dashed line define bathymetric contours and the southwest/northeast axis respectively. The ellipse delimits the main area of extraction.

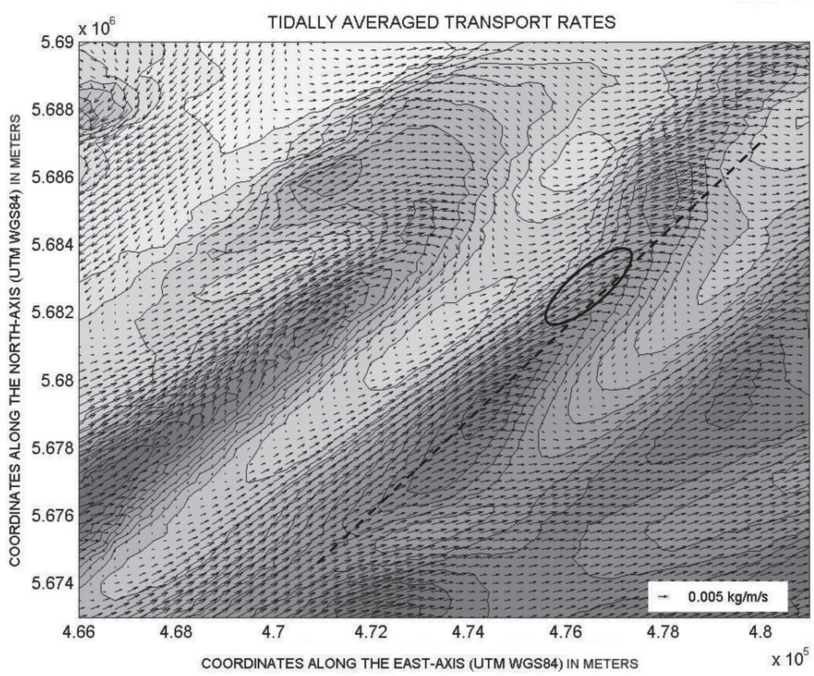


Figure 5. Residual sediment transport rates over the Kwinte Bank area. Full lines and dashed line define bathymetric contours and the southwest/northeast axis respectively. The ellipse delimits the main area of extraction.

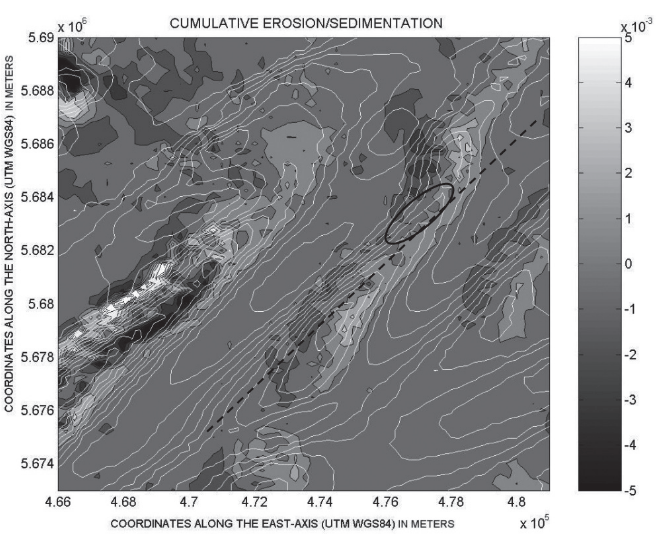


Figure 6. Cumulative erosion/accretion rate (m) over the Kwinte Bank area, over a 10 days period (02/03/2004 to 12/03/2004). Full lines and dashed line define bathymetric contours and the southwest/northeast axis respectively. The ellipse delimits the main area of extraction.

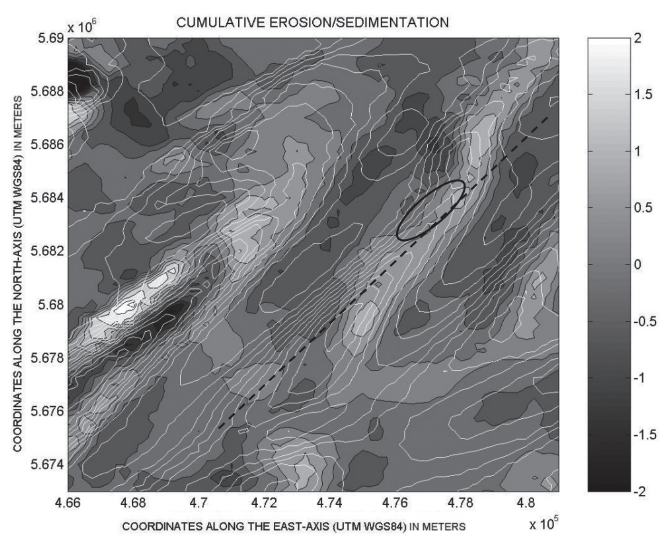


Figure 7. Tidal flow driven cumulative erosion/accretion rate (m) using an elongated tide, over the Kwinte Bank area, for a 30 years period. Full lines and dashed line define bathymetric contours and the southwest/northeast axis respectively. The ellipse delimits the main area of extraction.

The mean (absolute time- averaged) current speeds, together with the *RMSE*, *MAE*, *RMAE* and *ARMAE* errors are summarised in Table 1. The mean current speed is overestimated, by 13 % and 9 % respectively, at the S4 and ADCP measurement locations. The maximum numerical velocities occur during the flood flow, which differs from the experimental results. However, the *MAE* indices are 14 cm/s (S4 location) and 12 cm/s (ADCP location); these are low considering the mean current speed. Thus, the *RMAE* indices are 0.31 and 0.24. Following Sutherland, Peet and Soulsby (2004), the results can be classified in terms of their *ARMAE* values. This classification shows that the DELFT 3D simulations, described here, have a level of performance with results in the "excellent" category (0.10 and 0.08, respectively, at the S4 and ADCP locations).

Short-term Modelling: Flow and Sediment Transport Patterns

On the basis of the numerical results obtained over an 11 days- period (2/03 to 12/03), the tidally-averaged currents have been obtained for each tidal cycle, and have been integrated over the period.

Figure 4. shows that the mean residual currents vary considerably over the domain, with the general pattern consisting of counter-clockwise gyres, centering over the swales. As such, the residual currents are higher on the top of the banks, than in the swales. Over the banks, the circulation is in the opposite direction, describing clockwise vortices. The flood and the ebb are dominant on the western and eastern flanks of the Kwinte Bank, respectively; this is in agreement with the observations of Lanckneus *et al.,* (1992) and of Bellec *et al.* (this volume). Along the western part of the Kwinte Bank, the residual currents follow the depth contours towards the northeast. The flow pattern along the eastern flank is influenced by the gyre between the Middelkerke Bank and the Kwinte Bank. Consequently, the residual currents are directed to the southwest along the northern and central parts of the bank.

Conversely, the direction of the tidally-averaged currents is towards the north along the southern part of the flank. These results agree, qualitatively, with the numerical results obtained using the OPTOS model system (Van den Eynde *et al.*, this volume; and Van Lancker *et al.*, 2004).

Over the Kwinte Bank, the residual currents are directed mainly towards the west southwest in the northern part of the bank, and towards the north in the southern part. The depression area shows ebb-dominated residual currents, tending to be parallel to the bathymetric contours. However, on the basis of the tidally-averaged currents obtained for each tidal cycle, variability of the residual direction can be noted between 02/03 and 05/03, with an eastern dominance observed during a few tidal cycles. Such flood currents are related to the wind effect, as a 5 to 8 m/s southwesterly wind component was observed during the campaign. At both locations, the numerically-derived residual currents are around 5 cm/s; these are in agreement with the values obtained from the measurements.

Due to the non-linear character of sediment transport, residual sediment transport patterns may vary from the direction of the residual currents. In contrast with the flow pattern described previously, the residual sediment transport vectors describe a s-curve around the sand bank (Figure 5.), as shown previously by Van Lancker *et al.* (2004).

This pattern illustrates that the Kwinte Bank cannot be considered in isolation, but as part of a system of swales and sandbanks. Sand transport is directed towards the northeast along the western flank of the Kwinte Bank, whereas the eastern part is characterized by transports occurring in different directions (from southward to eastward). In the area of the central depression, the residual sediment transport vectors are opposed to the residual currents, i.e. directed towards the east. In contrast to the flow pattern (Figure 4.), the sediment transport vectors are more uniform over the study area with a constant rate of about 0.01 kg/m/s over the different tidal cycles. Sand can be expected to be eroded on the western side of the bank, but deposited on its eastern part (Figure 6.).

The erosion and sedimentation rates are of the same order of magnitude, at about 2.5 mm over an 11 days- period. These numerical predictions are in good agreement with those obtained by Van Lancker *et al.* (2004) and Van den Eynde *et al.* (this volume) using the OPTOS model system. They confirm also the results obtained by Garel (this volume); these data showed a net transport towards the northeast on the western part of the bank (depression and west flank) and described an ebb-dominated pattern on the eastern side, confirming that sediment transport is related to a particular phase of the tide on each side of the bank (Lanckneus *et al.,* 1992).

The short-term modelling of the Kwinte Bank, undertaken here, reveals spatial and temporal variability in the flow, due to tidal asymmetry and wind-driven currents.

Besides, wind waves are likely to play an important role on the flow and the sediment transport patterns. When the waves are taken into account, the sediment transport rates are higher over the Kwinte Bank and the direction of the flux is also different, with dominance towards the west (Van den Eynde *et al.*, this volume).

Finally, it should be noted that the small-scale morphologies, such as such sand waves and dunes, are not taken into account in the present study. These features may also influence the variability of the flow (Hulscher, De Swart and De Vriend, 1993).

DISCUSSION ON LONG-TERM MODELLING

As sandbanks evolve on a large time-scale, the long-term effects of sand extraction are of interest to coastal managers and policymakers (Peters and Hulscher, 2006). Such long-term impact can be investigated through the use of long-term morphodynamic modelling (Idier *et al.*, this volume).

Numerical Modelling

Practically, the complex full process-based models cannot be used straightforwardly for a long-term prediction, as they are too time-consuming in terms of computer time. Still, specific approximate methods have been developed to decrease their computational requirements (De Vriend *et al.*, 1993). To this end, representative wave, wind and tidal forcing are adopted commonly; this implies inherent predictability limits, as the morphodynamic process is stochastic. Regarding the tidal forcing, two methods are used widely (Latteux, 1995): (i) the continuity correction, and (ii) the lengthening of the tide. The first approach is based upon the input filtering: the morphodynamic change following a representative tide is extrapolated over *N* tides, using a continuity correction; this is as long as the bed changes do not exceed a critical value. The second approach is that of the lengthening of the tide, which is adequate to study propagative features as sandbanks (Latteux, 1995);

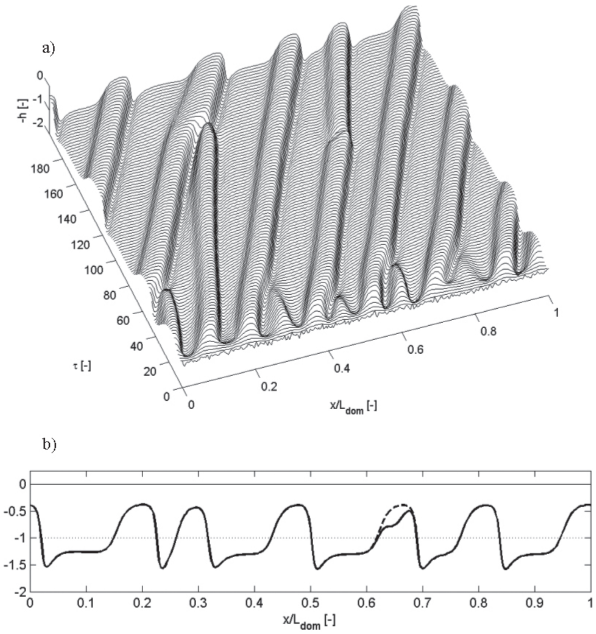


Figure 8. (a) Evolution of a sandpit, modeled as a local perturbation of a sequence of sandbanks (Roos, 2004; Roos and Hulscher, 2007). The x-axis describes the spatial dimension whereas the y-axis describes time (in units of 20 to 40 years) and the vertical axis the bed elevation (scaled against the mean water depth of about 30 m). The plot shows the autonomous dynamics of a sequence of sandbanks, as well as the response of a single bank to a local removal of sand (created in the crest at x/Ldom=0.65, tau=125). (b) The sandbank profile just before (dashed) and just after (solid) extraction. Note: the model geometry is one-dimensional, assuming uniformity in the along-bank direction, which implies that also the sand extraction is uniform in the along-bank direction. The extraction's cross-section has a Gaussian shape with a depth of 10 m implying an extraction of 4000 m3 per alongbank m. (Figure adapted after Roos and Hulscher, 2007).

this consists of increasing the morphological time-step by a so-called morphological factor (typically, N = 100 to 1000). This approach is implemented in the Delft 3D – Online modelling system. Nevertheless, we stress that these approximate methods are pragmatic and non-physical, in the sense that their main aim is to save computer time; caution is therefore required when applying large N-values.

A further disadvantage of the full process-based models is related to uncertainties associated with the boundary conditions. As such, the amplification of errors can have a large effect on the long-term behaviour of a small error in the hydrodynamics. However, full process-based models enable to study the dynamics of a complex geometry; for example, they provide an indication of the long-term evolution of the Kwinte Bank.

Hence, considering the spring tidal cycles observed during the field experiment of March 2004, and neglecting the wave and wind effects, the bed evolution has been computed over a 30 years period (Figure 7.).

The derived erosion/accretion rates suggest two patterns, depending upon location on the bank. Over its southern part, sand may be supplied from a bank located to the south of the Kwinte Bank, preventing the displacement of the feature. Over the northern and central parts, the bed is eroded on the western side of the bank and sediments are transported on the western flank. In this case, the crest may shift in an eastward (onshore) direction.

Besides, the Figure 7. shows that a supply from the swales can be also expected. De Moor (2002) discussed the stability of the Flemish Banks and of the swales. He concluded that sections of the swales might have provided sand for the regeneration of the dredged areas. However, Bellec *et al.* (this volume) noticed that there is only a limited Quaternary cover and that the Tertiary substratum is locally eroded, in the Kwinte Bank area; addressing consequently that there are no large amounts of sand available in the swales.

On the basis of the long-term full process-based modelling over 30 years, no clear tendency is evident in the evolution of the depression area, and no recovery of the depression can be anticipated.

Moreover, any interaction between the excavated area and the sandbank itself cannot be clearly discerned from Figure 7. Besides, any interpretation is limited by the fundamental problem of differentiating between anthropogenic and natural processes.

Idealised Modelling

As noted in the introduction, idealized process-based models provide an alternative to investigate the long-term dynamics of large-scale bed forms in the marine environment. A typical feature of these models is their strongly simplified geometry, the inclusion of only the essential physical mechanisms as well as the focus on the temporal scales of interest. These models are therefore suitable to obtain insight in the general physical mechanisms behind the morphodynamics. In the following we briefly describe and review how idealized models have been extended to study the system's response to sand extraction. However, owing to the idealized nature of the models, this should not be interpreted as a site-specific study of the Kwinte Bank case.

The formation stage of both tidal sandbanks (Hulscher, De Swart and De Vriend, 1993 ; and Huthnance, 1982) has been explained as inherent instabilities of a flat seabed subject to tidal flow and sediment transport. The underlying hydrodynamic mechanism, known as tidal rectification (Zimmerman, 1981), described the friction-topography and Coriolis-topography interactions of tidal flow over an uneven seabed. In particular, the stability analysis provides characteristics of a so-called fastest growing mode, i.e. preferred values of wavelength and orientation. Later on, Roos *et al.* (2004) investigated the finite-amplitude behaviour and found equilibrium profiles, expressing a tidally averaged balance between bank-building mechanisms associated with tidal rectification and the downslope sediment transport of (wind-wave stirred) material. The shape and height of the equilibrium profiles were found to depend on the tidal conditions, the mode of sediment transport, wave stirring as well as the relative importance of frictional and Coriolis effects. In each of the above approaches, a depth-averaged flow description has been employed, and Roos *et al.* (2004) accounted for wave effects in a parametric way, using a depth-dependent stirring factor in the sediment transport formulation. This approach relied on the formation theory, since the orientation and wavelength were fixed from the linear stability analysis.

Subsequently, Roos and Hulscher (2007) considered a larger domain in which a sequence of tidal sandbanks, uniform in the along-bank direction, was studied. This allowed for the investigation of both autonomous dynamics as well as the system's response to a local removal of sand. See Figure 8., where asymmetric tidal conditions were employed on a domain of about 130 km. From one of the banks, sand was extracted at tau=125, where *tau* is a dimensionless time, measured in units of roughly 20 to 40 years. It was concluded that on a time scale of several decades the bank tend to recover, but that the longer term fate of a bank is unknown.

Alternatively, De Swart and Calvete (2003) investigated the non-linear response of shore-face connected ridges, subject to sand extraction. The bed forms under consideration are of a similar size to tidal sandbanks, but they exist closer to the shoreface on the sloping bed of the inner continental shelf; as such, the physics of their formation is different. As shown by the model results, following the local removal of sand, the system tends to return to its original equilibrium state. This gradual process, taking place over several centuries, is attended with a supply of sand from both the outer shelf and the near-shore zone.

Clearly, this type of long-term behaviour cannot be investigated with the full process-based numerical simulation packages. One can further argue that, on such time scales, understanding the qualitative behaviour is more important than the quantitative details.

CONCLUSIONS

In order to satisfy the increasing demand of sand, tidal sandbanks of the North Sea act as a source of sediment; this may lead to the creation of large-scale pits, on these bedforms. Amongst others, the Kwinte Bank has been used to supply marine aggregates, resulting in the development of a large depression in the central part of the bank.

In this contribution, the dynamics of the bank and, in particular, the impact of sand extraction on its morphology, have been studied using morphodynamic modelling, using the full process-based model Delft 3D – Online.

Short-term modelling of the Kwinte Bank has been set up, on the basis of conditions measured during a field campaign, carried out in March 2004 (Garel, this volume). Comparison between the numerical results and the measurements showed good agreement (*ARMAE* values of about 0.1).

The derived flow pattern revealed that the flood and the ebb are dominant on the western and eastern flanks of the Kwinte Bank, respectively. Over the bank itself, the residual currents are directed mainly to the west southwest. The depression area is ebb-dominated, with currents tending to run parallel to the depth contours. Still, the residual sediment transport is flood-dominated. The derived residual sediment transport pattern has shown that the Kwinte Bank cannot be considered in isolation, but should be regarded as part of a system of swales and sandbanks. Sand transport is directed towards the northeast along the western flank of the bank, whereas the direction is generally southward along the eastern part. In the area of the depression, the predicted residual sediment transport pathways are opposed to the residual currents, i.e. directed to the east.

Long-term predictions are somewhat difficult to extrapolate from the short-term results. Thus, the long-term impact of sand extraction has been discussed, but considering complementary approaches, combining the benefits of complex numerical modelling with an idealised approach. The evolution of a tidal sandbank to equilibrium, following the removal of an amount of sand, is difficult to predict. No clear tendency is evident in the evolution of the depression area over 30 years, on the basis of the long-term full process-based modelling. However, on the basis of idealised modelling, the anticipated long-term trend of an excavated area is the recovery of the depression; this resulting in a new equilibrium of the sandbank, over a time-span of a few centuries.

ACKNOWLEDGEMENTS

This work presented herein has been undertaken with the financial support of the EUMARSAND Project (Project number HPRN-CT-2002-00222). The authors would like to thank Dries Van den Eynde, from The Management Unit of the North Sea Mathematical Models (MUMM) for providing us with the tidal signal at the flow model boundaries. Ghent University, Renard Centre of Marine Geology, provided grain-size data and gridded bathymetry based on soundings from the Ministry of the Flemish Community. UK Met Office provided the wind data. The MUMM is thanked for the deployment of the bottom-mounted ADCP; the University of Dunkerque, and in particular Stella Kortekaas, for the deployment of the S4 current meter. We are grateful to Dirk-Jan Walstra from WL | Delft Hydraulics for his advice and friendly support during the modelling set-up. Finally, Michael Collins is thanked for his critical comments on an early draft of the manuscript.

LITERATURE CITED

Bellec, V.; Van Lancker, V.; Degrendele, K.; Roche, M., and Le Bot, S., this volume. Geo-environmental characterization of the Kwinte Bank. *Journal of Coastal Research*.

De Moor, G., 2002. Evaluation de la morphodynamique sous-marine en Mer du Nord méridionale au cours de la période 1985-1995. *Géomorphologie : relief, processus, environnement*, 2, 135-150.

De Swart, H.E., and Calvete, D., 2003. Non-linear response of shoreface-connected sand ridges to interventions. *Ocean Dynamics*, 53 (3), 270-277.

De Vriend, H.J.; Capobianco, M.; Chescher, T.; De Swart, H.E.; Latteux, B., and Stive, M.J.F., 1993. Approaches to long-term modelling of coastal morphology: a review. *Coastal Engineering*, 21, 225-269.

Dodd, N.; Blondeaux, P.; Calvete, D.; De Swart, H. E.; Falqués, A.; Hulscher, S.J.M.H.; Rozynski, G., and Vittori, G., 2003, The use of stability methods for understanding the morphodynamical behavior of coastal systems. *Journal of Coastal Research*, 19(4), 849-865.

Dyer, K.R. and Huntley, D.A., 1999. The origin, classification and modeling of sand banks and ridges. *Continental Shelf Research*, 19, 1285-1330.

Garel, E., this volume. Short-term hydrodynamics and sediment transport on the Kwinte Bank (southern North Sea) from current meters measurements. *Journal of Coastal Research*.

Idier, D. and Astruc, D., 2003, Analytical and numerical modeling of large-scale rhythmic bedform dynamics. *Journal of Geophysical Research*, 108(C3), p. 3060, *doi:10.1029/ 2001JC001205*.

Idier, D.; Hommes, S.; Brière, C.; Roos, P.C.; Walstra, D.J.C., and Knaapen, M.A.F., this volume. Review of morphodynamic models to study the impact of offshore aggregate extraction. *Journal of Coastal Research*.

Hulscher, S.J.M.H.; De Swart, H.E., and De Vriend, H.J., 1993. The generation of offshore tidal sand banks and sand waves. *Continental Shelf Research*, 13(11), 1183-1204.

Hulscher, S.J.M.H. and Van den Brink, G.M., 2001. Comparison between predicted and observed sand waves and sand banks in the North Sea. *Journal of Geophysical Research*, 106(C5), 9327-9338.

Huthnance, J.M., 1982. On one mechanism forming linear sandbanks. *Estuarine Coastal Shelf Science*, 14, 79-99.

Lanckneus, J.; De Moor, G.; De Schaepmeester, G., and De Winne, E., 1992. Monitoring of a tidal sandbank: Evolution of bedforms, volumetric trends, sedimentological changes. Paper presented in Hydro '92, Eight Biennial International Symposium of the Hydrographic Society (Copenhagen, Denmark).

Latteux, B., 1995. Techniques for long-term morphological simulation under tidal action. *Marine Geology*, 126, 129-141.

Lesser, G.R.; Roelvink, J.A.; Van Kester, J.A.T.M., and Stelling, G.S., 2004. Development and validation of a three-dimensional morphological model. *Coastal Engineering*, 51, 883-915.

Luyten, P.J.; Jones, J.E.; Proctor, R.; Tabor, A.; Tett, P., and Wild-Allen, K., 1999. COHERENS, a Coupled Hydrodynamical-Ecological Model for Regional and Shelf Seas: User Documentation. *MUMM Report*, Management Unit of the Mathematical Models of the North Sea, 914 pp.

Peters, B.G.T.M. and Hulscher S.J.M.H., 2006. Large-Scale Offshore Sand Extraction: What can be the results of interaction between Model and Decision Process. *Ocean and Coastal Management,* in press.

Roos, P.C.; Hulscher, S.J.M.H.; Knaapen, M.A.F., and Van Damme, R.M.J., 2004. The cross-sectional shape of tidal sandbanks: modeling and observations. *Journal of Geophysical Research*, 109(F2): F022003. *doi:10.1029/2003JF000070*.

Roos, P.C., 2004. Seabed pattern dynamics and offshore sand extraction. The Netherlands: University of Twente, Ph.D. thesis, 166 p. *ISBN 90-365-2067-3*.

Roos, P.C. and Hulscher, S.J.M.H., 2007. Nonlinear modeling of tidal sandbanks: wavelength evolution and sand extraction. *In*: McKee Smith, J. (ed.), *Proc. of the 30th Int. Conference on Coastal Engineering* (ICCE2006), San Diego, US, ASCE, pp.2761-2771

Soulsby, R., 1997. *Dynamics of marine sands, a manual for pratical application*. Thomas Telford, H.R. Wallingford.

Sutherland, J.; Peet, A.H., and Soulsby, R.T., 2004. Evaluating the performance of morphological models. *Coastal Engineering*, 51, 917-939.

Van Cauwenberghe, C., 1971. Hydrografische analyse van de Vlaamse banken langs de Belgische-Frans kust. *Ingenieurdtijdingen Blatt*, 20, 141-149.

Van den Eynde, D.; Giardino, A.; Portilla, J.; Fettweis, M.; Francken, F., and Monbaliu, J., this volume. Modelling the effects of sand extraction on the sediment transport due to tides on the Kwinte Bank. *Journal of Coastal Research*.

Van Lancker, V.; Deleu, S.; Bellec, V.; Le Bot, S.; Verfaillie, E.; Fettweis, M.; Van Den Eynde, D.; Francken, F.; Pison, V.; Wartel, S.; Monbaliu, J.; Portilla, J.; Lanckneus, J.; Moerkerke, G., and Degraer, S., 2004. Management, research and budgeting of aggregates in shelf seas related to end-users (Marebasse). Scientific Report Year 2. Belgian Science Policy, *SPSDII North Sea*, 144 p.

Van Rijn, L.C., 1989. Handbook of sediment transport by currents and waves, *rep. H 461*, 1002 pp., Delft, The Netherlands, Delft Hydraulics,.

Van Rijn, L.C.; Grasmeijer, B.T., and Ruessink, B.G., 2000. Measurement errors of instruments for velocity, wave height, sand concentration and bed levels in field conditions, University of Utrecht/ Delft Hydraulics Report.

Williams, J.J.; MacDonald, N.J.; O'Connor, B.A., and Pan, S., 2000. Offshore sand bank dynamics. *Journal of Marine Systems*, 24, 153-173.

Zimmerman, J.T.F., 1981. Dynamics, diffusion and geomorphological significance of tidal residual eddies. *Nature*, 290, 549-555.

Journal of Coastal Research	SI	51	127-140	West Palm Beach, Florida	Summer 2010

Wave effects on the morphodynamic evolution of an offshore sand bank

Alessio Giardino[1*], Dries Van den Eynde[2], Jaak Monbaliu[1]

[1] Katholieke Universiteit Leuven, Hydraulics Laboratory, Department of Civil Engineering, Kasteelpark Arenberg 40, 3001 Heverlee, Belgium

[2] Royal Belgian Institute of Natural Sciences, Management Unit of the North Sea Mathematical Models, Gulledelle 100, B-1200 Brussels, Belgium.

* Present address: Deltares Unit Marine and Coastal Systems Department of Morphology and Coastal Systems, Rotterdamseweg 185, 2600 MH, Delft The Netherlands.
alessio.giardino@deltares.nl

ABSTRACT

The origin and morphodynamic evolution of linear sand banks have been widely studied in recent years. Several investigations have been carried out in order to understand the influence of tide-related parameters, bathymetry and Coriolis force on sand bank formation and maintenance. However, the effect of waves on the net flux of sediments over the sand banks has often been neglected on grounds of the short duration of significant wave activity compared to that of tidal cycles. Nevertheless, the interaction between wave activity and tidal currents leads to a high increase of bottom shear stress, especially at the sand bank crests and, as a consequence, to an increase of sand tranport. This paper investigates the effects of wave activity on the morphology and morphodynamics of the Kwinte Bank (Belgian shelf). Numerical simulations were carried out under different wave conditions to assess wave influence on sand bank evolution. Model verification involved analysis and comparison with field data collected during two different periods. The study shows that wave activity is not only responsible for a large increase in sediment transport but also for a change in direction of the net flux of sediments. Moreover, the morphological analysis of several sand banks supports the idea that wave activity might also have an impact on the shape of these sand banks. Wave climate data can be used to study long-term sand bank dynamics.

ADDITIONAL INDEX WORDS: *sand bank, waves, morphodynamic evolution, numerical models, wave climate, bed form asymmetry.*

INTRODUCTION

Sand banks are a typical feature on many continental shelves. Their size is in the order of 10 km in length, 2 km in width and they frequently extend to within a few meters of the sea surface. These bed forms are often located in groups of banks and they are found when a considerable amount of sand is available and tidal currents are sufficiently strong (0.5 – 2.5 m/s) (CARBAJAL and MONTANO, 2001).

The Belgian continental shelf, in the Southern part of the North Sea, is characterized by a large number of these banks and has been extensively studied (LANCKNEUS *et al.*, 2001), (Figure 1.). These banks can be grouped in Coastal Banks, Flemish Banks, Hinder Banks and Zeeland Ridges.

Considerable research has been done into understanding the influence of local tidal conditions on sand bank morphology. Using analytical (HUTHNANCE, 1982a) and numerical (HUTHNANCE, 1982b) models, Huthnance showed that strong currents and the presence of initial irregularities on the seabed are sufficient to create and maintain linear sand banks. By coupling a set of depth-averaged equations combined with a bedload transport equation, he predicted spacing between sand banks of about 250 times the mean water depth. The work was subsequently extended by HULSCHER *et al.* (1993) to include elliptical tidal currents and secondary currents. CARBAJAL and MONTANO (2001), by means of an analytical model, described the relationship among tidal currents, latitude, horizontal length scales and orientation of sand banks. For a fixed water depth they found an almost linear dependence between sand bank wavelength and tidal current amplitude. Furthermore, the

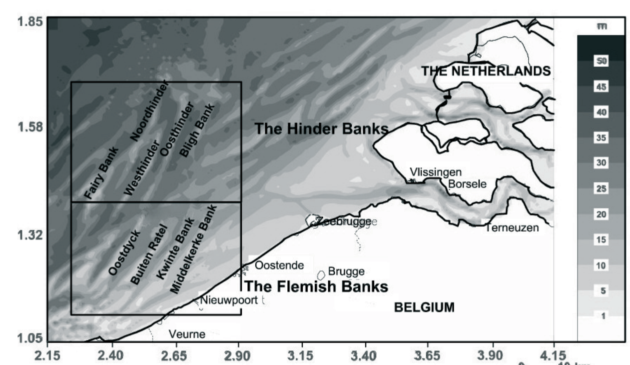


Figure 1. Bathymetry of the Belgian Continental Shelf (Flemish Authorities, Agency for Maritime & Coastal Services, Coastal Division. Gridding Ghent University, Renard Centre of Marine Geology).

DOI: 10.2112 / SI51-012.1 received 15 January 2007; accepted in revision 8 June 2007.

scale of sand banks was found to increase with increasing water depth. The angle between sand bank crest and the principle component of the tidal flow was inversely proportional to the amplitude of the tidal current. Moreover this angle was influenced by the latitude, due to a change in the Coriolis acceleration.

On the other hand, little is known concerning the role played by wave action on sand bank morphology and dynamics. Waves are known to be an agent for sand resuspension and, aided by the currents, to transport finer sediments from the crest to the flanks of the sand banks. Collins *et al.* (1995), by means of numerical simulations, showed that wave action tends to intensify the cross-bank component of sand tranport. Vincent *et al.* (1998) estimated net suspended transport from the product of profile-integrated suspended sand and current meter measurements at two locations on the Middelkerke Bank (Figure 1.). According to these measurements, the combination of high waves and strong currents during four different bursts, explains more than 50 % of the net flux of the whole measurement period. Moreover, these measurements show how waves can influence the average size of material in suspension without considerably affecting the suspended transport direction. Van de Meene and Van Rijn (2000) concentrated their attention on the long term morphological sand bank behaviour due to the combined effects of currents and waves. With a simplified numerical model they represented the yearly sediment transport across a linear sand bank. The overall result showed that the net sediment transport is mainly determined by currents in combination with the more frequent non-extreme waves ranging between 0 and 2 m. Villaret and Davies (2004) carried out a numerical study in the coastal area near Dunkerque, at the boarder between France and Belgium. The authors applied a wave model, a two-dimensional hydrodynamic model and a morphodynamic model to study sediment transport dynamics on the sand banks characterizing the area. Through successive runs of the hydrodynamic and wave models, they reproduced the effects of tides on the wave propagation, for a winter storm. The output was used to drive a morphodynamic model coupled to the hydrodynamic model. The authors showed that the wave modulation due to tidal effects was the dominant process, leading to a large increase of sediment transport towards the North-East (Belgium).

The present investigation studies the effects of wave activity on the Kwinte Bank (Figure 1.). Two numerical models were implemented and different scenarios simulated to assess the impact of wave conditions of different entities on the bank. The use of two different models revealed some interesting differences in the model intercomparison and, in addition, highlighted limitations of diverse sediment transport formulations. Model verification involved comparison with hydrodynamic, wave, suspended transport and bottom data. A careful analysis of the morphology of other sand banks at the Belgian shelf was carried out in order to derive a relation between local hydrodynamic conditions and the shape of the sand banks. Some ideas on the long term morphodynamic behaviour of the Kwinte Bank are put forward based on past observations and wave climate data.

The paper elaborates on the work of Van den Eynde *et al.* (this volume) which focused on the effects of currents on sediment transport at the Kwinte Bank and assessed the impact of sand extraction taking place in the area.

AREA UNDER INVESTIGATION

The Kwinte Bank is a southwest-northeast tidal current ridge forming part of the Flemish Bank system (Figure 1.). The sand bank has a length of approximately 15 km and a width varying from 2 km in the south to 1 km in the northern part. The minimum water depth ranges between 7 m below Mean Sea Level (MSL) in the southern part to 10 m below MSL in the northern part. The minimum water depth in the swales around the bank is about 22 m. The cross section of the sand bank is clearly asymmetrical with the steeper slope on the northwest side being up to 3°. This profile is consistent with the other sand banks of the Flemish system that show their steeper side opposite to the flood direction. The crest of the sand bank consists on a very large and flat dune, giving an indication of the importance of wave activity in shaping the sand bank morphology. Large to very large dunes are found up the stoss slope of the Kwinte Bank but they are atypical in the adjacent swales. Small to medium dunes are common in the swales and up the lee slope (steep slope).

The southern part of the bank is characterized by fine and medium sand with D_{50} (the sediment diameter for which 50 % is finer) ranging between 180 and 240 μm. Coarser material is found in the northern part with D_{50} up to 400 μm.

The hydrodynamic conditions at the Kwinte Bank have been widely investigated by Van den Eynde *et al.* (this volume) and Briere *et al.* (this volume). Current ellipses are slightly asymmetrical on the Kwinte Bank, with the main axis orientated at a small angle in clockwise direction with respect to the bank axis as observed for the first time by Huthnance (1973). In the swales the ellipses are more elongated and orientated nearly parallel to the bank axis. Maximum current velocities range between 0.4 – 0.5 m/s during neap tide up to 0.8 – 0.9 m/s during spring tide. Residual currents at the top of the sand bank are almost perpendicular to the sand bank crest and have a north-western direction.

Van Cauwenberghe (1971) compared sea charts of the Belgian shelf mapped during the years 1800-1968. Despite difficulties associated with the analysis of bathymetric surveys carried out by very diverse measuring techniques, he concluded that the Flemish Banks are characterized by a sort of dynamic equilibrium. Specifically, the Kwinte Bank could be considered as stable for the total length of the period considered.

MODELS, DATA AND METHODS

The models

Two different sets of models were implemented separately by the Hydraulics Laboratory of the K.U.Leuven and by the Management Unit of the North Sea Mathematical Models (MUMM), see Table 1. Hydrodynamic conditions, wave field and sediment transport were computed and the results for different simulated scenarios were compared.

The three models used at the K.U.Leuven, part of the same modelling package, are implemented on the same unstructured mesh and adopt a finite element scheme for the equation solution. The domain covers the region from 47°50'N to 71°10'N, and from 12°15'W to 12°15'E. The mesh size ranges between 70 km at the open boundary and 150 m on the Kwinte Bank.

Table 1. *Numerical models and settings used in this work.*

HYDRODYNAMICS MODELS		
Parameter	TELEMAC-2D	COHERENS
Model type	Two dimensional – finite element	Three dimensional – finite difference
Discretization	24851 nodes with resolution between 70 km – 150 m	Two regional models plus two coupled grids at the Belgian Shelf. Highest resolution: 272 m – 257 m and 10 σ-layers on the vertical.
Tidal components at the boundary	8	8 (for the regional model)
Time step	60 s	4 s (for the highest resolution model)
Law of bottom friction	Chezy with Chezy's coefficient variable with water depth	Quadratic friction law
Turbulence model	Constant viscosity	k-ε model
WAVE MODELS		
Parameter	TELEMAC-2D	MU-WAVE
Model type	Third generation – finite element	Second generation – finite difference
Discretization	24851 nodes with resolution between 70 km – 150 m	Two coupled grids. Highest resolution: 5 km – 5 km
Time step	100 s	Highest resolution model: 180 s
Number of directions	12	24
Number of frequencies	25	20
Minimal frequency	0.04 Hz	0.045 Hz
Wind input	JANSSEN (1989,1991)	GÜNTHER et al., (1979), HASSELMANN et al. (1973, 1976)
Bottom friction dissipation	Jonswap model (HASSELMANN et al., 1973)	GÜNTHER et al., (1979), HASSELMANN et al. (1973, 1976)
Whitecapping dissipation	KOMEN, HASSELMANN S., and HASSELMANN K. (1984), JANSSEN (1991)	GÜNTHER et al., (1979), HASSELMANN et al. (1973, 1976)
Quadruplets wave-wave interaction	DIA method (HASSELMANN et al., 1985)	GÜNTHER et al., (1979), HASSELMANN et al. (1973, 1976)
Triads wave-wave interaction	No	No
MORPHODYNAMIC MODELS		
Parameter	SISYPHE	MU-SEDIM
Model type	Two dimensional – finite element	Two dimensional – finite difference
Discretization	24851 nodes with resolution between 70 km – 150 m	Finest grid of the COHERENS model (resolution: 272 m – 257 m)
Time step	600 s	180 s
Sediment transport formula	Soulsby-Van Rijn (SOULSBY, 1997)	ACKERS and WHITE (1973) adapted by SWART (1976, 1977)
Sediment diameter	250 μm	Variable in space
Bottom roughness	Ripple bed conditions z0 = 0.006 m	Skin roughness z0s function of D65 according to: z0s = (2· D65)/30

The models implemented by MUMM are based on a series of nested grids and adopt a finite different scheme. The highest resolution grid covers part of the Belgian shelf with a resolution of 272 m in longitude and 257 m in latitude. The bathymetric data were provided by the Ministry of the Flemish Community (Flemish authorities, Agency for Maritime and Coastal Services, Coastal Division. Gridding was done by Ghent University, Renard Centre of Marine Geology).

The main advantage of the use of an unstructured mesh consists in the possibility of running at once the computation over the whole domain, with the possibility to highly refine, at the same time, the area of interest.

Atmospheric data (wind velocity at 10 m height and atmospheric pressure) were obtained from the United Kingdom Meteorological Office (Van den Eynde *et al.*, 1995).

Hydrodynamic models

Open sea boundary conditions were provided, taking into account four semi-diurnal tidal components (M_2, S_2, N_2, K_2) and four diurnal tidal components (O_1, K_1, P_1, Q_1).

The two-dimensional finite element model TELEMAC-2D (v.5.5) (Hervouet and Bates, 2000) solves the depth averaged Saint-Venant equations. Turbulent viscosity was considered constant over the whole domain.

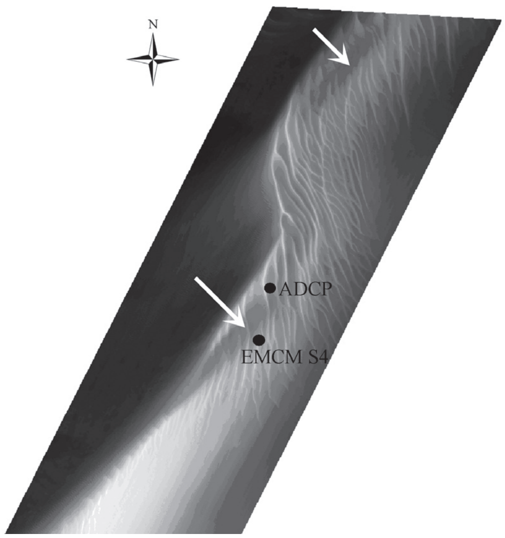


Figure 2. ADCP measurements at three different heights for a tidal cycle.

The three-dimensional MU-OPTOS model is based on the COHERENS model (LUYTEN *et al.*, 1999). The model solves the equations of momentum, continuity, temperature and salinity on a series of nested grids. The high resolution model employs 10 σ-layers over the vertical. The k-ε turbulence model was adopted.

The use of two different hydrodynamic models (depth averaged and three dimensional) to drive the morphodynamic models, was considered not to bias the overall results of the study. TONNON, VAN RIJN and WALSTRA (2007) compared results from morphodynamics simulations on an artificial sand wave using one-dimensional horizontal (1DH) and two-dimensional vertical (2DV) hydrodynamic models. The authors showed that the overall sand transport direction did not depend on the use of a 1DH or 2DV model. However, the sand wave growth could only be modelled by the 2DV model, due to the creation of a vertical circulation cell leading to a net sand transport towards the sand bank crest.

A plot of ADCP velocity vectors at three different heights is shown in Figure 2. The Figure shows that flow direction is unidirectional with minor differences in current direction at different water depths. This supports the validity of using a depth-averaged hydrodynamic model.

Wave models

The TOMAWAC model (v.5.5) (BENOIT et *al.*, 1996) is a third generation wave model which solves the balance equation of wave action density. The model was implemented with a spectral discretisation in 12 directions and 25 frequencies. Source terms included input from the wind, dissipation from whitecapping and from bottom friction and quadruplet non-linear interactions.

The core of the MU-WAVE model (VAN DEN EYNDE, 1992) is formed by the second generation HYPAS spectral wave model (GÜNTHER and ROSENTHAL, 1985). The model has been tested extensively and is used as an operational model for the prediction of waves on the Belgian continental shelf. The North Sea grid has a resolution of 50 km × 50 km, whereas for the Southern Bight a resolution of 5 km × 5 km is implemented.

Both wave models were run in non coupled mode. No effect of wave modulation due to the presence of tide was taken into account in the present work. However, previous work on the coupling between currents and waves in the Southern North Sea, showed that the tide modulation accounts only for a small variation of the wave height and period (OSUNA, 2002; OSUNA, and MONBALIU, 2004). This variation should not lead to a sensible variation of the transport direction.

Morphodynamic models

The SISYPHE model (v.5.5) (VILLARET, 2004) calculates the total load transport and the morphodynamic evolution as a function of the hydrodynamic conditions, through internal coupling with the TELEMAC-2D model, and the wave field, calculated by a previous uncoupled run of the TOMAWAC model. Total load transport was estimated by means of the Soulsby–Van Rijn formulation (SOULSBY, 1997) assuming a constant sediment diameter equal to 250 μm. The total transport rate due to the combined action of currents and waves is given by:

$$Q_{bs} = A_s U\left[\left(U^2 + \frac{0.018}{C_D}U_0^2\right)^{0.5} - U_{cr}\right]^{2.4}\left(1 - 1.6\tan\beta\right) \quad (1)$$

$$A_s = A_{sb} + A_{ss} \quad (2)$$

$$A_{sb} = \frac{0.005h(D_{50}/h)^{1.2}}{\left[(s-1)gD_{50}\right]^{1.2}} \quad (3)$$

$$A_{ss} = \frac{0.012D_{50}D_*^{-0.6}}{\left[(s-1)gD_{50}\right]^{1.2}} \quad (4)$$

$$C_D = \left[\frac{0.40}{\ln(h/z_0)-1}\right]^2 \quad (5)$$

$$D_* = \left(\frac{g(s-1)}{\nu^2}\right)^{1/3} D \quad (6)$$

where A_{sb} is the bedload component, A_{ss} is the suspended load component, U the depth-averaged flow velocity, C_D the drag coefficient due to current alone, U_0 the RMS wave orbital velocity at the bottom, U_{cr} the critical entrainment velocity, β the bed slope in streamwise direction here assumed equal to 0, h the water depth, D_* the non-dimensional diameter, s the relative density of sediment, g the acceleration due to gravity, z_0 the bed roughness length assumed equal to 0.006 m as suggested by SOULSBY (1997) in case of rippled beds and ν the kinematic viscosity of the water.

The MU-SEDIM model computes total load transport and morphodynamic evolution in function of the depth averaged current velocity calculated by the MU-OPTOS model and the wave field computed by MU-WAVE. The sediment transport was estimated by means of the Ackers and White (1973) formulation adapted by Swart (1976) and Swart (1977) as reported in Sleath (1984), to include the effects of waves on sediment transport. The total sediment transport is given by:

$$\frac{Q_s}{U} = D_{35}\left(\frac{U}{u_{*cw}}\right)^n C_1\left(\frac{F-A}{A}\right)^m \tag{7}$$

where Q_s is the total transport, D_{35} the sediment diameter for which 35 % is finer, u_{*cw} the wave-current friction velocity. n, m, A, C_1 are dimensionless parameters and F the sediment mobility number. The latter can be determined as:

$$F = \left(\frac{U}{5.66\log\dfrac{10h}{D_{35}}}\right)^{1-n} \frac{u_{*cw}^n}{\left((s-1)gD_{35}\right)^{1/2}} \tag{8}$$

The wave-current friction velocity $u_{*cw}=(\tau_{cw}/\rho)^{1/2}$ is calculated based on the formulation proposed by Bijker (1966) for the wave-current shear stress τ_{cw}:

$$\tau_{cw} = \tau_c\left[1+\frac{1}{2}\left(\frac{c}{\sqrt{2g}}\sqrt{f_w}\,\frac{u_b}{u_c}\right)^2\right] \tag{9}$$

being τ_c the current shear stress, c an empirical constant, f_w the wave friction factor, u_b the bottom orbital velocity and u_c the current velocity.

More details on the equations implemented in the MU-SEDIM model can be found in Van den Eynde and Ozer (1993).

The D_{50} was considered variable over the area. The D_{50} grid was calculated based on 2200 samples collected in the area. A weighted distance based method was used to interpolate the measured values on the model grid (Fettweis and Van den Eynde, 2000). The D_{35} was calculated assuming a constant ratio equal to 0.82193 between the D_{35} and the D_{50} (Cooreman *et al*., 2000).

Additional formulations were applied to validate the results: the Bijker (1968) and Bailard (1981) equations available in the SISYPHE model and the Van Rijn (1989), Bagnold (1966) and Yalin (1963) in the MU-SEDIM model.

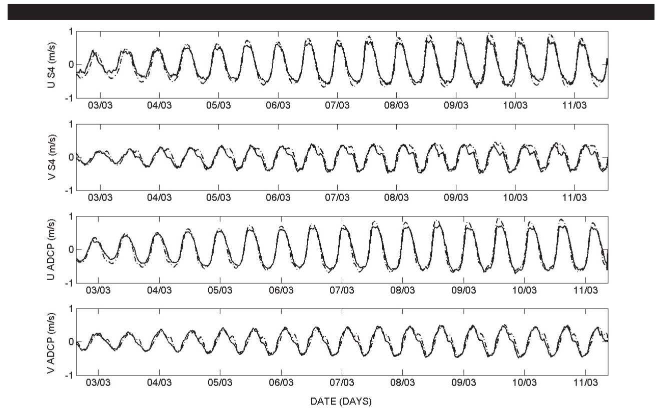


Figure 3. Modelled and measured depth averaged flow velocities for the period 2-12 March 2004.

Fieldwork

The data used in this study were collected within the framework of the MAREBASSE project (Van Lancker *et al*, 2002).

During two measurement campaigns (23-30 June 2003; 2-11 March 2004), a bottom mounted Acoustic Doppler Current Profiler (ADCP) and a multisensor benthic lander (tripod) were used. Both instruments were deployed from the oceano-

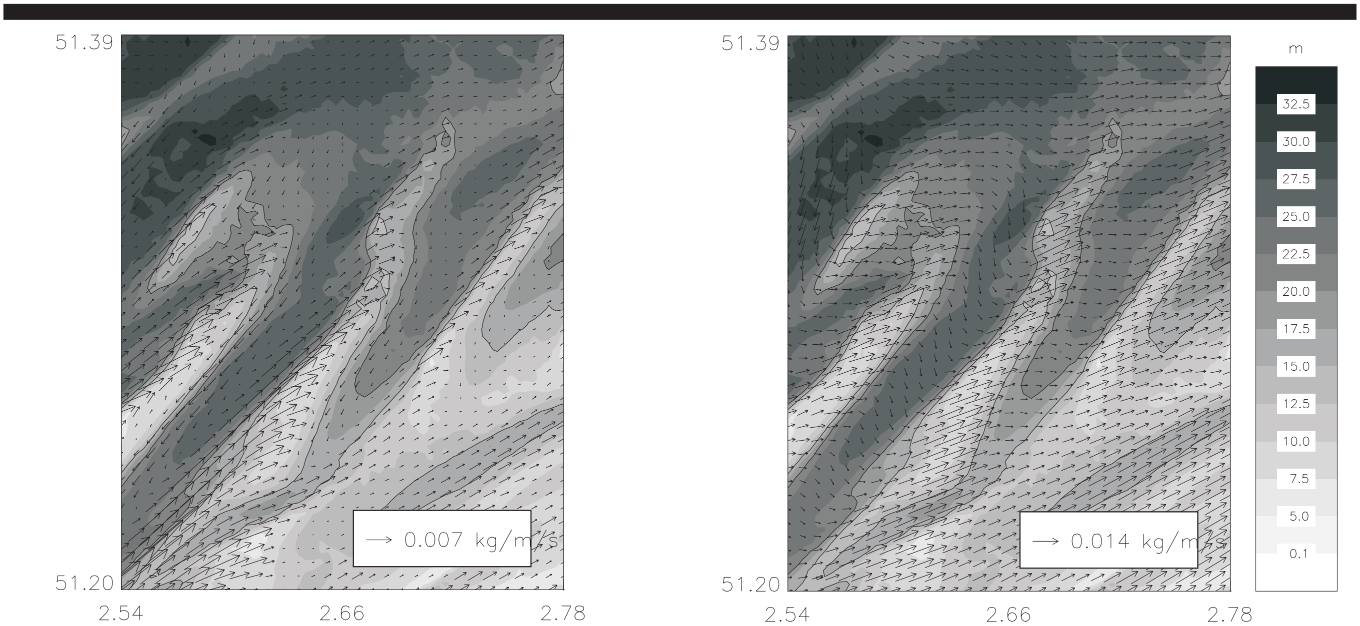


Figure 4. Sediment transport with only tides taken into account for the period 2-16 March 2004. The bathymetry is shown in the background. (a) Left: results of MU-SEDIM. One vector for each four grid points is shown. (b) Right: results of the SISYPHE model. Results on the same grid as the MU-SEDIM model.

graphic research vessel *RV Belgica*. A Conductivity, Temperature and Depth instrument (CTD), three Optical Backscatter Sensors (OBS) at 0.25, 0.5 and 1 m from the bottom and a Laser In-Situ Scattering & Transmittometer (LISST-100C) at 1 m from the bottom were attached to the tripod. ADCP measurements were used to validate the output from the hydrodynamic model, showing a general good agreement between modelled and observed data (VAN DEN EYNDE *et al.*, this volume) and Figure 3.

The OBS and LISST measurements gave volume concentration and particle diameters of material in suspension.

A wave buoy was deployed at the North of the Kwinte Bank during the campaign of June 2003. Additional buoy data were available for both periods from operational buoys at the locations Westhinder (51.38°N; 2.44° E) and Akkaert (51.41°N; 2.77°E). A validation of the wave models was carried out by means of these measurements. The root mean square error between model output (both TOMAWAC and MU-WAVE) and buoy measurements ranged between 0.2 and 0.3 m (VAN LANCKER *ET AL.*, 2005).

RESULTS

In order to assess the separate impact of tidal and wave action, three different scenarios were simulated by the two sets of models. First, a morphodynamic simulation was carried out considering tidal currents only as forcing. Two additional simulations include the effect of currents and waves of different intensity, *i.e.* one period with moderate wave and one with storm wave activity. All runs were carried out for a period corresponding to a spring-neap tidal cycle.

Tidal currents alone

This first run was carried out for the period 2-16 March 2004, neglecting the influence of waves and meteorological forces. Figure 3. shows a comparison of the simulated and measured depth averaged flow velocities for that period. Both models give a good representation of the current field, which supports the hyphothesis that flow characteristics at the Kwinte Bank can be well represented by a 2D model. The results from this scenario were discussed in VAN DEN EYNDE *et al.* (this volume).

The outputs from the two models show a general trend of residual transport going towards the northeast (Figure 4.).

This direction is due to effects of tidal asymmetry, which are especially evident at the sand bank crest and are characterized by the highest current velocities occurring during flood, directed towards the northeast and lower velocities during ebb, going to southwest. Peak currents during flood are about 10 % larger than currents during ebb (Figure 5.).

It follows that, and this is typical for a tidally dominated regime, strong flood currents more easily exceed the critical entrainment velocity U_{cr}. Estimated values for U_{cr}, for a sand diameter equal to 250 µm and water depth ranging between 5 and 20 m (typical values for the Kwinte Bank area), range between 0.3 m/s at the crest and 0.4 m/s in the swales (VAN RIJN, 1984). The difference in critical velocity between crest and swales is due to a different value of the water depth, which influences the calculation of U_{cr}. Sand transport at the Kwinte Bank crest is more important than in the swales due to higher flow velocities and lower critical velocity for sediment.

As a result of the sediment transport pattern, erosion occurs at the western flank of the sand bank while deposition takes place at the eastern flank (Figure 6.).

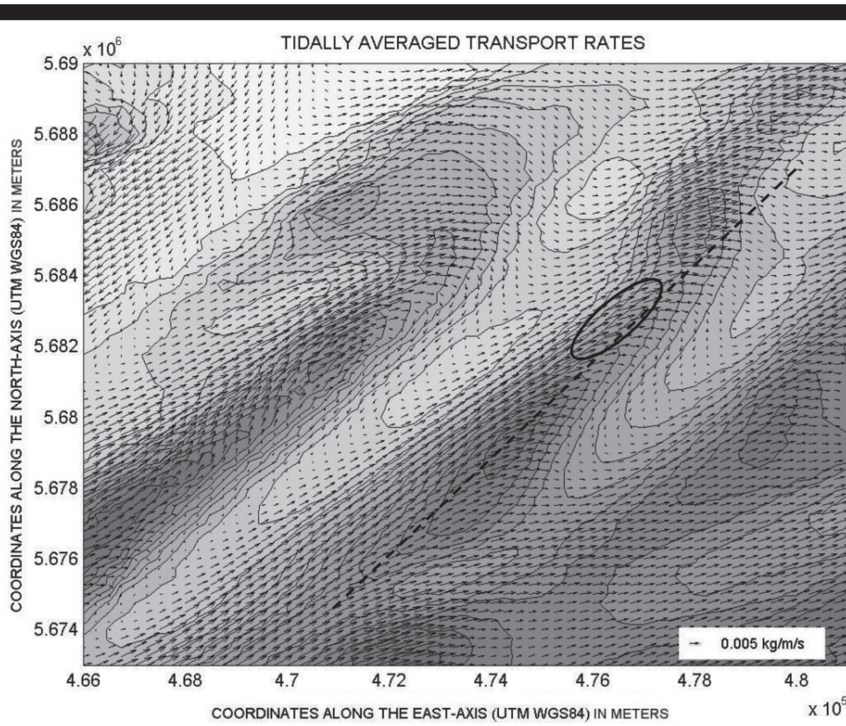


Figure 5. Asymmetry of tidal currents.

Table 2. *Values of mass transport predicted by the two models for the different scenarios at point (51.27°N, 2.63°E).*

	SISYPHE (kg/m/s)	Variation respect to standard run (SISYPHE)	MU-SEDIM (kg/m/s)	Variation respect to standard run (MU-SEDIM)
H_2004	0.01534	—	0.00861	—
H+W_2004	0.01890	1.23	0.08260	9.59
H+W_1995	1.90548	124.22	0.70182	81.51

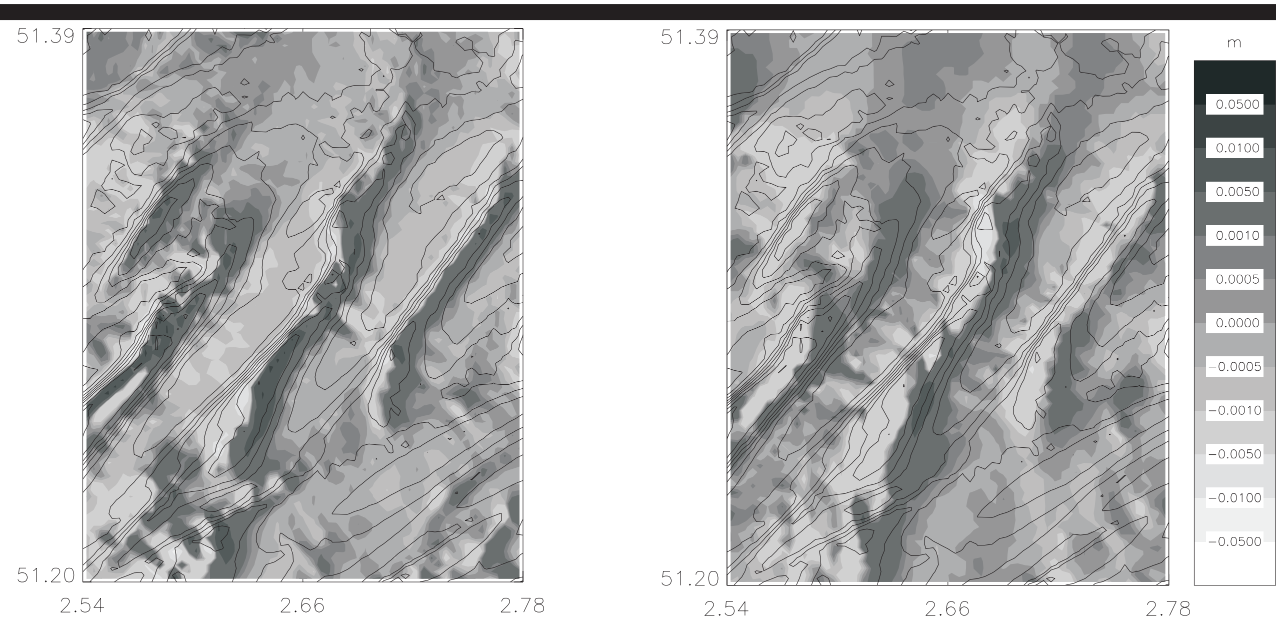


Figure 6. Erosion (light) and sedimentation (dark) patterns on the Kwinte Bank as simulated with only tides taken into account and for the period 2-16 March 2004. (a) Left: results of the MU-SEDIM model. (b) Right: results of the SISYPHE model.

Residual transport predicted by the SISYPHE model is about two times larger than the transport predicted by the MU-SEDIM model. Values of mass transport for a point located close to the crest are indicated in Table 2.

Tidal currents and waves

This simulation was carried out for the same period (2 -16 March 2004) but including the effects of waves and meteorological forces. Wave activity during the period considered was fairly low with maximum wave height reaching about 2 m (Figure 7).

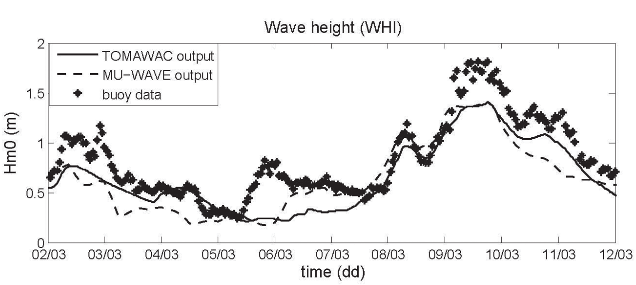


Figure 7. Modelled and measured significant wave height at Westhinder for the period 2-12 March 2004.

Model winds obtained from the United Kingdom Metereological Office were low compared to local wind measurements during that period (not shown). Although the height of the waves in not only a local process, the underestimation of the wave height calculated by the model can most likely be attributed to the limited spatial and time resolution of the model wind.

The residual transport computed by the two models is shown in Figure 8. In both models, the influence of wave activity leads to an increase in residual transport, especially evident at the sand bank crest where wave orbital velocities are higher. The increase in residual transport at the Kwinte Bank crest is about a factor 1.23 for the SISYPHE model, and about a factor 9.59 for the MU-SEDIM model (Table 2.) with respect to the simulation forced by tide only.

Moreover the SISYPHE model predicts a change in residual transport direction, locally visible at the Kwinte Bank crest. This leads to a different erosion-deposition pattern than the one observed considering tidal currents alone. This new pattern is characterized by erosion occurring at the east flank and deposition at the west flank of the sand bank (Figure 9.). The change in direction is not found in the MU-SEDIM results at the Kwinte Bank crest but it is visible, in both models, at the sand bank west of the Kwinte Bank (Buiten Ratel). Compared to the Kwinte Bank, the Buiten Ratel is characterized by a lower water depth at the crest, equal to about 5 m below MSL. Wave activity is therefore more important on this sand bank,

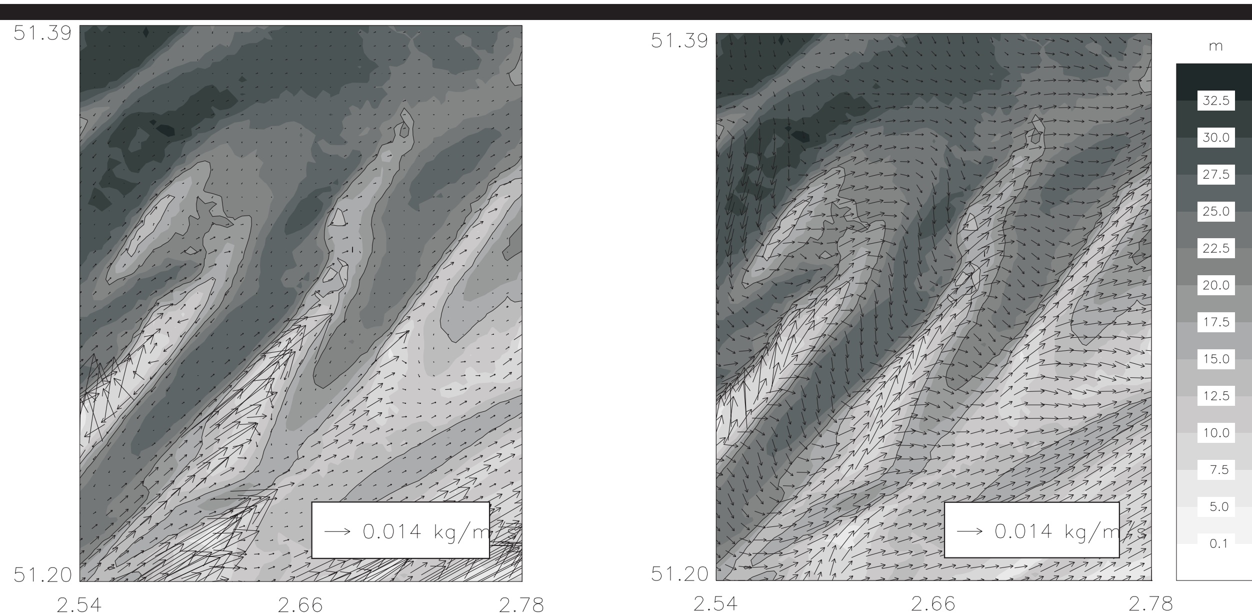


Figure 8. Sediment transport under the influence of tides, meteorological conditions and waves, for the period 2-16 March 2004. The bathymetry is shown in the background. (a) Left: results of MU-SEDIM. One vector for each four grid points is shown. (b) Right: results of the SISYPHE model. Results on the same grid as the MU-SEDIM model.

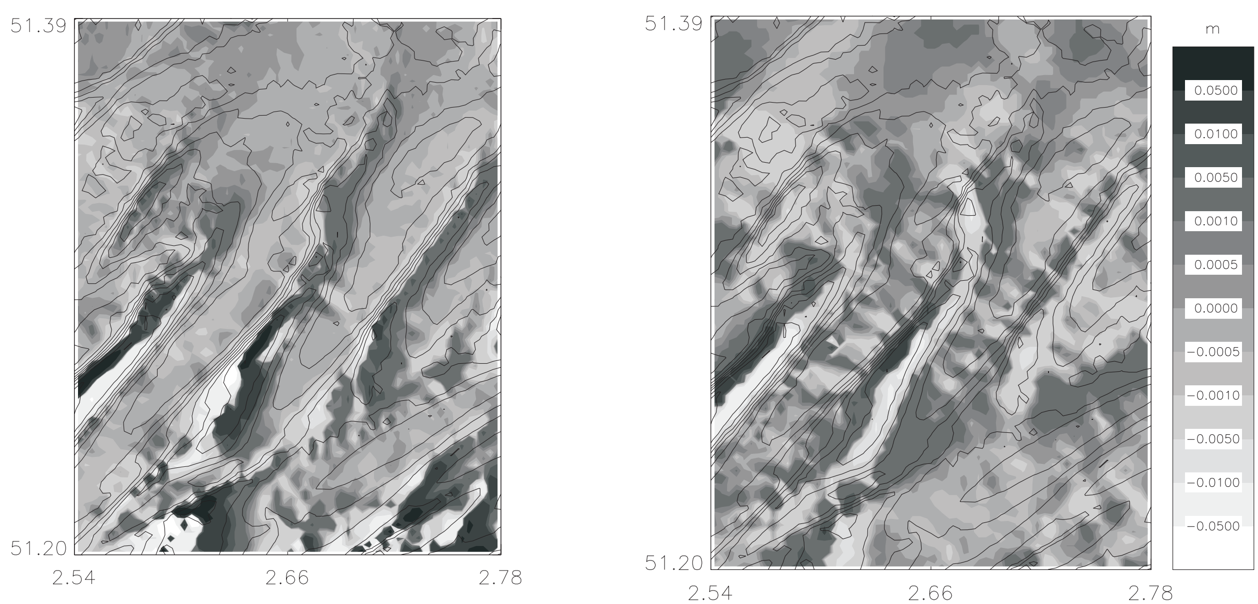


Figure 9. Erosion (light) and sedimentation (dark) patterns on the Kwinte Bank as simulated with tides, waves and meteorological conditions taken into account and for the period 2-16 March 2004. (a) Left: results of the MU-SEDIM model. (b) Right: results of the SISYPHE model.

leading to a change in sediment transport direction represented by both the formulations adopted in the two models.

Considering the fact that these two simulations were carried out applying equations which consider sediment transport direction determined by the direction of the currents, the observation that the addition of waves might change this direction is somehow unexpected. Two phenomena have to be considered to understand this change. Firstly, the asymmetry of the tide leads to ebb currents lasting about 10 % longer in time than flood currents. When wave activity is superimposed on current action, the critical entrainment velocity is exceeded for a longer period during ebb tide, weaker in intensity but longer in time. This can cause sediment transport to veer from flood to ebb current direction. Secondly, ebb currents reach their maximum intensity just before the water elevation is at its lowest. Considering the fact that the Kwinte Bank crest has a minimum water depth of about 7 m and that the tidal range, at spring tide, is about 5 m, it follows that orbital velocities at the bottom are, in average, considerably higher at ebb tide than at flood tide. This leads to a considerable increase in sediment transport at ebb tide.

The same simulation was repeated adopting other formulations for sediment transport. The BAILARD (1981), BIJKER (1968) formulations were tested in the SISYPHE model, while the VAN RIJN (1989), BAGNOLD (1966) and YALIN (1963) formulations were adopted in the MU-SEDIM model. Despite the fact that the results are quite different in magnitude, the change in sediment transport direction was predicted by all formulations.

Tidal currents and waves during a storm

A final simulation was carried out during a stormy period (1 - 15 January 1995) to assess the impact of an extreme event on the Kwinte Bank morphodynamics. Wave height at Westhinder reached in that period a maximum of about 5 m (Figure 10.).

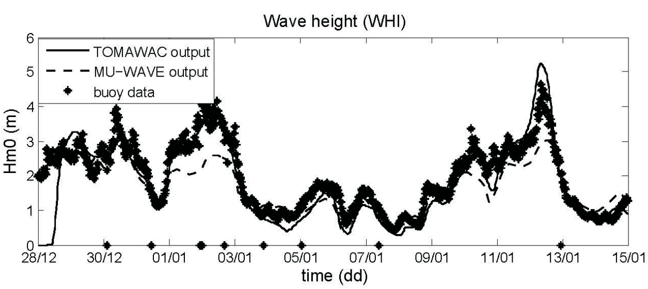


Figure 10. Modelled and measured significant wave height at Westhinder for the period 28 December 1994 to 15 January 1995.

Figure 11. shows the simulated residual transport during the stormy period. Sediment transport was increased by the presence of these exceptional waves by a factor 124.22 in the SISYPHE model and by a factor 81.51 in the MU-SEDIM model (Table 2.).

As a result, a bottom evolution in the order of one meter was predicted after this period (Figure 12.).

Concerning the direction in which sediments move, the SISYPHE model predicts a significant veering in residual transport, in the direction of the ebb currents. In this case the change in direction takes place not only at the Kwinte Bank crest but over the whole area due to the high wave intensity. The extreme waves that occurred during that period caused water particle velocity at the bottom to exceed the critical entrainment velocity during most of the period considered. Therefore, residual transport follows the direction of the ebb currents occurring for a longer period of time and when water depths are lower. In this respect, the output from the MU-SEDIM model is quite different, predicting a change in residual transport direction occurring only at the Buiten Ratel crest. An explanation for this difference may be found by looking at Figure 13. This Figure shows a sensitivity analysis of total load transport computed by the Ackers-White and by the Soulsby-Van Rijn formulas to a change in flow velocity and wave height. It is clear that the Ackers-White formula, as implemented in the MU-SEDIM model, is considerably more sensitive to strong currents than the Soulsby-Van Rijn formula. This causes transport to be dominated by tidal currents in the MU-SEDIM model, while the SISYPHE model is more sensitive to wave activity.

Once again, the calculation was repeated for different sediment transport formulations, showing the importance of wave activity in modifying the direction of residual transport and the proportionality of this change in direction to the increase in wave height.

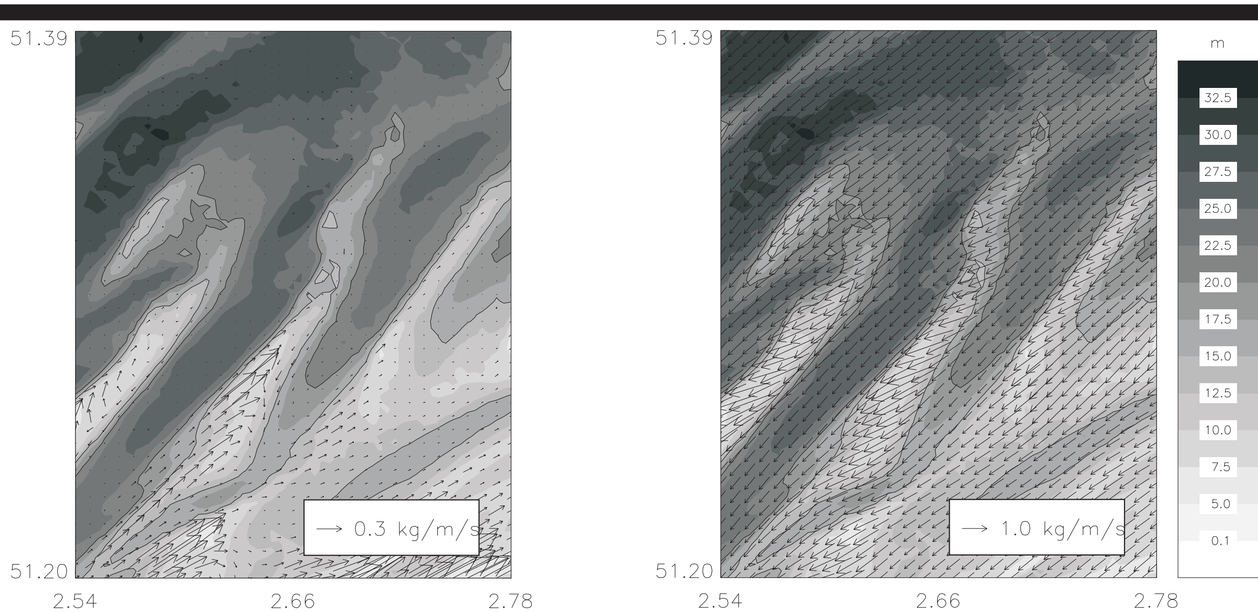


Figure 11. Sediment transport under the influence of tides, meteorological conditions and waves, for the period 1-15 January 1995. The bathymetry is shown in the background. (a) Left: Results of MU-SEDIM. One vector for each four grid points is shown. (b) Right: results of the SISYPHE model. Results on the same grid as the MU-SEDIM model.

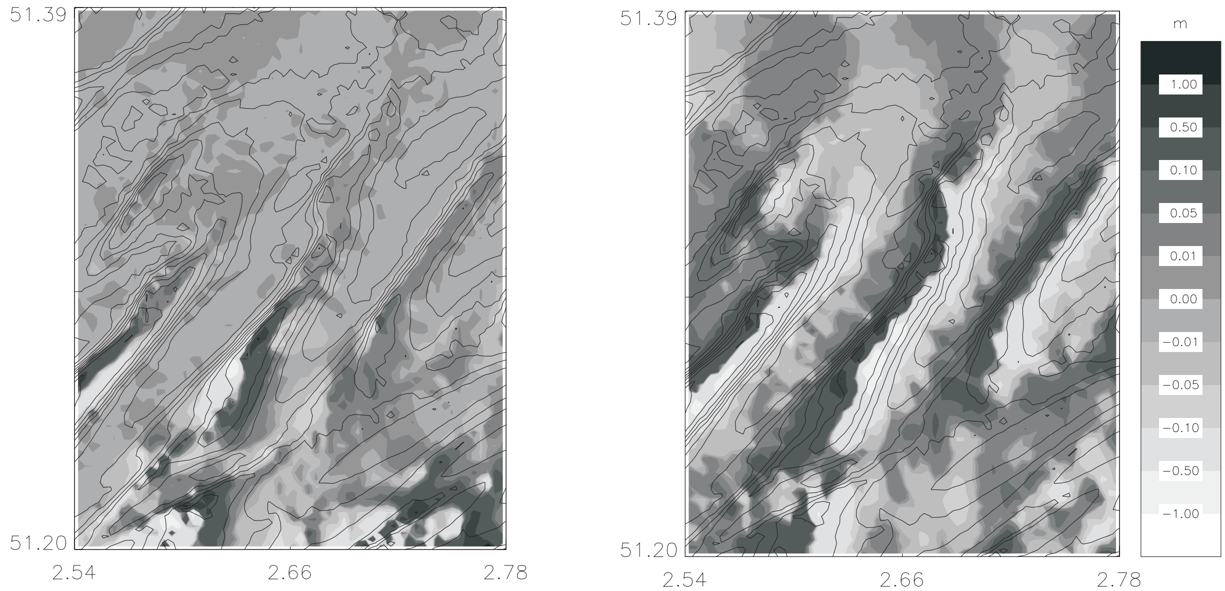


Figure 12. Erosion (light) and sedimentation (dark) patterns on the Kwinte Bank as simulated with tides, waves and meteorological conditions taken into account and for the period 1-15 January 1995. (a) Left: results of the MU-SEDIM model. (b) Right: results of the SISYPHE model.

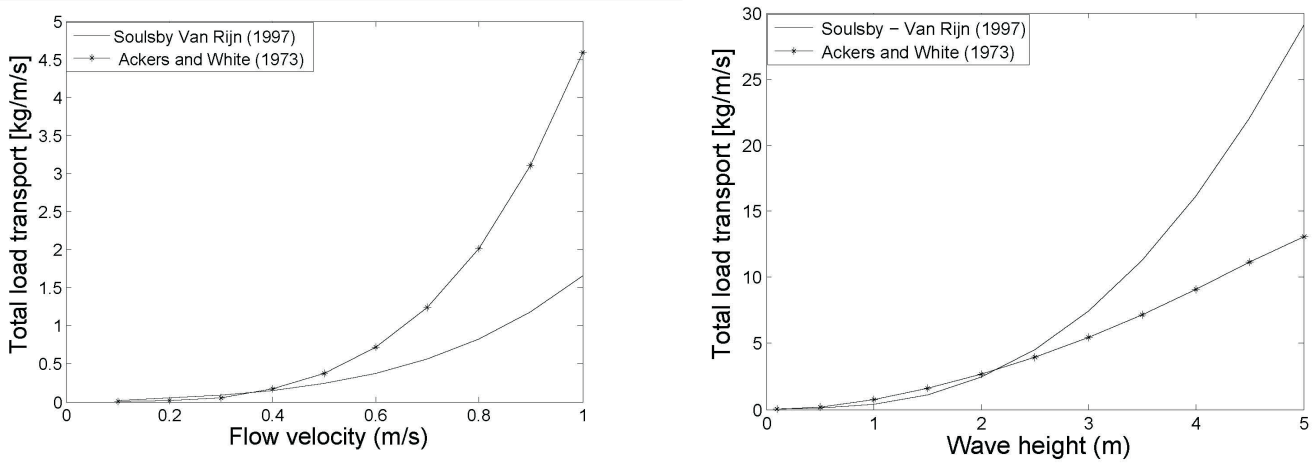


Figure 13. Sensitivity analysis of total load transport to flow velocity (left) and wave height (right). (a) Left: the flow velocity is combined with a constant wave field with significant wave height equal to 1 m and peak period equal to 6 s. Right: the wave height is combined with a constant flow velocity equal to 0.6 m/s.

Measurements of suspended sediment and bed form analysis

Suspended sediment measurements were collected by means of OBS and LISST devices during the March 2004 campaign. These data were analyzed in Giardino and Monbaliu (2006). Directions of residual transport were calculated by integrating over the vertical the product of flow velocities and sediment concentrations measured at different heights above the bottom. The set of measurements available did not give any confirmation concerning a change in residual transport direction for different wave heights. However, only concentration measurements at 0.25, 0.5 and 1 m from the bottom were collected. Calculation of suspended transport by integration of theoretical concentration profiles and flow velocity showed that, for standard flow conditions, more than 90 % of the transport occurs between 0 and 25 cm from the bottom, where no measurement was available. Moreover the instruments were located at a water depth ranging between 12 – 16 m, where wave effects are not as important as at the sand bank crest.

An indirect confirmation of the simulation results was found by looking at the asymmetry of the bed forms. Since little information, in this respect, was available for the Kwinte Bank, the sand bank west of the Kwinte Bank (Buiten Ratel) was taken into consideration. However, hydrodynamic and wave conditions can be considered comparable at the two sand bank and observations on the Buiten Ratel translatable to the Kwinte Bank. Baeye (2006) derived a map of sediment transport direction by

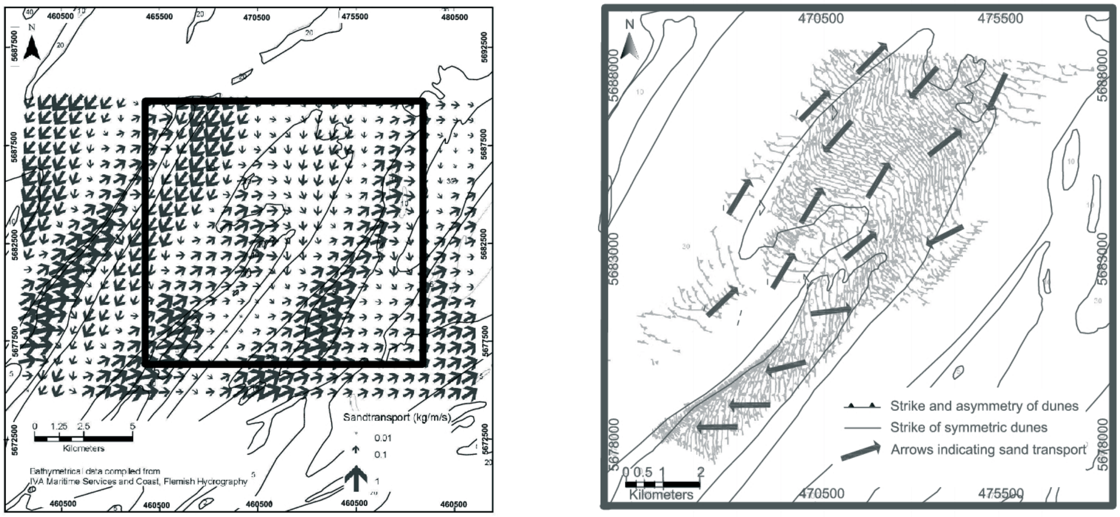


Figure 14. (a) Left: modelled residual sand transport under tidal action only (results of the MU-SEDIM model without taking waves into consideration). (b) Right: sand transport direction from dune asymmetry. The study was carried out at the Buiten Ratel sand bank (west of the Kwinte Bank) (Baeye, M., 2006).

looking at the shape of bedforms covering the Buiten Ratel (Figure 14.). Bottom images collected by means of a multibeam instrument during 5 different campaigns between 2002 and 2003 were used to reconstruct the shape of these bed forms.

Figure 14. shows a comparison of sediment transport direction derived from numerical simulations, with the direction of transport derived from dune asymmetry.

The numerical simulation was carried out by means of the MU-SEDIM model without taking waves into considerations. The modelled transport follows a general pattern similar to the pattern shown in Figure 4., driven by the stronger flood currents over the sand bank. However, dune asymmetry supplies a different picture of the overall transport, with sediment following the flood current direction in the northern part of the sand bank and transport towards the west flank in the southern part. In fact, the southern part is characterized by smaller water depth than the northern part. This would allow waves to penetrate more easily to the bottom, leading to a modification of the transport direction compared to the one determined by tidal currents only as shown by the previous numerical simulations. On the other hand, the larger water depths in the northern part would prevent waves from considerably influencing bottom dynamics, and in this case transport would be current dominated.

DISCUSSION

Long-term morphodynamic prediction of the Kwinte Bank

Analysis of the previous numerical simulations suggests the idea that wave activity, superimposed on the action of tidal currents, might lead to a variation in residual transport direction and to an inversion of the erosion-deposition pattern on the sand banks. However, different sediment transport formulations imply distinct wave thresholds responsible for this change in transport direction. These differences are essentially due to different weights entered in the formulations to the actions of waves and currents. As a consequence, equations in which wave action is considered more important, predict a change in transport direction up to deeper water depths while, according to other formulas, this change occurs only at the crest of the shallowest sand banks.

General conclusions on long-term morphodyamics of the Kwinte Bank may be drawn by looking at the output of the previous numerical simulations and relating them to wave climate statistics in the area. Table 3. shows statistical values for significant wave height registered at the Westhinder buoy during the period January 1977 – December 2002. Numerical simulations carried out adopting the Soulsby-Van Rijn formulation for sand transport, for example, show that an inversion of the erosion-

Table 3. *Significant wave height (cm) at Westhinder for the period January 1977 – December 2002 (from http://www.lin.vlaanderen.be/awz/hydro/www/klimaat/ golf_klimaat/mp7sb1h33/evst.htm)*

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
90% percentile	248	238	224	196	176	161	162	160	197	238	233	247
75% percentile	179	175	157	146	129	123	121	117	146	169	173	190
median	115	119	104	93	89	88	86	80	99	115	113	128
25% percentile	74	81	69	61	61	61	59	52	70	74	79	86
10% percentile	51	57	49	42	45	44	40	36	51	50	57	57

Table 4. *Sand banks at the Belgian Shelf and their morphology*

		Water depth at the crest (m below Mean Sea Level)	Steeper flank
Flemish banks	Oostdyck	5.05	West
	Buiten Ratel	5.03	West
	Kwinte Bank	7.46	West
	Middelkerke Bank	6.78	West
Hinder banks	Fairy Bank	10.75	East-West
	Noordhinder	15.57	East
	Westhinder	8.90	East - West
	Oosthinder	11.93	East
	Bligh Bank	12.43	East

deposition pattern due to wave action is visible at the Kwinte Bank crest whenever the average wave height, averaged during the period considered, exceeds a critical value of 0.4 – 0.6 m. In other words, whenever the average wave height is below this value, the western flank of the Kwinte Bank behaves as erosive and the eastern one as depositional. Inverse erosion-deposition pattern characterizes higher values of wave height. In terms of the wave climate, this threshold is exceeded about 80-90 % of the time. Hence, for most of the time, sediment transport as predicted by the Soulsby-Van Rijn formulation, will be directed from the eastern towards the western flank of the Kwinte Bank. In the long term, this would produce a migration of the sand bank towards the northwest. On the other hand, according to different historical observations, the Kwinte Bank seems behaving as a stable sand bank (Van Cauwenberghe, 1971). The difference found with the simulations might be due to an excessive weight given to wave activity in the Soulsby-Van Rijn formulation leading to a threshold which is higher in reality.

It is important to point out that for a long term morphodynamic analysis and prediction, additional phenomena related to climate change should be taken into account, such as possible increase in storminess and the sea level rise. The increase in storminess would contribute to increase the transport towards the western flank of the Kwinte Bank. However, a possible increase in storminess is still argument of debate between scientists. Results of several studies during the last decades show that the storm climate has been subjected to significant variations on time scales of decades (Wasa Group, 1998). Weisse, Von Storch, and Feser (2005) predicted for the Southern North Sea very little increase in storm frequency for the period 1958-2001 (about 1% - 2%). On the other hand, the rise in sea level would cause waves to be less effective at the bottom due to a reduction of the bottom orbital velocities, with a consequent decrease in sand transport. The rise in sea level for the southern North Sea has been estimated at about 1.2 mm/yr from observations over a 100 year period (Jensen *et al.*, 1990). This would reduce the wave penetration at the bottom counterbalancing the increase in storminess. An increase in wave height is also to be expected due to a reduction of bottom dissipation when sea level rises, in this case accompanied to an increase in sand transport. However, as pointed out by MacDonald and O'Connor (1996), the change in wave height for possible scenarios of sea level rise would be minor if not irrelevant at the Kwinte Bank.

Numerical simulations carried out by means of other sediment transport formulations produced different values for this threshold and, therefore also differences in long-term morphodynamic behaviour. Unfortunately, it remains unclear which formulation provides the better agreement with the real morphodynamic situation due to a lack of extensive measurements in space and time.

Sand bank morphology

The Kwinte Bank is part of a more complex sand bank system named *the Flemish Banks*. Various sand banks of this system present a tidal current and wave regime similar to the Kwinte Bank: the Oostdyck, the Buiten Ratel and the Middelkerke Bank (Figure 1.). Moreover, water depth and shape of these sand banks are similar, with a minimum water depth at the crest of about 5 – 7 m and the steeper side facing northwest (Van Lancker *et al.*, 2004) (Table 4.).

Another sand bank system, the *Hinder Banks*, is located north of the Flemish Banks. This system includes the Fairy Bank, the Noordhinder, the Westhinder, the Oosthinder and the Bligh Bank. The crests of these banks are slightly deeper than those of the Flemish Banks and are characterized by a steeper flank commonly facing the southeast side (Deleu *et al.*, 2004).

General belief has always attributed the difference in shape between the Flemish Banks and the Hinder Banks to a different equilibrium existing between flood and ebb currents. In this regard, wave action has always been neglected. The results from this study have brought new insight into the importance of waves in changing sediment transport patterns. A new hypothesis, which relates flow velocity at the bottom due to the combined effects of currents and waves to sand banks morphology, can therefore be formulated. This hypothesis is based on the fact that sand banks generally migrate in the direction of their steep side (Dyer and Huntley, 1999). For the Flemish Banks, which have their steeper flank facing northwest, this could be explained by the direction in which sediments are moving only when both waves and currents are considered. When only currents, or currents together with weak waves are taken into account, sediment transport would occur towards the stoss slope (gentle slope). This would create a sort of dynamic equilibrium due to the alternation between periods with low wave and periods with large wave activity. On the other hand, the steepest side of the Hinder Banks faces the southeast. This is the direction in which sediments move on those sand banks both when only currents are considered, and when waves and currents are superimposed. This phenomenon can be explained by the higher depth of these sand banks, which causes waves to be less effective at the bottom and sediment motion to be determined by the strongest flood currents. In other words, for both sand bank systems, a relationship seems to exist between water depth, wave activity at the bottom and sand bank shape.

Numerical modelling and physical observations seem to support the hypothesis that currents alone can not explain the difference in shape of the two sand bank systems. However, considerable additional research will be needed to really prove and to assess quantitatively the importance of wave activity in shaping the sand banks.

CONCLUSIONS

The present paper focused on the impact of wave activity on the bottom evolution of a sand bank (Kwinte Bank). Two different models were set up in order to compute the morphodynamic evolution of the Kwinte Bank under the combined effects of currents and waves. Despite differences between the two models, wave effects were found to be important for increasing the magnitude of sand transport. Moreover, wave activity together with tidal asymmetry seems to play an important role in changing the direction of residual sand transport. Several formulations for sand transport were compared, suggesting the idea that wave activity and tidal asymmetry give rise to a change in residual sand transport direction from a typical flood tide dominated environment towards an ebb tide dominated situation. This behavior was visible especially at the crest of the most shallow sand banks and increased in importance with increasing wave height. Bed form analysis from bottom images seems to confirm the idea that residual transport is occurring in some areas in the ebb tide direction. The change in residual transport direction would result in a change in the erosion deposition pattern at the Kwinte Bank producing an evolution of the sand bank towards its steeper west flank, in contrast to what could be expected considering the transport due to currents alone. In the long term, the two mechanisms (sand transport due to currents and low waves towards the eastern flank, and sand transport due to currents and significant waves towards the western flank) would balance each other out, leading to a sort of dynamic equilibrium.

Sediment concentration measurements did not give any confirmation regarding a change in residual transport direction at different wave heights. However, several limitations for this kind of study were found in the set of measurements currently available. For future research, sediment concentration and flow velocity profile measurements should be carried out at the sand bank crest and possibly cover a period with different wave conditions.

In conclusion, a new hypothesis was formulated, which relates the shape of the sand banks on the Belgian shelf to their water depth and, as consequence, to the local bottom dynamics. This hypothesis would explain why the Flemish Banks are characterized by a steeper flank facing the northwest, while the Hinder Banks system is characterized by a reversed morphology. According to this hypothesis the different shape would be related to the different water depth of the two sand bank systems, which would reflect on a different wave impact at the bottom and on a different residual transport direction.

ACKNOWLEDGEMENTS

The study was conducted within the framework of MAREBASSE (Management, Research and Budgeting of Aggregates in Shelf Seas related to End-Users), supported by the Belgian Federal Federal Science Policy. Additional support was provided by the Research Foundation Flanders project G.0477.04. The captain and crew of the *R.V. Belgica* are thanked for their help and assistance during the measurement campaigns. Our thanks are extended to Elke Van Ael for her comments and corrections which resulted in an improved manuscript.

LITERATURE CITED

Ackers, P. and White, W. R., 1973. Sediment transport: new approach and analysis, *Proceedings of the ASCE Journal of Hydraulics Division*, 99, 2041-2060

Baeye, M., 2006. Sediment - en morfodynamische evaluatie van de "Buiten Ratel" zandbank in het perspectief van een duurzame ontginningsstrategie, Ghent University, Renard Centre of Marine Geology, Master's thesis, 1-163

Bagnold, R., 1966. An approach to the sediment transport model from general physics, *US Geological Survey Professional Paper*, 422-I

Bailard, J., 1981. An energetics total load transport model for a plane sloping beach, *Journal of Geophysical Research*, 86, C11, 10938-10954

Benoit, M.; Marcos, F., and Beck, F., 1996. Development of a third generation shallow-water wave model with unstructured spatial meshing, *Proceedings of the 25th International Conference on Coastal Engineering*, (Orlando, Florida, USA, ASCEE), 465-478

Bijker, E.W., 1966. The increase of bed shear in a current due to wave motion. *Proceedings of the 10th Conference on Coastal Engineering*, American Society of Civil Engineers, Tokyo, Japan, 746-765

Bijker, E. W., 1968. Development of a third generation shallow-water wave model with unstructured spatial meshing, *Proceedings of the 11th Coastal Engineering*, (London, UK, ASCEE), 415-435

Brière, C.; Roos, P.C.; Garel, E., and Hulscher, S.J.M.H., this volume. Modelling the morphodynamic effects of sand extraction from the Kwinte Bank, Southern North Sea. *Journal of Coastal Research, Special Volume of Eumarsand - Marebasse project*

Carbajal, N. and Montano, Y., 2001. Comparison between Predicted and Observed Physical Features of Sandbanks, *Journal of Estuarine, Coastal and Shelf Science*, 52, 435-443

Collins, M. B.; Shimwell, S. J.; Gao, S.; Powell, H.; Hewitson, C., and Taylor, J. A., 1995. Water and sediment movement in the vicinity of linear sandbanks: the Norfolk Banks, southern North Sea, *Journal of Marine Geology*, 123, 3-4, 125-142

Cooreman, K.; Hillewaert, H.; Guns, M., and Van Hoeyweghen, P., 2000. Biological monitoring of dumping of dredged material at the Belgian coast (1997-1999) (in Dutch). Ministerie van Middenstand en Landbouw, Departement Zeevisserij, Oostende, *Report 97060/BAG/5*.

Deleu, S.; Van Lancker, V.; Van den Eynde, D., and Moerkerke, G., 2004. Morphodynamic evolution of the kink of an offshore tidal sandbank: the Westhinder Bank (Southern North Sea), *Journal of Continental Shelf Research*, 24, 1587-1610

Dyer, K. R. and Huntley, D. A., 1999. The origin, classification and modelling of sand banks and ridges, *Continental Shelf Research*, 19, 1285-1330

Fettweis, M. and Van den Eynde, D., 2000. Assessment of the sediment balance for the Belgian coastal waters: calculation with sediment transport models (in Dutch). Management Unit of the North Sea Mathematical Models, *Report SEBAB/1/MF/200006/NL/AR/2*, 45 pp.

Giardino, A. and Monbaliu, J, 2006. Wave effects on Sand Bank Morphodynamics, *Proceedings of the 2nd International Short Course and Workshop on COASTAL PROCESSES and PORT ENGINEERING*, Cosenza (Italy)

Günther, H., Rosenthal, W., 1985. The hybrid parametrical (HYPAS) wave model. *Ocean wave modelling, Swamp group*. Plenum Press, New York, 211-214.

Hasselmann, K.; Barnett, T. P.; Bouws, E.; Carson, H.; Cartwright, D.E.; Enke, K.; Wieng, J.A.; Gienapp, H.; Hasselmann, D.E.; Krusemann, P.; Meerburg, A.; Müller, P.; Olbers, D.J.; Richter, K.; Sell, W., and Walden, H., 1973. Measurements of wind-wave growth and swell decay during the Joint North Sea Wave project (JONSWAP), *Deutchen Hydrographischen Zeitung*, suppl. A., 8 (12), 95 pp.

Hasselmann, K.; Ross, D.B.; Müller, P., and Sell, W., 1976. A parametrical wave prediction model. *Journal of Physical Oceanography*, 6, 201-228.

Hasselmann, S.; Hasselmann,K.; Allender,J.H., and Barnett, T.P., 1985 Computations and parametrizations of the nonlinear energy transfer in a gravity-wave spectrum. Part 2: Parametrizations of the nonlinear energy transfer for application in wave models. *Journal of Physical Oceanography*, 15, 1378-1391.

Hervouet, J.-M. and Bates, P., 2000. The TELEMAC Modelling System Special Issue, *Hydrological Processes*, 14, 13, 2207-2363

Hulscher, S. J. M. H.; De Swart, H. E., and De Vriend H.J., 1993. The generation of offshore tidal sand banks and sand waves, *Journal of Continental Shelf Research*, 13, 1183-1204.

Huthnance, J. M., 1973. Tidal currents asymmetries over the Norfolk sandbanks, *Journal of Estuarine and Coastal Marine Science*, 1, 89-99

Huthnance, J. M., 1982b. On the formation of sand banks of finite extent, *Journal of Estuarine, Coastal and Shelf Science*, 15, 277-299

Huthnance, J. M., 1982a. On one mechanism forming linear sand banks, *Journal of Estuarine and Coastal Marine Science*, 14, 19-99

Janssen, P.A.E.M., 1989. Wave-induced stress and the drag of the air flow over sea waves, *Journal of Physical Oceanography*, 19, 745-754

Janssen, P.A.E.M., 1991. Quasi-linear theory of wind-wave generation applied to wave forecasting, *Journal of Physical Oceanography*, 21, 1631-1642

Jensen,J.; Mügge, H-E., and Schönfeld, W., 1990. Development of water level changes in the German Bight, an analysis based on single value time series. *Proceedings of the 22nd International Coastal Engineering Conference*, 1, 2839-2851

Komen,S.; Hasselmann, S., and Hasselmann,K., 1984. On the existence of a fully developed wind-sea spectrum, *Journal of Physical Oceanography,* 14, 1271-1285, 1984

Lanckneus, J.; Van Lancker, V.; Moerkerke, G.; Van den Eynde, D.; Fettweis, M.; De Batist., and M., Jacobs, P., 2001. Investigation of the natural sand transport on the Belgian continental shelf (BUDGET), Federal Office for Scientific, Technical and Cultural Affairs (OSTC), *Final Report*

Luyten, P. J.; Jones, J. E.; Proctor, R.; Tabor, A.; Tett, P., and Wild-Allen, K., 1999. *COHERENS: A Coupled Hydrodynamical-Ecological Model for Regional and Shelf Seas: User Documentation*, Management Unit of the North Sea Mathematical Models, Brussels, 1-914.

MacDonald,N.J., and O'Connor,B.A. 1996. Changes in wave impact on the Flemish coast due to increased mean sea level, *Journal of Marine Systems*, 7, 133-144

Osuna Cañedo, J.P., 2002. On the high-resolution simulation of the dynamic interaction between currents and waves in coastal waters: an application to the southern North Sea, Civil Engineering Department, Katholieke Univeristeit Leuven, Belgium, Ph.D. thesis, 196 p.

Osuna Cañedo, J.P., Monbaliu, J., 2004. Wave-current interaction in the Southern North Sea, *Journal of Marine Systems*, 52, 65-87

Sleath, J.F.A., 1984. _Sea Bed Mechanics_, Wiley-Interscience, New York, 1-335

Soulsby, R. L., 1997. Dynamic of marine sands, Thomas Telford, London, 1-249

Swart, D. H., 1976. Coastal Sediment Transport. Computation of Longshore Transport, Delft Hydraulics Laboratory, The Netherlands, *Report R968*

Swart, D. H., 1977. Weighted value of depth of initiation of movement, Stellenbosch, South Africa, *Report NR10*

Tonnon, P.K., Van Rijn, L.C., Walstra,D.J.R., 2007. The morphodynamic modelling of tidal sand waves on the shoreface, Delft Hydraulics Laboratory, The Netherlands, *Journal of Coastal Engineering*, 54, 279-296

Van Cauwenberghe, C., 1971. Hydrografische analyse van de Vlaamse banken langs de Belgisch-Frans kust, *Het Ingenieursblad 40*, 19, 563-571

Van de Meene, Y. W. H. and Van Rijn, L. C., 2000. The shoreface-connected ridges along the central Dutch coast - part 2: morphological modelling, Journal of *Continental Shelf Research*, 20, 2325-2345

Van den Eynde, D.; Giardino, A.; Portilla, J.; Fettweis, M.; Francken, F., and Monbaliu, J., this volume. Modelling the effects of sand extraction on the sediment transport due to tides on the Kwinte Bank., *Journal of Coastal Research*, *Special Volume of Eumarsand - Marebasse project.*

Van den Eynde, D., 1992. mu-WAVE: an operational wave forecasting system for the Belgian coast. *Proceedings of the Third International Workshop on Wave Hindcasting and Forecasting*, (Montréal, Canada), 313-324.

Van den Eynde, D. and Ozer, J., 1993. Sediment Trend Analysis: calculation of the sediment transport with a numerical model (in Dutch). Management Unit of the North Sea Mathematical Models, *Rapport BMM/STA/TR01*, 1-49

Van den Eynde, D.; Scory, S., and Malisse, J.-P., 1995. Operational modelling of tides and waves in the North Sea on the Convex C230 at MUMM, *Proceedings of the European Convex User's Conference 1995,* (Brussels, Belgium).

Van Lancker, V.; Moerkerke, G.; Fettweis, M.; Van den Eynde, D.; Monbaliu, J.; Lanckneus, J., and Degraer, S., (2002). Nood aan evaluatiemiddelen voor de opvolging van kustsystemen. [The need for evaluation tools for coastal system monitoring], Colloquium 'Kustzonebeheer vanuit geo-ecologische en economische invalshoek', [Symposium 'Coastal zone management from a geo-ecological and economical perspective'], *VLIZ Special Publication*, 10. Genootschap van Geologen van de Universiteit Gent (GGG)/Vlaams Instituut voor de Zee (VLIZ): Oostende, Belgium, 1-5.

Van Lancker, V.; Deleu, S.; Bellec, V.; Le Bot, S.; Verfaille, E.; Fettweis, M.; Van den Eynde, D.; Francken, F.; Pison, V.; Wartel.S.; Monbaliu, J.; Portilla, J.; Lanckneus, J.; Moerkerke, G., and Degraer, S., 2004. Management, research and budgeting of aggregates in shelf seas related to end-users (Marebasse), Federal Office of Scientific, Technical and Cultural Affairs (OSTC), *Scientific report 2*, 1-144.

Van Lancker, V.; Deleu, S.; Bellec, V.; Verfaille, E.; Du Four, I.; Fettweis, M.; Van den Eynde, D.; Francken, F.; Monbaliu, J.; Portilla, J.; Giardino, A.; Moerkerke, G., and Degraer, S., 2005. Management, research and budgeting of aggregates in shelf seas related to end-users (Marebasse), Federal Office of Scientific, Technical and Cultural Affairs (OSTC), *Scientific report 3*, 2-103.

Van Rijn, L., 1989. Handbook Sediment Transport by Currents and Waves, Delft Hydraulics, *Report H461.*

Van Rijn, L. C., 1984. Sediment transport: part I: bed load transport; part II: suspended load transport; part III: bed forms and alluvional roughness, *Journal of Hydraulic Engineering*, 110, 1431-56; 1613-41; 1733-54.

Villaret, C., 2004. SISYPHE RELEASE 5.4 User Manual, EDF/LNHE, *Report P75G17*, 1-69.

Villaret, C., and Davies, A.G., 2004. Numerical modelling of littoral sand transport, *Proceedings of the 29th International Conference on Coastal Engineering*, Lisbon, 1678-1689.

Vincent, C. E.; Stolk, A., and Porter, C. F. C., 1998. Sand suspension and transport on the Middelkerke Bank (southern North Sea) by storms and tidal currents, *Journal of Marine Geology*, 150, 113-129.

Wasa Group, 1998. Changing waves and storms in the Northeast Atlantic? *Bulletin of the American Meteorological Society*, 79, 741-760.

Weisse,R.; Von Storch,H., and Feser,F., 2005. Northeast Atlantic and North Sea Storminess as Simulated by a Regional Climate Model during 1958-2001 and Comparison with Observations, *Journal of Climate*, American Meteorological Society, 465-479.

Yalin, M.S., 1963. An expression for bed-load transportation, *Journal of the Hydraulics Division*, ASCE, 89, 221-250.

Journal of Coastal Research	SI	51	141-150	West Palm Beach, Florida	Summer 2010

Macrobenthos characteristics and distribution, following intensive sand extraction from a subtidal sandbank

Wendy Bonne[1*]

[1] AZTI Foundation
Marine Research Division
Herrera Kaia, Portualdea s/n
20110, Pasaia, Spain

[*] Present address:
Marine Environment Service, Directorate
General Environment,
Federal Public Service Health, Food Chain
Safety and Environment,
Belgian Federal Government
Victor Hortaplein 40 box 10
1060 Brussels, Belgium
Wendy.Bonne@health.fgov.be

ABSTRACT

Macrobenthic fauna are investigated, to establish the nature and vulnerability of benthic communities to aggregate mining on a subtidal sandbank, the Kwinte Bank, in the Southern Bight of the North Sea. Within the central part of this sandbank, a depression (5 m deep) has been created, as a result of 20 years of dredging over the same small area (1 km long and 700 m wide). Three stations were sampled within this central depression; two on the western border; and two to the east of the depression. Another station was sampled in a "non-exploited" area to the north of the depression. Four stations were sampled outside of the concession area, on the adjacent Middelkerke Bank. The hypothesis is tested as to whether or not the density, species richness, taxon and community composition do not differ, between the depression and the adjacent sites (with similar sediment composition) on top of the sandbank. In addition, it is examined whether these parameters differ between the depression and reference sites, at the adjacent undisturbed sandbank. Differences in density and species richness could not be detected, between the different locations. Compared to the reference stations at the Middelkerke Bank and locations next to the depression, crustaceans (amphipods and in particular *Bathyporeia* spp.) and echinoderms (*Ophiura* spp. and *Echinocardium cordatum*) were more abundant in the area of the depression, suggesting a higher similarity to the swale environment, than was the case previously. The observed trends were similar, for both of the sampling periods, February and November 2004. However, the species composition difference has been observed within the context of the wide range of species assemblages described earlier for the Kwinte Bank, together with other Belgian subtidal sandbanks. Sand extraction has created small-scale habitat differences on the Kwinte Bank, to which the benthic fauna have adjusted; however, this is not significant on a true larger scale of the sandbank system, one year after cessation of the intensive disturbance.

ADDITIONAL INDEX WORDS: *ecological impact, human disturbance, sand extraction, recovery, Kwinte Bank, Middelkerke Bank, North Sea.*

INTRODUCTION

The investigation of the ecological impact of sand extraction has a long history (ICES, 1992, 2001). This observation applies also to the Kwinte Bank in the Belgian sector of the North Sea, where the first impact assessment of sand extraction was undertaken in the late 1970s (VANOSMAEL *et al.*, 1979; VANOSMAEL *et al.*, 1982). In spite of the fact that sand extraction from sandbanks in Belgian marine waters has been monitored for more than 30 years, the effect on macrobenthic communities has not been detected, before the present investigation. The spatial variation in extraction intensity was not analysed in detail before 2000, as an essential prerequisite to characterising the environmental impact. BONNE (2003) attempted to relate benthic copepod communities of different areas at the Kwinte Bank to sand extraction intensity, for each sampling station, from the "black-box" records of the extraction vessels. The benthic copepod communities identified in 1997, in high extraction intensity areas, varied from those observed in 1976, from the same area. A central depression on the Kwinte Bank was detected, in multibeam imagery, in 2000; this was characterised by intensive sand extraction activities and an impoverishment of the copepod communities. However, a preliminary analysis of available macrobenthos data (from the University of Ghent) did not reveal the same pattern. Based upon these data, any differences in density or species number could not be detected, since the commencement of sand extraction on the Kwinte Bank. However, a deviation in species composition was observed (BONNE, 2003) and confirmed by VANAVERBEKE *et al.* (2007). The extraction of sand from the Kwinte Bank accounted always for more than 95 % of the total volume extracted from Belgian subtidal sandbanks, up to 2003. Until this time the effect of sand extraction on the Kwinte Bank has not been assessed with more than two sampling stations, for monitoring purposes. Hence, an appropriate macrobenthos dataset and an assessment of sand extraction on this intensively (commercially) targeted sandbank, were lacking. Within this context, macrobenthos is accepted widely as an appropriate tool to investigate and detect changes, caused by human dis-

DOI: 10.2112 / SI51-013.1 received 15 January 2007; accepted in revision 8 June 2008.

turbances. In general, most studies undertaken into the impacts of marine sand and gravel extraction have focused upon macrofauna (Boyd *et al.*, 2005; Kenny and Rees, 1996; Newell, Seiderer, and Hitchcock, 1998; Sarda *et al.*, 2000; van Dalfsen *et al.*, 2000). The present investigation attempts to characterise this faunal grouping, for the central depression of the Kwinte Bank; likewise, to compared them with adjacent sites and an unexploited (reference) part of a sandbank. The central depression of the Kwinte Bank was closed for sand extraction, in February 2003. In February and November 2004, the fauna was sampled, to establish any short-term recovery. The hypothesis is tested here that density, species richness, taxon and community composition do not differ between the depression and adjacent sites, with a similar sediment composition on top of the sandbank. In addition, whether these parameters differ between the depression and reference sites, on an adjacent undisturbed sandbank.

SITE DESCRIPTION

The Kwinte Bank and the Middelkerke Bank belong to the Flemish Banks, a group of (7) linear subtidal sandbanks, located to the west of Oostende, at 10 to 30 km off the Belgian coast (Figure 1.). These sandbanks are SW-NE oriented and are separated by swales, which dip to the northeast (Lanckneus, De Moor, and Stolk, 1994).

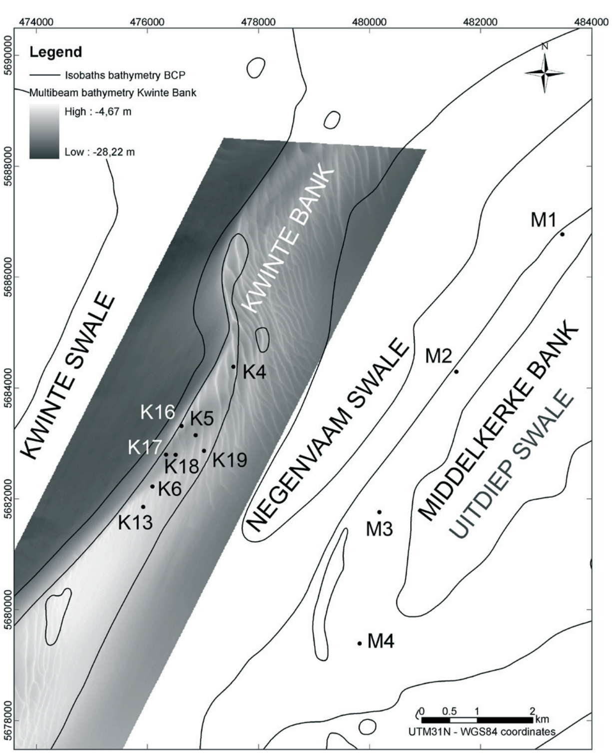


Figure 1. Map showing the location of the sampling stations on the Kwinte and the Middelkerke Banks: The Kwinte Bank crest stations are superimposed onto a multibeam image. The bathymetry and morphology (banks and swales) of the sandbanks are shown including the central depression on the sandbank.

The Kwinte Bank (Figure 1.) is an elongated linear subtidal sandbank, of about 15 km in length, 3 km in width and rising between 10 m (in the north) and 20 m (in the south), above the surrounding seafloor. The mean water depth varies between 6 m over the central part, to over 20 m in the northern and southern edges of the bank (Lanckneus *et al.*, 1992). The characteristics of the depression, together with its creation by sand extraction, are described in detail in Degrendele *et al.* (this volume); it is about 1 km long and 700 m wide, located along the western crest and beneath the "kink" in the central part of the sandbank (Figure 1.). The two swales adjacent to the Kwinte Bank are known, respectively, as the Kwinte (to the northwest) and the Negenvaam (to the southeast). The latter is located between the Kwinte Bank and the Middelkerke Bank.

The Middelkerke Bank (Figure 1.) has a length of 12 km, a mean width of 1,5 km and a height above the surrounding sea floor which varies between 8 m in the northeast, to 15 m in the southwest. The depth (MLLWS) varies between 4 m in the southwest, to 20 m in the northeast (Trentesaux *et al.*, 1994). The swale on the northwestern side is known as the Negenvaam (see above), whilst the southeastern side of the bank borders the Uitdiep.

METHODS

Sampling and Processing

Eight stations were sampled in February and November 2004, over the central part of the Kwinte Bank, together with 4 stations on the adjacent Middelkerke Bank in November 2004 (Figure 1.). The latter sandbank represents a reference area for medium-sized sands; this sandbank lies outside the concession areas, having never been exploited. On the Kwinte Bank, 3 stations were located within the central depression (K5, K18, K6), 2 stations along its western border (K16, K17) and 2 at its eastern border, at the crest of the sandbank (K13, K19). The grouping of these stations is based upon an analysis of the extraction intensity at the different stations, until cessation of extraction in February 2003. The vessel "black-box" records indicated that stations K5, K18 and K6 have been disturbed frequently. One station (K4) was sampled at the crest, in an unexploited part of the bank associated with coarse sediments lying just to the north of the depression on the Kwinte Bank. This station has been sampled to investigate if it can be considered as a reference for the coarse sediments, present over the western flank of the depression.

Macrobenthos samples were collected from each station using a Van Veen grab; for each, 5 replicate grabs were obtained. From each of the grabs, a sub-sample was taken with a 1.5 cm^2 perspex coring tube. These sub-samples were dried immediately at 60°C, for granulometric analysis. The macrobenthic samples were first fixed with formaldehyde, then sieved onboard over a 1 mm mesh-sized sieve. After staining with Rose Bengal, the samples were washed by decantation (repeated 10 times), in the laboratory and over a 300 µm sieve, to retain fragmented organisms. Anthozoa, Oligochaeta and Nemertea were counted as groups and representatives of the Polychaeta, Mollusca, Archiannelida, Crustacea and Echinodermata were identified under a stereoscopic microscope to species level where possible.

Sediment sub-samples were sieved in the laboratory, using a complete column of sieves (4000 to 63 mm). Grain-size parameters have been calculated according to the approach of

FOLK and WARD (1957). Sediment classification was defined according to the Wentworth scale (WENTWORTH, 1922).

Water depth measurements were standardised to Mean Low Water Springs (MLWS), using the M2 reduction model[1].

Statistics

Differences in macrobenthos density (log(x+1) transformed) and species richness (untransformed), between both sampling periods and the different locations distinguished for the Kwinte Bank and the Middelkerke Bank, were analysed by means of a two-way ANOVA. Overall significant differences were pairwise-compared using the Tukey honest significant difference test, for unequal sample sizes. For the non-parametric data, such as the percentages and abundances of particular taxa, the Kruskall-Wallis ANOVA by Ranks was preferred; after this, overall significant differences were further pairwise-analysed, following CONOVER (1971). All of the univariate statistical analyses were performed with STATISTICA software (Microsoft, StatSoft, Inc., 2000).

An ordination was performed on fourth-root transformed absolute species abundances. A Detrended Correspondence Analysis (DCA, HILL, 1979) and a Canonical Correspondence Analysis (CCA, HILL 1979) were selected as indirect and direct gradient analyses, respectively, to illustrate the (dis)similarities in species composition, between different periods and locations; likewise, to relate them to sediment characteristics.

RESULTS

Sediment Characteristics

A gradient can be discerned over the Kwinte Bank, ranging from very coarse sediment to the north of the depression (station K4), through the slightly less coarse western border and the heterogeneous sediments of the depression, towards the finer sediments at the eastern border of the depression (Figure 2.).

The depression is characterised by relatively high percentages of fine sand, compared to the other locations. Within the depression at the Kwinte Bank and within the reference area of the Middelkerke Bank, some differences in sediment composition can be distinguished. In order to take into account sediment composition, when comparing densities of specific taxa and genera between the depression and the reference area at the Middelkerke Bank, K5 will be compared with M1 and M2; K6 with M4; and K18 with M3. However, these "station-to-station" comparisons correspond to a relatively low power of the analysis, to detect significant differences.

Biological Parameters

Density, species number and macrobenthos taxa composition have been compared, between: (a) the western border of the depression; (b) the depression; (c) the eastern border of the depression; (d) the unexploited part to the north of the central depression; (e) and the entire Middelkerke Bank, as an undisturbed reference area. Seasonal differences, between February and November 2004, have been assessed for the Kwinte Bank.

Density and species number

In November 2004, essentially higher densities were recorded than in February 2004 (Figure 3.). However, such seasonal differences were only significant for the eastern border of the depression ($p < 0,05$). Similarly, the species number increased, in general, from February to November 2004, but

[1] (Flemish Hydrography, Division Coast, Agentschap voor Maritieme Dienstverlening en Kust (MDK), of the Flemish Public Administration).

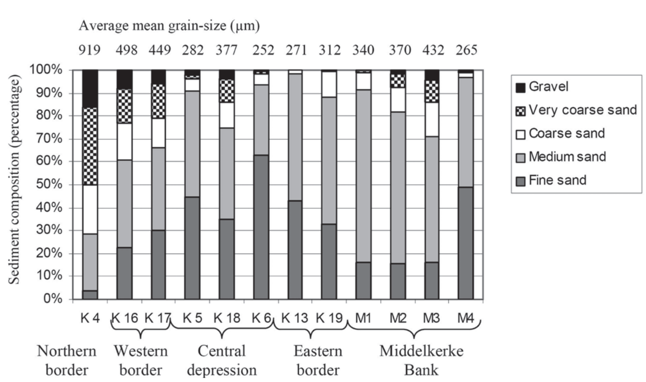


Figure 2. Average sediment composition at the sampling stations of the Kwinte Bank and the Middelkerke Bank. The average mean grain-size is listed for each station, at the top of the column. Note: for station locations, see Figure 1.

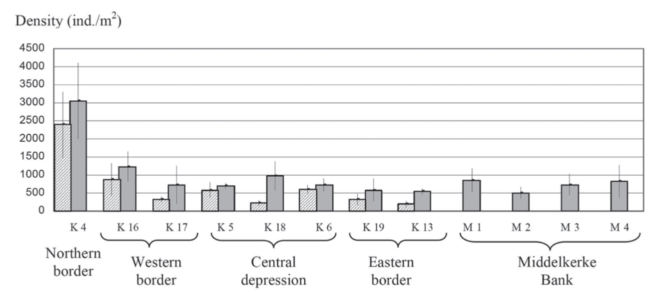


Figure 3. Macrobenthos density per station, at the different locations of the Kwinte Bank and at the Middelkerke Bank, for February 2004 (light grey bars) and November 2004 (darker shaded bars). Note: for station locations, see Figure 1.

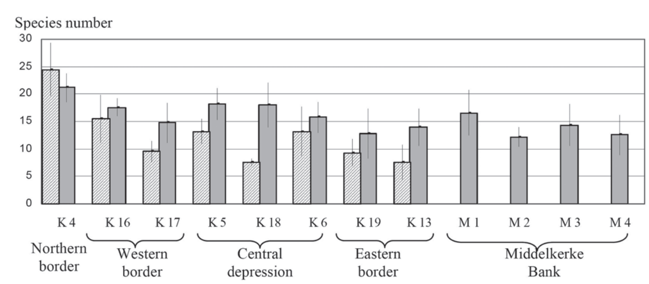


Figure 4. Macrobenthos species richness per station, at the different locations of the Kwinte Bank and at the Middelkerke Bank, for February 2004 (light grey bars) and November 2004 (darker shaded bars). Note: for station locations, see Figure 1.

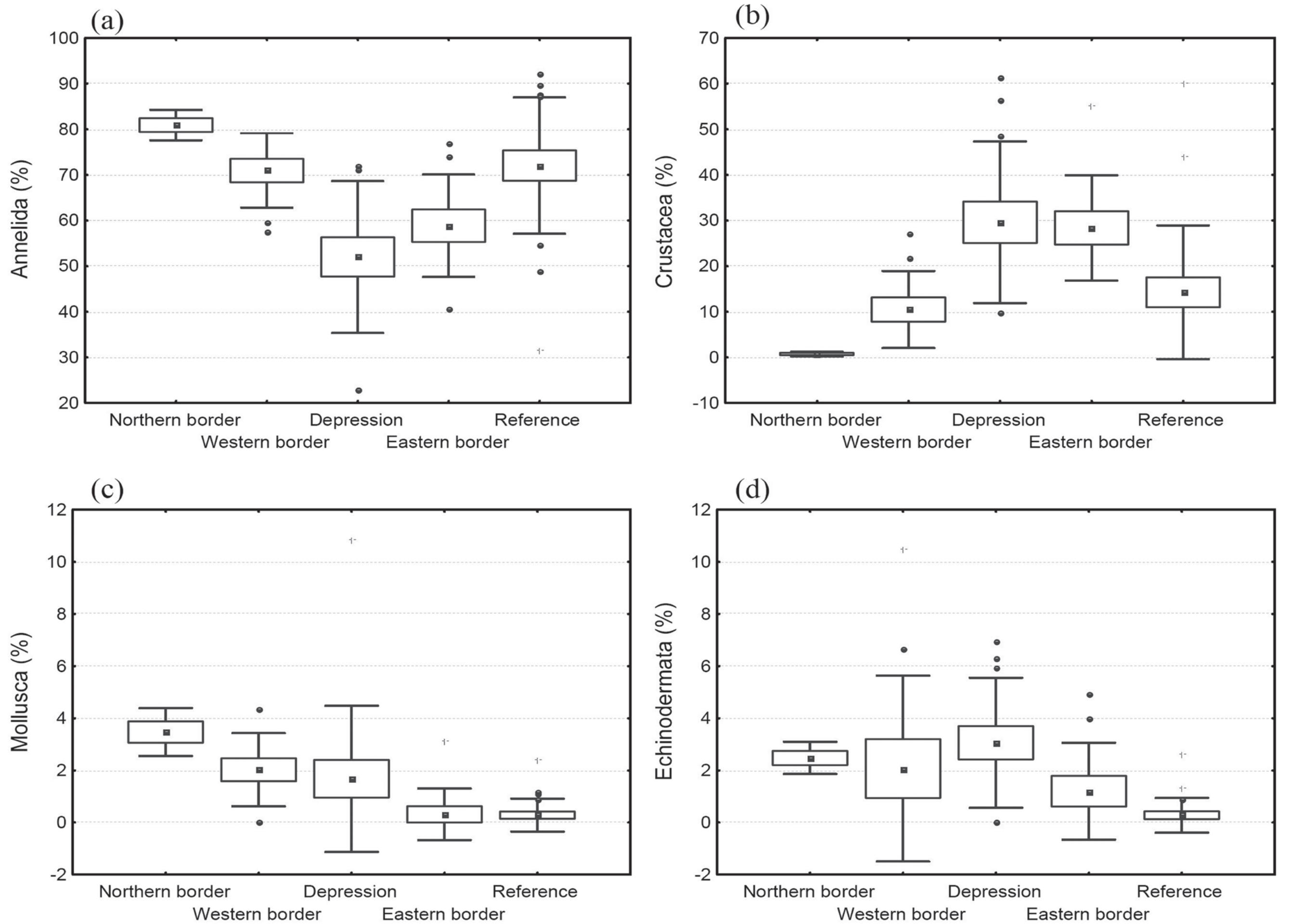


Figure 5. Relative abundance per location at the Kwinte Bank (Northern border, Western border, Depression, Eastern border) and the Middelkerke Bank (reference location) for different macrobenthos taxa: (a) Annelida; (b) Crustacea; (c) Mollusca; and (d) Echinodermata.

Table 1. *Significant differences in the relative abundance of particular macrobenthic taxa, between the different locations on the Kwinte Bank and the Middelkerke Bank. Key: * = p < 0,5; ** = p < 0.01; and *** = p < 0.001. Note: for the station locations and their description, see Figures 1. and 2.*

Taxon				**Annelida**		
	Location	Station 4	Western border	Depression	Eastern border	Reference area
Crustacea	Station 4		*	***	***	n.s.
	Western border	**		**	n.s.	n.s.
	Depression	***	***		n.s.	***
	Eastern border	***	***	n.s.		**
	Reference area	**	n.s.	***	***	

Taxon				**Mollusca**		
	Location	Station 4	Western border	Depression	Eastern border	Reference area
Echinodermata	Station 4		n.s.	**	***	***
	Western border	n.s.		n.s.	***	***
	Depression	n.s.	n.s.		*	*
	Eastern border	*	n.s.	*		n.s.
	Reference area	***	*	***	n.s.	

Table 2. *Significant differences in density of particular macrobenthic taxa between the different locations at the Kwinte Bank and the Middelkerke Bank (* = p < 0,5, ** = p < 0.01, *** = p < 0.001).*

	Taxon	Ophiura species				
	Location	Station 4	Western border	Depression	Eastern border	Reference area
Echinocardium cordatum	Station 4		n.s.	n.s.	n.s.	n.s.
	Western border	n.s.		*	n.s.	n.s.
	Depression	*	**		**	***
	Eastern border	n.s.	n.s.	n.s.		n.s.
	Reference area	n.s.	n.s.	*	n.s.	
	Taxon	**Amphipoda**				
	Location	Station 4	Western border	Depression	Eastern border	Reference area
Bathyporeia species	Station 4		*	***	***	*
	Western border	n.s.		**	n.s.	n.s.
	Depression	**	*		n.s.	***
	Eastern border	n.s.	n.s.	n.s.		*
	Reference area	n.s.	n.s.	*	n.s.	
	Taxon	**Tellimya ferruginosa**				
	Location	Station 4	Western border	Depression	Eastern border	Reference area
			n.s.	*	n.s.	n.s.
	Western border			**	n.s.	n.s.
	Depression				n.s.	**
	Eastern border					n.s.

significant only in the depression (p < 0,01). Only to the north of the depression (Station K4), the species number decreased slightly between the two sampling periods.

Density and species number were significantly higher at Station K4 (p < 0,005, p < 0,0005, respectively), in comparison with all the other Kwinte Bank locations, in February 2004. This difference still existed for density in November 2004, but was not observed anymore for the species number, since the species number in November decreased at station 4 and increased at the other stations in comparison with February (Figure 4.). Density and species richness are also significantly higher at station K4, in comparison with the entire Middelkerke Bank (p < 0,0005 and p < 0,05, respectively).

Density or species number data do not permit differentiation of the depression, from its western border or from its eastern border, for neither of the two periods. The depression is characterised by an intermediate density, between those of the western and the eastern borders. The species number was very similar over the entire central part of the Kwinte Bank, without any distinction between the depression and the western or the eastern borders. No differences could be detected, in terms of density or species number, between the central part of the Kwinte Bank and the entire Middelkerke Bank.

Taxon composition

In contrast to the findings concerning total macrobenthic density and species number (see above), clear differences in taxon composition could be detected between different locations on the Kwinte Bank.

The relative abundance of Annelida was clearly lowest in the depression and differed significantly from the coarser sediments of Station K4 (northern border), the western border, and the Middelkerke Bank (Figure 5a. and Table 1.). The lowest relative abundance of Annelida corresponded with the highest relative abundance of Crustacea, within the depression (Figure 5b.).

The contribution of molluscs decreases from the coarsest undisturbed part, over the western border of the depression and the depression, towards the eastern border and the Middelkerke Bank (Figure 5c.). The depression is associated with an intermediate amount of molluscs. Values for

Table 3. *Significant differences in density of particular macrobenthic taxa, between specific stations in the depression of the Kwinte Bank and stations with a similar sediment composition to that at the Middelkerke Bank. (* = p < 0,5, ** = p < 0.01, *** = p < 0.001).*

	K5 compared to M1 - M2	K6 compared to M4	K18 compared to M3 or K16 - K17 (1)
Annelida	*	n.s.	n.s.
Crustacea	*	*	* *
Mollusca	n.s.	*	n.s.
Echinodermata	* *	*	n.s.
Ophiura	* * *	*	n.s.
Echinocardium	n.s.	n.s.	* (1)
Amphipoda	* *	n.s.	*
Bathyporeia	*	n.s.	n.s.
Tellimya	n.s.	n.s.	n.s.

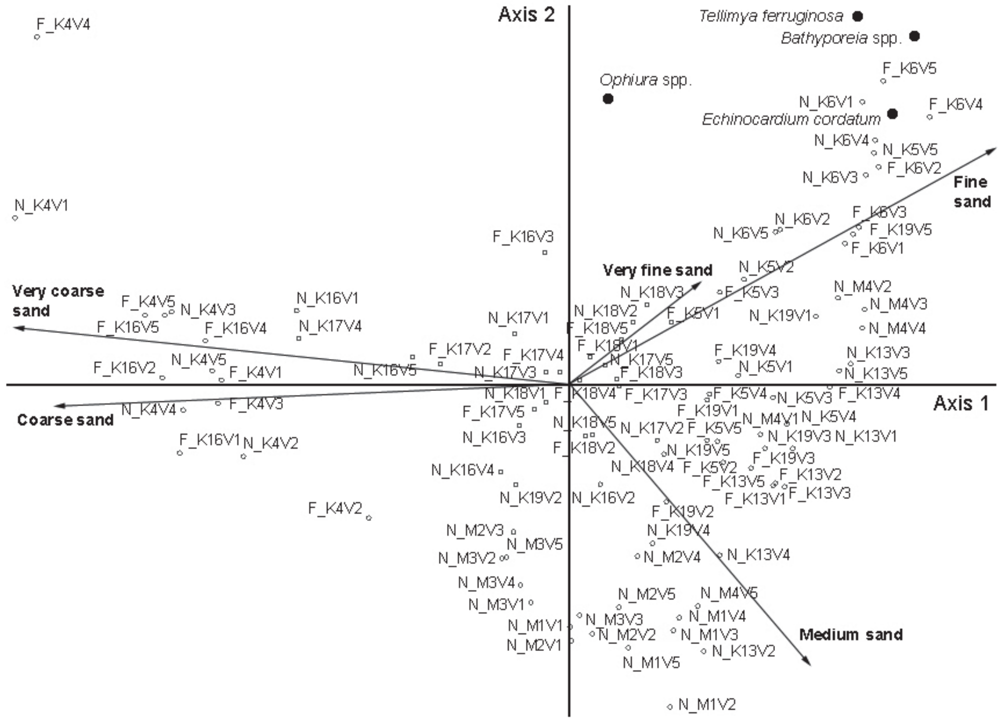


Figure 6. CCA-plot of all of the stations, with some species characterizing the depression. Important sediment characteristics are plotted on the graph. Key: F- February 2004; N- November 2004; K- Kwinte Bank; and M- Middelkere Bank).

the depression are significantly lower than at Station K4; they are significantly higher than the eastern border and on the Middelkerke Bank (Table 1.). A similar decreasing linear trend can be identified for the echinoderms (Figure 5d.). However, for this taxon the depression yields the highest relative abundance;it is slightly greater than at Station K4, and significantly more than over the eastern part and the Middelkerke Bank (Table 1.).

Trends in the distribution of these taxa, over different locations at the Kwinte Bank, could be detected for both periods.

In summary, the depression yields relatively less annelids and more crustaceans and echinoderms, than any of the sites; likewise an intermediate number of molluscs between the coarser sediments, to the west and north, and the sediments of the eastern border and the Middelkerke Bank. The depression shows a somewhat higher similarity to the western border, for the relative abundance of molluscs and echinoderms, and seems more similar to the eastern border in relation to the realtive abundance of annelids and crustaceans.

The particular characteristics of the depression were confirmed also by the DCA- and CCA analyses (Figure 6.). Station K4 is separated clearly from the other locations and is related closest to the western border; this, in turn, is characterised by an impoverished coarse sand community. The Middelkerke Bank shows approximately the highest similarity to the western border of the Kwinte Bank, along the first axis, whereas the eastern part and (clearly) the depression are separated along the second axis. On the CCA-plot, some species that can be associated with the differences in species composition of the stations, within the central depression, have been plotted.

Figure 7. illustrates that the depression yields higher mean densities of *Ophiura* species (13 ind./m^2), *Echinocardium cordatum* (11 ind./m^2), *Tellimya ferruginosa* (9 ind./m^2), Amphipoda (145 ind./m^2) and, in particular, *Bathyporeia* species (70 ind./m^2) (see Table 2. for significant differences), than the other locations. These species are important in distinguishing the different areas within the DCA- and CCA analyses. Significant differences for all of these taxa were obtained for both February and November 2004. Comparing each station of the depression, with stations having similar sediment characteristics as at the Middelkerke Bank, thus reducing the power of the analysis, many of the differences remain significant (Table 3.).

DISCUSSION

Density and Species Number

Impacts of dredging activities on macrobenthos are well documented elsewhere and describe changes in density, diversity and community structure (see Boyd *et al.*, 2003; Newell, Seiderer, and Hitchcock, 1998, for references). As a result of sand extraction, a decrease in macrobenthic density and species richness can be expected (Desprez, 2000; Newell, Seiderer, and Hitchcock, 1998). Dredges impact directly upon the species that live on or near the seafloor, as the dredge pipes physically disturb the habitat, when they are dragged across the seafloor.

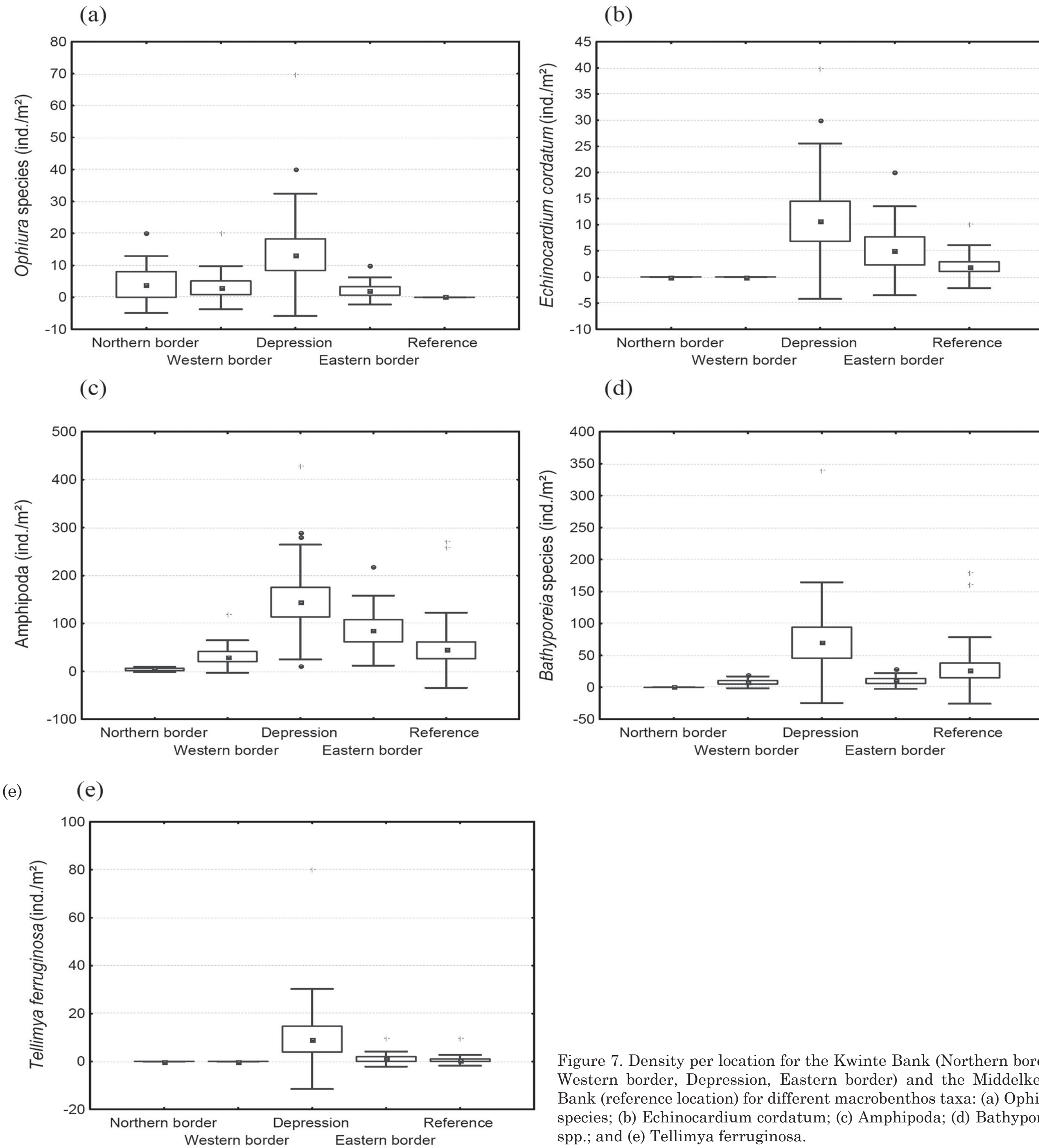


Figure 7. Density per location for the Kwinte Bank (Northern border, Western border, Depression, Eastern border) and the Middelkerke Bank (reference location) for different macrobenthos taxa: (a) Ophiura species; (b) Echinocardium cordatum; (c) Amphipoda; (d) Bathyporeia spp.; and (e) Tellimya ferruginosa.

As study, the direct impacts, through the removal of the fauna, are undeniable. VANOSMAEL *et al.* (1979) studied the removal of macrobenthic organisms by sand extraction *in- situ* in Belgian territorial waters, by following the dumping of dead and live organisms by the sand extraction vessel. 45 % of the animals retained on the sieve aboard the vessel, then dumped into the sea, were fatally damaged; these accounted for 70 % of the biomass. Molluscs contributed mainly to this percentage of fatally damaged fauna. Sampling the extraction site before and after dredging revealed a reduction in the macrobenthic abundance, by 80 % (VANOSMAEL *et al.*, 1979). In the present study, no differences in density and species richness could be detected, between an intensively exploited area and the reference sites on the Middelkerke Bank. The higher density at Station K4 is related mainly to the naturally higher abundance of interstitial polychaetes, within these coarse sediments (Vanosmael *et al.*, 1982). Data presented in this study date are characteristic of the depression, after or during ecological recovery, since dredging over this area has been prohibited since February 2003. Hence, post-extraction characteristics are described for an area, topographically and geomorphologically altered by sand extraction; this, in turn, may imply lasting ecological differences with the natural surroundings. Communities inhabiting sandy sediments are maintained in a transitional state by natural environmental disturbance and are likely to recover within a period of 2-3 years, after the cessation of dredging (Newell, Seiderer, and Hitchcock, 1998). The rate of recovery is highly variable, depending upon the type of community, the latitude and the extent to which the community adapts naturally to high levels of sediment disturbance and suspended particulate load (Newell, Seiderer, and Hitchcock, 1998). According to Rees (1987), colonisation by a range of infaunal species will occur in soft sediments within weeks or months, depending upon season, largely through larval recruitment. Also, diversity will increase by the immigration of invading species. According to Newell, Seiderer, and Hitchcock, (1998), density is the first community parameter which reaches the pre-disturbance level, one year after the cessation of the disturbance activity. Subsequently, the species richness stabilizes following potential increase during the period over which the community evolves into its final state. Since sampling for the present study has taken place one year after the cessation of dredging, the direct effects of the disturbance are not being detected anymore; as such, the community represents a transitional state. Vanaverbeke *et al.*, (2007) have ilustrated recently that macrobenthic density and diversity in the Kwinte Bank central depression was low, immediately following the cessation of dredging (March 2003), increasing distinctly one year later.

Species Composition

The depression is distinguished clearly from its surroundings, on the basis of geomorphological and sedimentological characteristics (Bellec *et al.*; Degrendele *et al.*, this volume). However, the differences in ecological parameters were not as straightforward.

Vanosmael *et al.* (1982) described two major communities on the Kwinte Bank, at the end of the 1970s: a rich community over the northern part of the sandbank, including Station K4, together with poorer central and southern communities. These communities correspond to the *Nephtys cirrosa* community and the *Ophelia limacina - Glycera lapidum* community, respectively; or, more particularly, to a transitional species association between these two communities (Van Hoey, Degraer, and Vincx (2004)). In Van Hoey, Degraer, and Vincx (2004) sieving live specimens understimated the mean density of the *Ophelia limacina - Glycera lapidum* community, due to the high loss of interstitial polychaetes. The macrobenthic taxon compositions, detected between the different sites of the present study, all fall within the range of the species compositions described for the typical sandbank communities (Van Hoey, Degraer, and Vincx , 2004). Stations K5 and K6 were sampled previously by Vanosmael *et al.* (1982). At that time, Station K6 was classified within the southern Kwinte Bank community, but Station K5 showed a higher similarity to the community found at Station K4, than in the present study. Such a difference may be a consequence of the disappearance of very large dunes at that station, which were present in the 1970´s but have largely disappeared from the present depression (Degrendele *et al.*, this volume). The higher similarity of Station K5 to Station K4, in the 1970´s corresponded also with a higher similarity in sediment characteristics, between both of the stations (Vanosmael *et al.*, 1982).

Within the present study, significant differences have been detected in the relative abundance of annelids, crustaceans, echinoderms and molluscs and, in particular, *Ophiura* species, *Echinocardium cordatum*, amphipods (*Bathyporeia* species) and the bivalve *Tellimya ferruginosa*, between the different locations. The latter species has a commensal relationship with *E. cordatum* (Daan, Mulder, and Vanleeuwen, 1994). *Urothoe poseidonis*, an amphipod living in the burrow of the echinoid *E. cordatum* (Gillan, Ribesse, and de Ridder, 2004), was observed frequently also in the depression in the present study. *E. cordatum* has been described as a typical species belonging to an equilibrium community and, as such, of the final stage after recovery took place (Newell, Seiderer and Hitchcock, 1998). An interesting observation is that the present state of the community in the depression yields more *E. cordatum* individuals, than were found on the eastern border or on the Middelkerke Bank, or during any of the sampling undertaken in the 1970´s or 1990´s (Bonne, 2003; Vanosmael *et al.*, 1982). *E. cordatum* has been described as one of the dominant species of the macrobenthic community found within the Belgian Coastal Banks (Degraer *et al.*, 1999), where material in suspension is generally higher than over the Flemish Banks (Govaere *et al.*, 1980). Since *E. cordatum* is a selective deposit feeder, it may be concluded that the high abundance of *E. cordatum* in the depression (with a mean of 11 ind./m^2), indicates that more organic material may be deposited in the depression than is normally the case on the surrounding sandbank crest. Bellec *et al.* (this volume), have pointed out that fluid muddy layer is deposited, during the ebb phase of the tide, in the depression. Colonisation depends upon the availability of suitable food, but may occur opportunistically, through migration of adults into the area, or via larval recruitment (Rees, 1987). Active migration of adult *E. cordatum* individuals, to their most favorable habitat, has been observed (Ozolin'sh and Nekrasova, 2003). Sedimentation of organic material is considered to permit the development of a dense population of *E. cordatum*. This species reworks the organic matter, into the sediment, which may have caused the bioturbation observed in the cores of the depression (Bellec *et al.*, this volume). The higher echinoderm density confirms that the depression has similar sedimentological characteristics to these in the swale where, generally, much more organic material is available and denser macrobenthos communities and a higher bioturbation are found (Bonne, 2003; Trentesaux *et al.*, 1994; Van Hoey, Degraer, and Vincx, 2004). *Gastrosaccus spinifer* occurred abundantly in the samples within the depression, indicating another similarity with the swale environment. At the Flemish Banks, mysids are significantly more abundant in the swales, than on the sandbank crests (Dewicke, 2001). At its southern end, the depression connects to the Kwinte Swale and is subject to strong flood tidal currents (Bellec *et al.*, this volume; Degrendele *et al.*, this volume). Such currents cause erosion over the western part of the Kwinte Bank and induce hydrodynamic characteristics which are similar to the swale environment in the depression (Garel, this volume).

Vanaverbeke *et al.*, (2007) did not identify any differences in taxon composition over the central part of the Kwinte Bank related to the lack of any taxon composition analyses, at a small spatial scale. These investigators analysed total proportion of major taxonomic groups incorporating the data from all of the stations, without distinguishing the western and eastern border, from the depression. Moreover, they sampled only the central and the northern part of the depression omitting the southern part of the depression, where the highest densities of *E. cordatum* have been recorded in the present study.

The annelid, crustacean and echinoderm contributions, between the various locations, does not reflect a significant difference with the different communities, as they have been defined for the Kwinte Bank and other Belgian subtidal sandbanks. On the Kwintebank, a transitional species association between the *Nepthys cirrosa* and the *Ophelia limacina - Glycera lapidum* community can be defined in general terms, characterised by mobile polychaetes (e.g. *Nephtys cirrosa*) and crustaceans (e.g. *Bathyporeia* spp.). Species contribution differences, between several combinations of transitional species assemblages, exist but are not distinguished as a separate community on the larger spatial scale. The high mobility of the species, the poverty and the wide niche-width of the community, together with the extent to which the community is adapted to high levels of sediment disturbance in these dynamic systems, makes it difficult to detect the effect of anthoprogenically-induced physical disturbance. Moreover, communities of high-stress areas are characterised by higher growth rates (Jennes and Duineveld, 1985) and, hence, more capable of readjustement to the impact of dredging operations (Desprez, 2000). Sand extraction has created a different habitat on the Kwinte Bank, to which the benthic fauna has adjusted, within the wide niche width of the community. Such adjustments do not mean that no change has been detected, it is just not significant on the larger spatial scale; it indicates that, locally, a sandbank environment has been created with greater similarity to the swale system (than would naturally be the case). The evolution of the community depends upon that of the sediments and geomorphology and hydrodynamics, within the depression. Nonetheless, it is unlikely that the original western flank will be restored, since the area is subject to erosion (Brière *et al.* this volume; Garel, Van den Eynde *et al.,* this volume). In the longer term, it is anticipated that the sandbank will shift slightly to the east, to establish a new equilibrium (Brière *et al.*, this volume). In the latter case, the macrobenthic fauna in the depression will develop further towards a typical "swale community". Monitoring the northern depression on the Kwinte Bank, created also by sand extraction, will establish if the evolution in the north, where there is no connection between the depression and an ajoining swale, will differ from the observed trend in the central depression.

CONCLUSIONS

- Macrobenthos density and species richness was similar over the entire central part of the Kwinte Bank and the Middelkerke Bank.
- Seasonal variation was less important, than spatial differences.
- A depression created by sand extraction was characterised by a lower relative abundance of annelids (%), together with a higher relative abundance of crustaceans (%) and echinoderms (%) than its surroundings and an unexploited sandbank as reference location. Higher densities of *Ophiura* species (13 ind./m^2), *Echinocardium cordatum* (11 ind./m^2), *Tellimya ferruginosa* (9 ind./m^2), Amphipoda (145 ind./m^2) and, in particular, *Bathyporeia* species (70 ind./m^2) were responsible for these higher taxon contributions.
- The central depression (which is probably not going to infill under prevailing hydrodynamic conditions) shows similarities to the swale environment, based also upon the macrobenthic fauna.
- The species composition observed in the depression compares to the wide range of species assemblages described earlier for the Kwinte Bank together with other Belgian subtidal sandbanks.
- Sand extraction has created a local-different habitat on the Kwinte Bank, to which the benthic fauna has adjusted. Such small-scale change is not significant, within the context of the larger scale of the sandbank system.

ACKNOWLEDGEMENTS

The author of the paper was in receipt of a Marie Curie Fellowship, within the FP5 Research Training Network EUMARSAND (contract HPRN-CT-2002-00222). The Flemish Institute of the Sea (VLIZ) granted ship-time on the *R/V Zeeleeuw*. The Captain, officers and crew are acknowledged warmly for their flexibility and hard work. Also indebted are the Marine Biology Section of the Ghent University for the use of additional sampling gear and the logistic and sampling support provided by students and researchers of this laboratory. Also, Iñigo Muxika and Germán Rodríguez (AZTI-Tecnalia), together with Els Verfaillie and Samuel Deleu of the Renard Centre of Marine Geology from Ghent University who assisted in the sampling. Thanks are extended to other individuals who helped in sorting the samples in the laboratory (Richard Saenz Jimenez, Oihana Irurzun Ibañez and Goretti Garcia). Germán Rodríguez (AZTI-Tecnalia) undertook the granulometric analyses. The INSUB Group was established within the taxonomical analyses of 17 of the 100 samples. The Fund for Sand Extraction, Federal Public Service Economy, SMEs, Self-employed and Energy, Brussels, is acknowledged for the multibeam imagery of the Kwinte Bank.

LITERATURE CITED

Bellec, V.; Van Lancker, V.; Degrendele, K.; Roche, M., and Le Bot, S., this volume. Geo-environmental characterization of the Kwinte Bank in relation to sand extraction. *Journal of Coastal Research.*

Bonne, W., 2003. Benthic copepod communities in relation to natural and anthopogenic influences in the North Sea. Gent, Belgium: University of Gent, Ph.D. thesis, 289p.

Boyd, S.E.; Rees, H.L.; Vivian C.M.G., and Limpenny, D.S., 2003. Review of current state of knowledge of the impacts of marine aggregate extraction – a U.K. perspective. Proceedings of the *EMSAGG Conference European marine sand and gravel – shaping the future*, Delft University, The Netherlands, pp. 97-102.

Boyd, S.E.; Limpenny, D.S.; Rees, H.L., and Cooper, K.M., 2005. The effects of marine sand and gravel extraction on the macrobenthos at a commercial dredging site (results 6 years post-dredging). *ICES Journal of Marine Science*, 62, 145-162.

Brière, C.; Roos, P.C.; Garel, E., and Hulscher, S.J.M.H., this volume. Modelling the morphodynamic effects of sand extraction from the Kwinte Bank, Southern North Sea. *Journal of Coastal Research.*

Conover, W.J., 1971. *Practical non parametric statistics*. John Wiley & Sons, New York, 462p.

Daan, R.; Mulder, M., and Vanleeuwen, A., 1994. Contaminated drill cuttings in the North-Sea. *Netherlands Journal of Sea Research*, 33(1), 113-127.

Degraer, S.; Vincx, M.; Meire, P., and Offringa, H., 1999. The macrozoobenthos of an important wintering area of the common scoter (*Melanitta nigra*). *Journal of the Marine Biological Association of the United Kingdom*, 79(2), 243-251

Degrendele, K.; Roche, M.; Schotte, P.; Van Lancker, V.; Bellec, V., and Bonne, W., this volume. Morphological evolution of the Kwinte Bank central depression before and after cessation of aggregate extraction. *Journal of Coastal Research.*

Desprez, M., 2000. Physical and biological impact of marine aggregate extraction along the French coast of the Eastern English Channel. Short and long-term post-dredging restoration. *ICES Journal of Marine Science*, 57, 1428-1438.

Dewicke, A., 2001. Hyperbenthic communities of the North Sea. Gent, Belgium: University of Gent, Ph.D. thesis, 219p.

Folk, R.L. and Ward, W., 1957.Brazos River Bar: a study of the significance of grain-size variables. *Journal of Sedimentary Petrology*, 27, 3-26.

Garel, E., this volume. Short-term hydrodynamics and sediment transport on the Kwinte Bank, Southern North Sea. *Journal of Coastal Research.*

Gillan, D.C.; Ribesse, J., and de Ridder, C., 2004. The iron-encrusted microbial community of Urothoe poseidonis (Crustacea, Amphipoda). *Journal of Sea Research*, 52(1), 21-32.

Govaere, J.C.R.; Van Damme, D.; Heip, C., and De Coninck, L.A.P., 1980. Benthic communities in the Southern Bight of the North Sea and their use in ecological monitoring. *Helgoländer wissenschaftliche Meeresuntersuchungen*, 33, 507-521.

Hill, M.O., 1979. *DECORANA - A FORTRAN program for detrended correspondence analysis and reciprocal averaging.* Ecology and Systematics, Cornell University, Ithaca, New York, 30p.

ICES, 1992. Effects of Extraction of Marine Sediments on Fisheries. Cooperative Research Report No.182. *International Council for the Exploration of the Sea, Copenhagen*, 78p.

ICES, 2001. Effects of Extraction of Marine Sediments on the Marine Ecosystem. Cooperative Research Report No. 247. *International Council for the Exploration of the Sea, Copenhagen*, 80p.

Jennes, M.I. and Duineveld, G.C.A., 1985. Effects of tidal currents on chlorophyll a content of sandy sediments in the southern North Sea. *Marine Ecology-Progress Series*, 21, 283-287.

Kenny, A. J. and Rees, H. L., 1996. The effects of marine gravel extraction on the macrobenthos: Results 2 years post-dredging. *Marine Pollution Bulletin,* 32(8/9), 615-622.

Lanckneus, J.; De Moor, G.; De Schaepmeester, G.; De Winne, E. and Meyus, I., 1992. Monitoring of a tidal sandbank: evolution of bedforms, volumetric trends, sedimentological changes. HYDRO '92. *Eight biennial int. Symposium of the Hydrographic Society, Copenhagen*, Denmark, 19p.

Lanckneus, J.; De Moor, G. and Stolk, A., 1994. Environmental setting, morphology and volumetric evolution of the Middelkerke Bank (southern North Sea). *Marine Geology,* 121, 1-21.

Newell, R.C.; L.J. Seiderer and Hitchcock, D.R., 1998. The impact of dredging works in the coastal waters; a review of the sensitivity to disturbance and subsequent recovery of biological resources on the sea bed. *Oceanography and Marine Biology, Ann. Rev.*, 36, 127-178.

Ozolin'sh, A.V. and Nekrasova, M.I., 2003. The forming of spatial structure of the soft bottom communities around Furugel'm Island (Sea of Japan). *Oceanology*, 43(1), 83-90.

Rees, H.L., 1987. A survey of the benthic fauna inhabiting gravel deposits off Hastings, Southern England. ICES CM 1987/L 19, 9p.

Sardá, R.; Pinedo, S.; Gremare A., and Taboada, S., 2000. Changes in the dynamics of shallow sandy-bottom assemblages due to sand extraction in the Catalan Western Mediterranean Sea. *ICES Journal of Marine Science*, 57, 1446-1453.

Trentesaux, A.; Stolk, A.; Tessier, B., and Chamley, H., 1994. Surficial sedimentology of the Middelkerke Bank (southern North Sea). *Marine Geology* 121, 43-55.

Vanaverbeke, J.; Bellec, V.; Bonne, W.; Deprez, T.; Hostens, K.; Moulaert, I.; Van Lancker, V. and Vincx, M., 2007. *Study of post-extraction ecological effects in the Kwintebank sand dredging area (SPEEK)*, Belgian Science Policy, Brussels, 92p.

Van Dalfsen, J.A.; Essink, K.; Toxvig madsen, H.; Birklund, J.; Romero, J., and Manzanera, M., 2000. Differential response of macrozoobenthos to marine sand extraction in the North Sea and the Western Mediterranean. *ICES Journal of Marine Science*, 57(5), 1439-1445.

Van den Eynde, D.; Giardino, A.; Portilla, J.; Fettweis, M.; Francken, F. and Monbaliu, J., this volume. Modelling the effects of sand extraction on the sediment transport due to tides on the Kwinte Bank. *Journal of Coastal Research.*

Van Hoey, G.; Degraer, S., and Vincx, M., 2004. Macrobenthic community structure of soft-bottom sediments at the Belgian Continental Shelf. *Estuarine, Coastal and Shelf Science* 59, 599-613.

Vanosmael, C.; Heip, C.; Vincx, M.; Claeys, D.; Rappé, G.; Braeckman, A., and Van Gansbeke, D., 1979. *De invloed van zandwinning op de bodemfauna voor de Belgische kust*. Brussels: Ministerie van volksgezondheid en leefmilieu, 50p.

Vanosmael, C.; Willems, K.A.; Claeys, D.; Vincx, M., and Heip, C., 1982. Macrobenthos of a sublittoral sandbank in the Southern Bight of the North Sea. *Journal of the Marine Biological Association of the United Kingdom*, 62, 521-534.

Wentworth, C.K., 1922. A scale of grade and class terms for clastic sediments. *Journal of Geology*, 30, 377-392.

Journal of Coastal Research	SI	51	151-164	West Palm Beach, Florida	Summer 2010

Recommendations for the sustainable exploitation of tidal sandbanks

Vera, R.M. Van Lancker[1*], Wendy Bonne[2], Erwan Garel[3***], Koen Degrendele[4], Marc Roche[4], Dries Van den Eynde[5], Valérie Bellec[1, 6****], Christophe Brière[7*****], Michael B. Collins[2,3] and Adonis F. Velegrakis[6]**

[1]Ghent University, Renard Centre of Marine Geology
Krijgslaan 281, S8, 9000 Gent, Belgium

[*] Present address: Royal Belgian Institute of Natural Sciences. Management Unit of the North Sea Mathematical Models
Gulledelle 100, B-1200 Brussels, Belgium
vera.vanlancker@mumm.ac.be

[2]AZTI - Tecnalia / Marine Research Division
Herrera kaia portualdea z/g, 20110 Pasaia (Gipuzkoa)
Spain

[**] Present address: Marine Environment Service, Directorate General Environment, Federal Public Service Health, Food Chain Safety and Environment, Federal Government of Belgium
Victor Hortaplein 40 box 10
1060 Brussels, Belgium

[3] School of Ocean and Earth Science. National Oceanography Centre, Southampton
European Way, Southampton, SO143ZH
United Kingdom

[***] Present address: CIACOMAR. University of Algarve
Avenida 16 de Junho, s/n. 8700-311 Olhão
Portugal

[4] Federal Public Service Economy, SME's, Self-employed and Energy – Fund for Sand Extraction (NGIII)
Simon Bolivarlaan 30, B-1000 Brussel,Belgium

[5] Royal Belgian Institute of Natural Sciences. Management Unit of the North Sea Mathematical Models
Gulledelle 100, B-1200 Brussels, Belgium

[6]University of the Aegean, Department of Marine Science
University Hill, Mytilene 81100, Greece

[****] Present address: Geological Survey of Norway. Leiv Eirikssons vei 39
7040 Trondheim, Norway

[7]Universiteit Twente, Water & Engineering Management
P.O. Box 217, 7500 AE Enschede
The Netherlands

[*****] Present address: Deltares
P.O. Box 177, 2600 MH Delft
The Netherlands

ABSTRACT

A basic requirement for allowing marine aggregate (sand) extraction on the Belgian Continental Shelf (which takes place on sandbanks) is that it should not result in major environmental changes. However, a tidal sandbank (Kwinte Bank, Flemish Banks), exploited intensively since the 1970's, has shown evidence of significant morphological changes with the development of a 5 m deep depression in its middle section; thus, since February 2003, sand extraction has ceased in this area in order to study the environmental impacts and the regeneration potential of the seabed. The present contribution synthesises the results of the multidisciplinary research, which has taken place in the area and, on the basis of these findings, considers the need for an efficient management framework, in both the planning and monitoring stages of the extraction. The investigation has shown that extraction has had significant impacts on the seabed sedimentary character and ecology and the local hydro-and sediment dynamic regime. Under these conditions, regeneration of the seabed is not likely in the short-term and, although modelling exercises have indicated possible recovery in the medium- and long-term, this is likely to be inhibited by the lack of appropriate sediments in the area. The results have provided the basis of the identification of a 'suite' of criteria, which can assist in the strategic planning/design of marine aggregate concession zones, the efficient management of marine aggregate extraction and the planning of effective environmental monitoring; these criteria are related to considerations on resource location, the nature/thickness of the targeted deposits, morphodynamics and sediment dynamics, biology and ecology and extraction practices. The Kwinte Bank investigation has demonstrated also the need for intensive monitoring schemes in order to identify the morphological, sedimentary and ecological impacts, related to the dredging activities. A critical part of these schemes should be the evaluation of the dredging-related effects, against the background of the natural dynamics of the seabed; thus, baseline information is crucial, as, in its absence, impact assessments are likely to remain inconclusive.

ADDITIONAL INDEX WORDS: *marine aggregate extraction; dredging; environmental impact assessment; environmental monitoring; sustainable development; mining guidelines; seabed regeneration.*

INTRODUCTION

The formulation of recommendations and guidelines, concerning 'the best practice' in marine aggregate (MA) extraction is a complex issue, as it is driven by both 'top-down' considerations (i.e. considerations related to the regulation and management of extraction activities) and 'bottom-up' constraints (i.e. constraints associated with the diagnosis and prognosis of the complex physical environmental processes). The regulation of MA exploitation is associated with different levels of legislation, consisting of international Conventions, European Directives and national laws; however, although all European Member States have to comply with the rules prescribed by ratified international Conventions and the European environmental legislation, there are also significant differences in the management and regulation of MA exploitation between them. These differences stem mainly from the different approaches adopted by the Member States in the incorporation into their national legislation of the relevant environmental European Directives (particularly the Environmental Impact Assessment (EIA), the

DOI: 10.2112 / SI51-014.1 received 14 February 2007; accepted in revision 9 January 2008.

Strategic Environmental Impact Assessment (SEA) and the Habitats Directives), as well as from the particularities of the Member States' administrative structures (see RADZEVICIUS *et al.,* this volume). Hence, the national regulatory framework, related to MA exploitation, is not consistent throughout Europe, with a wide variety of processes and procedures existing in terms of resource policy, data and information management and research co-ordination and dissemination.

The main issue, involved in the regulation of MA exploitation, is associated with resource sustainability, as well as with the environmental impacts of the extraction and their assessment. With respect to the assessment of the environmental impacts, there are many different interpretations on how to identify 'best practices'. This is due partly to the presence of a large array of habitats along the European coast, which have different characteristics and are associated with different environmental risks, when being disturbed. In addition, there are disparities between the different EU Member States concerning the 'know-how' necessary to address effectively the various scientific problems associated with resource prospecting and the environmental impact of MA extraction (see also VELEGRAKIS *et al.*, this volume). Many of the environmental effects of MA extraction are likely to be site-specific, but general conclusions can be drawn from the results of site-specific research. Nowadays, developing technology and an increase in the efficiency of environmental monitoring, in combination with innovative and effective research, allow an improved estimation of the effects of MA extraction.

Groups with industry-interest (e.g. the European Marine Sand and Gravel Group (EMSAGG)), the International Council for the Exploration of the Sea (ICES) and Non-Governmental Organisations (e.g. World Wildlife Fund (WWF)) are working already on initiatives related to MA extraction and the promotion of appropriate research, to address problems at a supra-national (regional) level. Within ICES, the Working Group on the Effects of Extraction of Marine Sediments on the Marine Ecosystem (WGEXT) produces Annual Reports including overviews of: (a) extraction activities; (b) seabed resource mapping programmes; (c) approaches to environmental impact assessments; and (d) related environmental research developments. The group has also formulated guidelines concerning the information which has to be collated/acquired in order to assess effectively the environmental impacts of MA extraction (ICES, 2003). The OSPAR Commission has stated that the OSPAR Contracting Parties should take these guidelines into account, within their procedures, for the authorization of the extraction of marine sediments (see RADZEVICIUS *et al.,* this volume). According to the ICES guidelines (ICES, 2003), wide-ranging information is required for evaluating the physical impacts of MA extraction, i.e. information on: (1) the impacts of sediment extraction on the coastal and offshore sedimentary and hydrodynamic processes, including potential draw-down of neighbouring beaches, changes to sediment supply and transport pathways and modifications to wave and tidal regimes; (2) potential changes to the seabed morphology and sediment type; (3) exposure of different substrates; (4) changes in the behaviour of bedforms, within the extraction and adjacent areas; (5) the potential risk of the release of contaminants during aggregate dredging and exposure of potentially toxic natural substances; (6) the transport and redeposition of fine-grained sediments, which are either resuspended by the dredging activities or are released into the water column through hopper overflow or on-board aggregate processing; (7) the effects on the water quality of increases in the concentration of resuspended fine material; (8) changes in local water circulation, resulting from removal or creation of topographic features on the seabed; and (9) the time-scale for potential physical "recovery" of the seabed. In order to assess the biological impacts, ICES guidelines recommend studying: (1) changes in the benthic community structure and in any ecologically-sensitive species, or habitat that may be vulnerable to extraction operations; (2) the effects of aggregate dredging on pelagic biota; (3) the impacts on the fishery and shell fishery resources, including spawning fish, nursery areas, over-wintering grounds for ovigerous crustaceans and known routes of migration; (4) the effects on trophic relationships, e.g. between the benthos and demersal fish populations; (5) the impacts on sites designated under local, national or international regulations (see above); (6) rates and modes of recolonisation of exploited sites, taking into account initial community structure, natural temporal changes, local hydrodynamics and any predicted changes in sediment type; (7) the effects on marine flora and fauna, including seabirds and mammals; and (8) the impacts on the ecology of boulder fields/stone reefs.

The aim of the present contribution is to present and evaluate the procedures concerning some of the topics identified in the ICES guidelines and to provide recommendations on the improvement of some aspects of the environmental monitoring of MA extraction sites. Toward this objective, the results obtained from the environmental monitoring of the central part of the Kwinte Bank (Flemish Banks, southern North Sea), where a depression has formed due to intensive MA extraction, are synthesised and discussed. Physical, ecological and potential cumulative impacts are evaluated, whilst a suite of criteria is provided which can assist in limiting the environmental impacts of MA extraction. Finally, a more general methodological research framework is proposed, together with recommendations on the refinement of monitoring schemes.

BACKGROUND TO THE KWINTE BANK MA EXTRACTION

The topics, included in the ICES guidelines, are discussed with reference to the Kwinte Bank (see Figure 11., VELEGRAKIS *et al.,* this volume); this is a tidal sandbank situated in the southern North Sea, on the Belgian Continental Shelf in water depths of -8 to -25 m MLLWS (mean lowest low water level, at spring tides) (Figure 1.). MA extraction commenced on the bank in the 1970's and, from 1997 until 2003, 75 % (11,620,000 m^3) of all the Belgian MA extraction was related to this sandbank. Since 2003, MA extraction activities have seized on the bank, in order to evaluate the environmental impacts and monitor changes and recovery rates (see VAN LANCKER *et al.*, this volume). As such, the Kwinte Bank provides an ideal example for the investigation of the impacts of MA extraction, within a tidally dominated environment.

Within Belgium, sediment removal from sandbanks is, for each individual extraction activity, restricted to an excavation depth of 0.50 m; as such, only the upper surface sediments are removed. This approach has been considered to cause only minimal environmental impacts, as it has long been believed that sandbank maintenance processes would counterbalance the loss of the extracted sediments (VAN LANCKER *et al.*, this

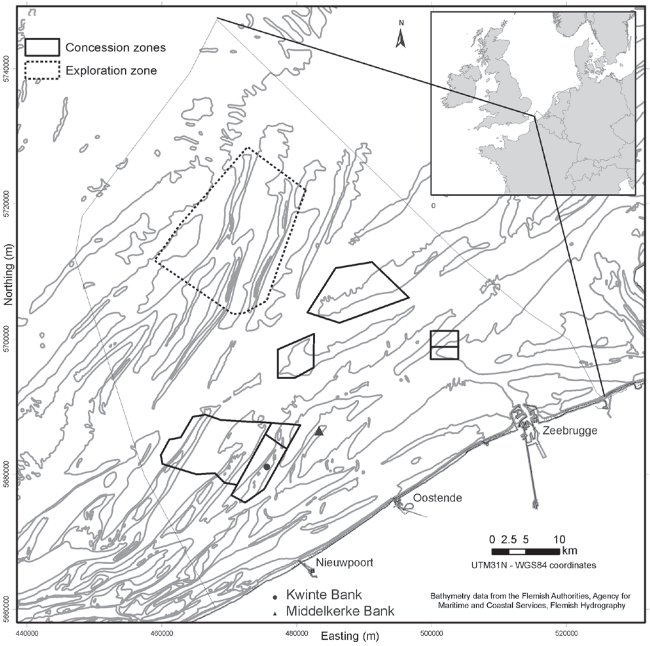


Figure 1. Concession zones on the Belgian Continental Shelf. The more offshore exploration zone for future marine aggregate extraction is indicated also.

volume). Since 1976, the exploited sandbanks have been monitored and, until recently, only limited physical environmental impacts had been reported. However, in 2000, a depression (5 m deep, 700 m wide and 1 km long) was identified along the most intensively exploited upper part (crown) of the sandbank (see Figure 3., Degrendele *et al.,* this volume). To allow regeneration of this section of the sandbank, sand extraction has been prohibited, since February 2003. Multidisciplinary research programmes, covering a 2-year period, have been set-up to address the regeneration potential, from a physical and ecological perspective; these have been based upon state-of-the-art methodology and instrumentation. The physical impact of extraction, on the seabed, has been assessed using hydro-, sediment- and morphodynamic modelling and calibrated/validated using *in-situ* measurements. The ecological impact was focussed upon the macrobenthos and included a comparison between exploited and non-exploited sandbanks. The framework for the investigations, together with the issues arising after 30-year of monitoring, are discussed in Van Lancker *et al.* (this volume).

Apart from the impacts related to the depression area of the sandbank, the long-term monitoring results did show a significant loss of the total bank's volume (Norro *et al.,* 2006). Moreover, De Moor (2002) had reported a general erosive tendency for the whole of the Flemish Bank region, including both exploited and non-exploited sandbanks, with the swales between the banks being either stable or slightly erosional. This pattern indicates that aggregate extraction may not be the only cause for the observed erosive trends; nonetheless, it emphasises the need for a more sustainable exploitation approach.

SYNTHESIS OF THE NEW RESULTS

Physical Impacts

Bellec *et al.* (this volume) and Degrendele *et al.,* (this volume) studied the geology, morphology and sedimentology of the Kwinte Bank and its central depression. Comparing bathymetric profiles obtained in 1992 and 1999, a difference of up to 6 m was observed between the deepest part of the depression (-16 m MLLWS) and the former crown (-10 m MLLWS) of the sandbank; in comparison, the western swale remained stable, at around –25 m MLLWS (Degrendele *et al.,* this volume). Following cessation of dredging activities, the depression's bathymetry remained quite stable and its morphodynamics became similar to those of the adjacent, non-exploited crown of the sandbank (Degrendele *et al.*, this volume). No clear evidence of morphological regeneration could be established, at least over a 2-year observation period. The depression could be distinguished also from its surroundings on the basis of acoustic imagery and seabed classification. Large dunes were found also in the depression, but they were characterised by locally lower heights, whereas their steep face was observed to be pointing progressively towards the NE, i.e. in the direction of the flood flow (Bellec *et al.*, this volume). Interestingly, a lot of the dunes, found within the depression, appear to have uninterrupted crests (see Figure 3., Degrendele *et al.,* this volume), suggesting early recovery of the basic bedform morphology.

Intensive sediment sampling showed that the sandbank might be divided into subareas, each with a particular sedimentary character (Bellec *et al.,* this volume). The seabed of the depression showed a wide range of fine- to medium-grained sediments, with variable shell content, whereas, the sediments in the surrounding areas of the bank were found to consist of poorly-sorted and coarse-grained, shelly sediments in the west and reasonably homogeneous, well-sorted, finer-grained sediments in the east. The observations indicated that the depression might act as a 'transport corridor' for shelly material, transported by the flood flow. Over a 2-year period, the overall sediment characteristics in the depression remained fairly consistent, suggesting very limited sediment exchanges. However, the evolution of the mean grain size of sediments, within the depression, showed trends resembling those of the more heterogeneous swale sediments; as such, these sediments are different from those anticipated for the crown of a sandbank. Within the depression, observations obtained during the ebb (flow in a SW direction), have revealed the presence of ephemeral muddy deposits; this indicates that the depression has the potential to trap also fine-grained sediments. Combined with the shelly coarser-grained material, brought in by the flood flow, this might initiate a slow regeneration of the depression.

The potential for sediment transport towards the depression and, hence, for natural regeneration, has been studied on the basis of short-term hydro-sedimentary observations (Garel, this volume). Tidal cycle measurements, carried out under reduced wave activity, have shown differences between the near-bed tidal ellipses and the across-bank component of the peak (ebb and flood) flow inside the depression and those at the crown of the bank. Divergent net sand transport was predicted for the area of the depression, suggesting seabed erosion. Sediment transport pathways were investigated also on the basis of grain size trend analysis (Poulos and Ballay, this volume). Two main transport pathways were identified: (a) to the NE (flood-directed) in the central depression and along the western

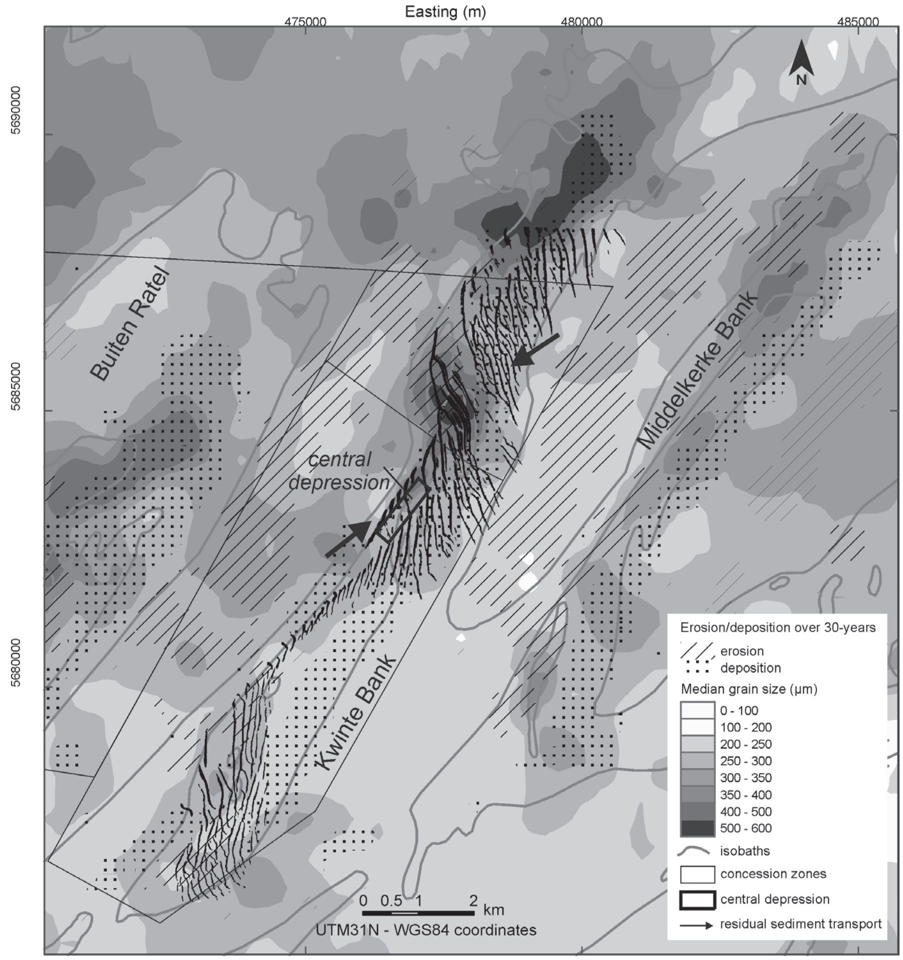


Figure 2. Concession zones and grain size (median grain size after Verfaillie, Van Lancker, and Van Meirvenne, 2006) distribution of the surficial sediments of the Kwinte Bank and surrounding areas. The crestlines of large to very large subaqueous dunes are also shown on the Figure, as well as the type of sedimentary environments and the major transport sediment pathways (for details, see text). The location of the central depression is indicated.

flank; and (b) to the SW (ebb-directed) along the gentle eastern slope of the Kwinte Bank; these results contrast to those of a previous similar study over the Kwinte Bank (Gao *et al.*, 1994), which had suggested across-bank sediment transport mainly. Generally, it appears that the central depression acts more as a transit area, than as a depocentre, for the sediments.

Process-based, 'bottom-up' modelling has been used to investigate the general seabed dynamics of tidal sandbanks (Brière *et al.,* this volume, and Van den Eynde *et al.,* this volume). Generally, there was good agreement between the derived numerical results and the obtained field measurements. Flood and ebb tidal flows were found to dominate the western and eastern flanks of the Kwinte Bank, respectively, whereas the overall residual currents were found to be mainly towards the WSW, indicating ebb-dominance for this part of the bank. In addition, distinct erosion/deposition patterns were simulated; these appeared to be similar, for different levels of dredging-induced lowering of the sandbank (Van den Eynde *et al.,* this volume). Under such conditions, no destabilisation of the sandbank was indicated. Modelling of the sediment transport under wave-current interaction was undertaken, as the crests of shallow tidal sandbanks have been shown to be particularly vulnerable to wave action; as such tidal erosion/deposition patterns may change, according to superimposed wave activity (Giardino, Van den Eynde, and Monbaliu, this volume). The modelling showed a high increase in sediment transport, but also a change in direction of the net flux of sediments (Giardino, Van den Eynde, and Monbaliu, this volume). The dominance of the ebb flow along the eastern flank can be suppressed by southerly (or SW) winds, which is the prevailing wind direction over this area. Previous studies (Van Cauwenberghe, 1971) had indicated that the sandbanks have not migrated; this might be due to the long-term 'balancing out' of the sediment transport over the bank under the influence of waves, i.e. the sediment transport under the combined action of tidal currents and (relatively low) waves along the eastern flank and the sediment transport due to tidal currents and higher waves along the more exposed western flank (Giardino, Van den Eynde, and Monbaliu, this volume).

The long-term impact of sand extraction has been modelled, using complementary approaches, which combined the benefits from numerical, 'bottom-up' modelling and idealised models

Table 1. *Evolution of the central depression, after cessation of dredging. Indications of erosion. The references can be found in this Special Issue.*

Methodology	Indications of an erosional trend
Multibeam bathymetry	The depression is 5 m deeper than the surrounding sandbank and since 2003; there is still a minor increase in depth (natural processes?). Large sand dunes are lower in height and move faster in the depression than outside of it (Degrendele et al.). The higher current speeds likely prevent deposition during the flood (Bellec et al.).
Surficial sediment sampling	Temporal grain size trends in the depression resemble more the evolution of sediments in the swale; they differ significantly from those along the crest of a sandbank (Bellec et al.). Along the axis of the depression, significant NE directed sediment transport is indicated, on the basis of grain size trend analysis (Poulos and Ballay). The presence of the depression is more a sediment transit area, than a depocentre, (Bellec et al., and Poulos and Ballay).
Hydrodynamics ADCP – S4	Due to the canalisation of the flow, there is a stronger erosional potential during flood. A divergence of net sand (bed load) transport has been calculated inside the depression, with net erosion during the tidal cycle (Garel).
Process-based model Delft 3D	Throughout a tidal cycle, erosion over the central depression was modelled (0.001 m of erosion during 10 days, in the absence of waves) (Brière et al.).
MU-SEDIM and SISYPHE models	Without atmospheric conditions and waves being taken into account, erosion occurs in the depression and on the western flank of the sandbank (Van den Eynde et al.). Giardino et al. demonstrate higher sediment transport capacities and changing residual transport directions, under the combined action of tidal currents and waves.
Biological sampling	No further impoverishment, but a species composition difference has been observed within the wide niche width of the sandbank transitional species assemblages, with lower relative polychaete and higher relative crustaceans and echinoderms abundance. Nonetheless, similar macrobenthos density and species richness exists (Bonne).

(Brière *et al.*, this volume). The latter showed that the expected long-term trend of an excavated area is recovery, resulting in a new sandbank equilibrium. Such long-term predictions contrast to those by the morphodynamic observations (Degrendele *et al.*, this volume) as well as to those indicated by the hydrodynamic observations and the short-term, 'bottom-up' modelling (see above); these do not suggest regeneration for the area of the depression. Such differences between the idealised modelling results and those by the other approaches might be due to the basic assumption of the modelling used, i.e. the presence of an infinite source of sand in the area, which, in reality, is not the case (Le Bot *et al.*, 2003, for an overview).

The impact of the different levels of the lowering of the sandbank (see above), on the coast, has been studied also

Table 2. *Evolution of the central depression, after cessation of dredging. Indications of recovery. The time-scale and the significance of the process is provided. The references can be found in this Special Issue.*

Method	Indications of recovery	Time-scale
Multibeam backscatter classification	Slight tendency for a relative increase in fine sediments, in the depression (Degrendele et al.).	3 years (Significant?)
Sediment sampling	Central depression appears to trap shelly and coarse-grained material (Bellec et al.), albeit locally. Deposition of mud, under ebb and neap tidal cycle conditions (not observed on the crest) (Bellec et al.).	Event related, Significant (Significant?)
Hydrodynamics (ADCP/S4)	Convergence of net sand transport, at the bank's crest (Garel).	Tidal cycle, Significant
Process-based model (Delft3D)	Residual transport direction from the SW (swale) towards the NE, over the sandbank crest (Brière et al.).	Two weeks, Significant
Idealised modelling	On the long-term (100 years), the system tends to a new equilibrium, displaying recovery of the depression (Brière et al.).	100 years
Biological sampling	Macrobenthic species assemblage has changed slightly, but develops well (Bonne).	3 years, Significant

within the context that intensive offshore dredging would increase a 1000-year wave height (Verwaest and Verelst, 2006). However, no significant impact could be deduced. This is considered to be due primarily to the large distance (> 12 km) of the extraction site from the coast, together with the presence of other sandbanks between the Kwinte Bank and the coast that leads to a significant dissipation of wave energy.

For environmental and resource management purposes, the physical information available from the Kwinte Bank is synthesised in Figure 2. The most economically interesting (in relation to the MA industry) grain sizes (> 300 µm) are found to the north of the Flemish Banks, although patches of coarser grain sizes occur, locally, in the remainder of the concession zones, where fine to medium sands prevail. The asymmetry of the large and very large subaqueous dunes indicates flood-dominance along the western steep flank and ebb-dominance along the gentle eastern slope of the Kwinte Bank. Modelling results, concerning areas of erosion and deposition, in the wider area, over a 30-year period (Brière *et al.*, this volume), indicate mostly erosion in the swale areas (+/- 1 m) and along the western steep flanks of the banks, together with the kink areas. In comparison, the eastern gentle flanks of the banks have been predicted to be depositional; this is also the case with the highest part of the crown of the Kwinte Bank that is situated more towards the south. According to the inferred sediment transport pathways, the sedimentary cover in the swale to the west of the Kwinte Bank could be a potential source of sediments to the depression area. However, the grain size is finer than in the depression and the thickness of the Quaternary cover in the swales is less than 2.5 m to absent (Le Bot *et al.,* 2003, for an overview). Hence, the major source of coarse sand (> grain size 300 µm), needed to rebuild this section of the bank, is located to the north of the depression.

Biological/ecological impacts

The nature and vulnerability of benthic communities to MA extraction on the Kwinte Bank, has been investigated using macrobenthic fauna sampling (Bonne, this volume). Sampling stations were located within the central depression, along its sides and outside the exploited area. In addition, the adjacent, non-exploited Middelkerke Bank (Figure 1.) was also sampled, for reference purposes. Compared to the historical data from the Kwinte Bank and the reference stations on the Middelkerke Bank, crustaceans and echinoderms have become more important over the area of the depression; this suggests a greater similarity between the depression and a swale environment. The difference in species composition in the depression can be considered within the wide niche width of the sandbank transitional species assemblages, described previously for the Kwinte Bank and the Belgian Continental Shelf (Van Hoey, Degraer, and Vincx, 2004). On this basis, sand extraction appears to have created a 'locally-different' habitat on the Kwinte Bank, with adaptation of the benthic fauna; however, the changes have not been found significant, at least on the scale of the sandbank system. It must be noted, that within the framework of the present investigation, only the macrobenthos has been considered. Vanaverbeke *et al.* (2007) have discussed elsewhere the ecological effects, based upon changes in macrobenthic, nematode and copepod communities, including also an evaluation of their short-term recovery, after the cessation of dredging. The conclusions pointed out that even without morphological changes, the increased dynamics, introduced by the creation and filling up of the dredging furrows would affect the benthos.

Erosion/recovery trends

Trends in the evolution of the depression after cessation of dredging, based on the results of the present investigation are listed in Tables 1. and 2. It appears that, in the short-term, erosion dominates, whilst recovery seems appropriate over the medium- to long-term.

DISCUSSION AND RECOMMENDATIONS

Marine environments are dynamic and complex and their knowledge base is limited; thus, many changes are not observed until it is too late for a rigorous demonstration of cause and effect (Thrush *et al.*, 1998). The same applies to the Kwinte Bank, as it was only after the formation of a 5 m deep depression along the crown of the sandbank, that an intensive research strategy was established. The results of the morphological, sedimentological and biological surveys, carried out following the cessation of dredging, have not revealed any significant recovery of the depression, at least over a 2-year observational period. The fact that such depressions develop indicates that sandbanks should not be considered as infinite resources of renewable MA deposits.

The identification of best practice in MA extraction from tidal sandbanks is linked, inherently, to the consideration of whether renewable or non-renewable sediments are being extracted; this, in turn, has implications on sustainability. Guidelines on sustainable exploitation have been described by Wellmer and Becker-Platen (2002), who addressed the sustainability of mineral resources, in general. For renewable resources, "*the rate of consumption should not exceed the rate at which they are regenerated"*. Non-renewable resources imply that "*the consumption should not exceed the amount that can be replaced by functionally equivalent renewable resources, or by attaining a higher efficiency in the use of renewable or non-renewable resources"*. Moreover, these investigators observed "*material and energy input into the environment should not exceed the capacity of the environment to absorb them with minimal detrimental effects*". Likewise, that "*the rate of anthropogenic input and environmental interference should be measured against the time required for natural processes to react and cope with environmental change"*. Such considerations are highly relevant to the management of MA resources, at least, if extraction is envisaged within the system's natural variability. If non-renewable resources are exploited increasingly, there is a need for a more efficient use of the seabed, a search for functionally equivalent renewable resources and minimising the detrimental effects of the extraction.

Relevance of the results against sustainable MA exploitation

Physical impacts

Generally, the most severe direct physical impact of MA extraction relates to substratum removal, alteration of bottom topography and re-deposition of resuspended/jettisoned fine material (e.g. De Groot, 1996; Newell, Seiderer, and Hitchcock, 1998). Dredging-induced changes in sediment composition relate mostly to: (a) surficial grain size alterations (McCauley, Parr, and Hancock, 1977; Poiner and Kennedy, 1984); (b) an increase in the proportion of fine sands (Boyd *et al.*, 2005; Desprez, 2000; Van Dalfsen *et al.*, 2000), or silt (Van der Veer, Bergman and Beukema, 1985); and (c) an increase in gravel, through the exposure of coarser sediments (Kenny *et al.*, 1998).

Generally, depressions or pits, created by MA extraction, have been reported to be enduring seabed features, for several years. Boers (2005) has reviewed the morphological behaviour of different pits, trenches and channels, excavated in sand on the Dutch Continental Shelf. The recovery time of the depressions/pits has been shown to vary, depending on the local environmental conditions (water depth, waves, flow velocity, sediment characteristics) and pit/trench characteristics (volume, shape, orientation). Thus, the regeneration time of the depressions/pits has been found to range from months in shallow water, to decades or centuries in deep water settings; characteristic regeneration time-scales for large-scale sand extractions (> 10 million m^3), in water depths of more than 20 m, have been found to be in the order of centuries (Roos, 2004). Using process-based modelling, Van Rijn *et al.* (2005) concluded that the orientation of the pit, towards the flow, is the most important parameter. Pits or channels, lying perpendicular or oblique to the flow, enhance sedimentation, whereas those parallel to the flow promote sedimentation in the case of wide pits (Hoogewoning and Boers, 2001; Ribberink, 1989), but slight erosion in the case of narrow pits (Ribberink, 1989). If pit/depression evolution is modelled as a local topographic perturbation, the system may shift to a new equilibrium profile (Roos, 2004), with the corresponding time-scales (approx. a century) being shortest for deep and narrow pits, formed on the bank's crest.

On the Kwinte Bank, the direct impact of dredging is revealed by the presence of elongated depressions, formed within the topzones of sandbanks (Degrendele *et al.*, this volume).

Instead of homogeneous well-sorted medium to coarse sand, patches of fine and coarse sand occur next to areas of ephemeral mud deposits (Bellec *et al.*, this volume). At least, over a period of 3 years, no significant sediment infill has been observed in the depressions; this is somewhat unusual, since the crests of sandbanks are generally regarded as being dynamic, sediment pathway convergence zones (e.g. Pattiaratchi and Collins, 1987). The modelling results predict recovery of these areas, but only after a time-span of, at least, a century and on the condition that the necessary sand supply is available in the system. Nevertheless, if the extracted sediments are different from those that are transported easily within the system, restoration of the bank is more difficult to take place. There are also concerns about the effects of these depressions on the flow, as flow modification may introduce changes in the original erosion/sedimentation patterns. In some cases, such changes might lead to increased erosion in the neighbouring coasts, although no clear impacts have been described within the literature, even for extraction areas close to the coast (e.g. Brampton, Evans, and Velegrakis, 1998; Queensland, 2005).

Biological/ecological impact

Assessing ecological changes is difficult in sandbank environments. The high mobility of species, the poverty and the wide niche width of the community, together with the extent to which the community adapts to high levels of sediment reworking, makes it difficult to isolate the effect of human-induced physical disturbance. Moreover, communities in areas of high stress are characterized by higher growth rates (Jennes and Duineveld, 1985); hence, they adapt more readily to the impact of any dredging operation (Desprez, 2000). The macrobenthos at the Kwinte Bank changed, but the changes were not significant at the larger community scale indicative for the Flemish Banks; this is due to the considerable adaptability of the community with highly mobile species. The observed, relatively, small changes showed that recovery can be considered as sufficient and relatively fast. However, some of the changing biological characteristics confirmed the tendency of the excavated depression to show more similarity with the behaviour of the deeper swale areas, next to the bank. Water depth changes may indeed cause changes to benthic fauna assemblages, such as changes in the composition, species diversity and abundance (Queensland, 2005).

Potential cumulative impacts

In the increasingly anthropogenically-stressed coastal marine environment, cumulative environmental effects may be anticipated. For example, sandbanks are associated also with fishery activities, which are focussed mainly on the swales and the base of the sandbanks; in high intensity trawling zones, the seabed has been shown (by multibeam imagery) to be completely scraped (Fund for Sand Extraction, unpublished). Since these areas are very significant components of the system, forming important constituents of the sediment recirculation cells and, thus, of the sandbank maintenance mechanism (e.g. Dyer and Huntley, 1999; Pattiarachi and Collins, 1987), the cumulative impacts of fishery activities require further investigation. In addition, the modification of the seabed dynamics in relation to the installation of marine Aeolian parks (windmill farms) has not been thoroughly investigated; nevertheless, these changes could affect the dynamics of nearby MA extraction zones. Cumulative impacts may also occur, when the potential effects of sea-level rise and increased storminess are considered (e.g. Solomon *et al.,* 2007); these effects are, however, difficult to establish, since long-term datasets are required.

Criteria for sustainable exploitation

Generally, the environmental impacts of extraction are site-specific, due to variations in sediment type, mobility and bottom topography and hydrodynamic activity (Desprez, 2000); as such, the establishment of general guidelines for minimising environmental effects is a rather difficult exercise. Nonetheless, in many cases, MA extraction zones are planned in areas that are not favourable for aggregate extraction in the long-term, e.g. due to limited resource availability and/or expected environmental constraints. If criteria can be set that are clear and quantifiable, they can: (a) provide guidance to the design of MA concession zones; (b) guide decisions on the management of MA extraction; and (c) be used for effective environmental monitoring. The strictness of such criteria will depend strongly upon the view of the relevant regulatory authorities on the acceptable environmental risks.

Location criteria

One of the major criteria for selecting MA extraction sites is the potential impact on the coast. In many coastal areas, the appropriate regulatory authorities have set location criteria on the basis of the water depth, the 'closure depth' or the distance from the coast in order to limit undesirable effects of MA extraction on the neighbouring coasts as, for example, in The Netherlands and the US (e.g. Campbell *et al.*, 2003). Depending on the distance from the coast, the infill rate of dredged areas will differ as also the impact on inshore wave climate (modified refraction and diffraction) and gradients of littoral drift (Van Rijn *et al.,* 2005). It must be noted, however, that the establishment of such criteria is also constrained by economic considerations related to costs due to the increased depth of extraction and the distance from the landing facilities (e.g. Bate *et al.*, 1997).

Geological criteria

Selecting concession areas with most suitable sediment resources, guaranteed also in the long-term, requires an improved knowledge of the continental shelf geology, particularly in the case of sandbanks. Sandbanks are characterised by a variable and complex internal architecture, with some banks exhibiting complex internal structures, suggesting multi-phase formation (e.g. Trentesaux, Stolk, and Berne, 1999) and others showing simple structures (e.g. Collins *et al.*, 1995). These differences may be related to the antecedent morphology and type of substrate, as well as the sedimentary framework in which the sandbanks were formed. Sandbanks with a multi-phase formation are often founded on an erosional (incised) surface which is infilled by coarser material over which estuarine and shallow marine deposits with varying lithologies are draped (Trentesaux *et al.*, 1999). Only the upper part of these banks is tidally dominated, consisting of sediments, representative of the present-day hydrodynamic regime. In these cases, exploitation should be restricted to the upper body of the sandbank, both from a resource perspective (i.e. consistent quality) and an environmental impact perspective (i.e. regeneration potential). On the basis of the results of the Kwinte Bank bathymetry monitoring, the thickness of the modern tidal sedimentary cover should not be less than 5 m, as intensive dredging may otherwise uncover the underlying deposits in a relatively short time

Table 3. *Large-scale information/maps needed to support sustainable exploitation.*

Information	Function
Detailed Grain size Distribution	Target the appropriate aggregate quality Id entify potential source areas for regeneration;
Thickness/Suitability of the deposits	Ensure long-term availability and consistency in quality;
Spatial/temporal information on flow information and sediment transport and erosion/deposition patterns, supported by information on bedform dynamics and morphological changes	Indicate areas with higher dynamics Identify bedload convergence/divergence zones and the evolution of the sedimentary environments to avoid areas with poor regeneration potential (e.g. 'kink' areas and extremities of the banks) and minimise detrimental physical impacts ;
Wave Energy Distribution	Evaluate event-driven possible impacts on the extraction zones and neighbouring coasts;
Ecological Functioning	Avoid sensitive areas, or important habitats;
Other seabed uses	Minimise conflicts, optimise concurrent use.

period (Bellec *et al.,* this volume). Further, it is important that areas are selected where a sufficient unconsolidated Quaternary cover is guaranteed over larger areas, including the swales between the banks, as it appears that swale areas close to extraction sites are more erosive than others (De Moor, 2002); hence swales likely form primary sources of sediments, for bank regeneration

Morphological criteria

Less stable areas of sandbanks are best to be avoided in terms of removal of sediments, i.e. MA extraction should be avoided over 'kink' areas (if present) and bank extremities. It has been suggested (Bellec *et al.*, this volume; Deleu *et al.*, 2004; Smith, 1988) that the 'kink' areas of sandbanks are associated with higher dynamics. In some cases, these areas are somewhat lower in height (Deleu *et al.*, 2004), but the dynamics of their bedforms is often rapid and readily adjustable to the varying hydro-meteorological conditions. Moreover, modelling experiments, undertaken over a 30-year period, have shown an erosional trend for the 'kink' area of the Kwinte Bank (Brière *et al.*, this volume). In addition, flow speed and direction may change rapidly in these areas, hampering recovery.

The dynamics along the sandbank extremities are also not easily predictable. In the Flemish Bank region, bank extremities appear interesting as resource areas, with higher bedforms and coarser-grained sediments. However, sediment volumes fluctuate more here and are more susceptible to storm action than those of the middle sections of the sandbanks. On the basis of historical data, De Moor (2002) has shown that the northern extremities of the Flemish Banks are recent sedimentary accumulations, formed within the last century. This is supported by seismic evidence, which have shown that only a thin sand sheet forms these modern, tidally-controlled sandbank sections (Bellec *et al.,* this volume). In addition, due to the more dynamic bedform movement, it is difficult to distinguish natural from anthropogenic changes in these areas; consequently, negative impacts of the sediment extraction will not be timely (and easily) observed. Finally, extraction over interdune areas can have adverse environmental impacts, if the crests and troughs of the dunes represent different sedimentary environments, with the troughs usually being heterogeneous in terms of sediment composition and often richer in benthic fauna than the crests (Mackie *et al.,* 2006).

Sediment dynamics criteria

If extraction is viewed within the framework of the natural variability of the sandbank's volume, then it would be beneficial if sediment extraction involves deposits with grain sizes that can be regenerated easily, i.e. deposits with grain sizes that are readily available in the potential source areas. In addition, the extraction zones should be restricted to areas known as being depositional. Sandbanks are generally areas of sediment accumulation (e.g. Pattiarachi and Collins, 1987); nonetheless, sections of the sandbanks can be erosional, as suggested also by the results of the Kwinte Bank investigation (Van den Eynde *et al.,* this volume, and Brière *et al.*, this volume).

A difficult criterion to define relates to the sediment volumes that can be extracted, without causing any long-term impact; this requires knowledge on the natural volume fluctuations. Based upon an extensive, monitoring programme, Degrendele *et al.* (this volume) have proposed a mean natural evolution of the bank volume of +/- 0.05 m^3/m^2/year; ideally, the rate of extraction should not exceed this rate. On the basis of 12 observations, Van Lancker (1999) has identified also such variability in the erosion/sedimentation patterns of the Belgian nearshore area, but found that it is mostly 'event dependent'. As such, this rate of change can occur between successive observations, on the short-term and may be balanced out on a year's basis. Present extraction activities, on a local basis, exceed significantly this rate; inside the depression, a rate of 1.08 m^3/m^2/year has been estimated, with the rates for the surrounding area and the overall extraction zone being 0.47 m^3/m^2/year and 0.64 m^3/m^2, respectively (Degrendele *et al.*, this volume). Thus, the extraction activities in the area cannot be balanced by the natural dynamics.

Biological/ecological criteria

Sustainable management of renewable natural resources should be based upon a balance between exploitation and adverse effects on the other components of the ecosystem (Thrush *et al.*, 1998). The results of van Moorsel (1994), Kenny and Rees (1996) and Desprez (2000) have illustrated that extensive dredging may modify the sedimentary deposits slightly, but the benthic communities considerably. As such, it may be preferable to concentrate extraction within small areas of the sandbank i.e. follow an 'intensive dredging' model. Nevertheless, prolonged extraction in confined areas can also cause serious effects on seabed morphology and sediment quality

Table 4. *Overview of knowledge/data and tools/innovation needs, to support the sustainable exploitation of a particular extraction site.*

	Geology	Morphology	Sedimentology	Sediment dynamics	Biology/Ecology
Knowledge / Data need	Resource availibility *sufficient unconsolidated Quaternary cover* Good characterisation of subsoil strata (homogeneity of the subsurface layers) Resource origin	Volume calculations Fine-scale Morphometric analysis Bedforms	Spatial distribution Quality mapping << industry needs	Fine-scale hydrodynamics 2D/3D (currents + waves) Sediment transport (bedload/suspended) Sediment balance (erosion/deposition) +grain size	Identification of ecologically sensitive areas Habitat characterisation Define ecological value
	← *Theoretical work on sensors* →				
Tools / Innovation need	Very-high resolution Seismics	High frequency Acoustics	High frequency Acoustics	High frequency Acoustics/Optics/ Electro Magnetic	High frequency Acoustics
	← *Sensor improvement* →				
	+ Coring+Geotechnics	+ Video/Still	+ Sampling+Geotechnics	+ Sampling	+ Video/Sampling
		Monitoring – adequate time series – good reference framework			
	Predictive modelling – long-term				
Risk and Uncertainty Analysis					

(Desprez, 2000; Vanaverbeke *et al.,* 2007). For comparison, there exists a 'threshold scale' and a 'frequency of disturbance events' at which long-lasting ecological effects may occur, even in the case of non-anthropogenic (natural) disturbance (Kaiser and Spencer, 1996). The results obtained here for the Kwinte Bank support these suggestions.

Criteria related to the extraction activity itself

Van Rijn *et al.* (2005) regard the orientation of the pit in relation to the flow, as the most important parameter controlling the rates of infill (see above). From navigational safety and practical perspectives, it appears logical that extraction should take place along the direction of the main current (e.g. Bate *et al.,* 1997). However, the present investigation (Degrendele *et al.,* this volume) has shown that the depression is located slightly obliquely to the crest and parallel to the flow; this has caused an opening of the depression, towards the northwestern swale (see Figure 3., Degrendele *et al.,* this volume) with the flood flow becoming 'channelised' (Garel*,* this volume). Such a situation should be avoided, as it enhances erosion. Other crucial criteria relate to the amount extracted on each dredging visit and the number of extractions over a given time-span (Schrijvers *et al*., 2007). Thresholds on these issues cannot be set on the basis of the available information, but they may be established in the future, with data becoming increasingly available on environmental impacts and dredging activities. Other issues relate to minimising the overflow, or fine material screening; however, these have been found less important on the Belgian Continental Shelf (Schrijvers *et al*., 2007).

Example of the application of some of the criteria to other extraction zones

Applying the above mentioned criteria to the concession zones in the Flemish Banks region, leads to the selection of the eastern part of the Buiten Ratel sandbank (Figure 2.) as being most suitable: water depths are still around 10-15 m MLLWS; the distance to the coast remains around 12 km; the sedimentary deposits have a sufficient thickness (> 5m) to support long-term extraction; the sediments are characterised by grain sizes in excess of 300 μm; the area is depositional; and the overall surface area with suitable sediments is large. Bedforms over this area reach up to 4-6 m in height; their asymmetry confirms the modelling results, which suggest that this area forms a bedload convergence zone and, thus, is a depositional sedimentary environment. Moreover, the grain sizes in the swale, lying to the east, are similar to those found on the bank, hence suitable for the regeneration of the areas of extraction. The present extraction zone, which is located on the steep, western flank of the bank, does not comply with most of the above criteria. At this location, the sediment grain size is somewhat less than 300 μm and, this area has been suggested to be an erosional sedimentary environment with the adjacent swale to the west, consisting mostly of gravel (Van Lancker *et al.,* 2007b, for resource maps). Therefore, the present extraction zone is regarded unsuitable and with low regeneration potential, as regeneration is likely to be hampered by a lack of suitable material sources. Consequently, comparable problems to those described for the Kwinte Bank are likely to occur in the future, i.e. formation of a depression on the western flank of the Buiten Ratel Bank, which will not be easily restored and will affect the local ecology, which is likely to be similar to that identified for the Kwinte Bank.

Need for an improved management framework

If it is further confirmed that non-renewable sediment resources are being exploited increasingly, there is a need for an improved resource evaluation and a more efficient and targeted use of the seabed. These requirements call for a strategic management framework (e.g. a plan according to the SEA Directive, see Radzevicius *et al.,* this volume), incorporating detailed resource and environmental information, at large and small scales (Table 3.). The basis of this framework should always be high quality geological maps, incorporating the surficial extent of the resource and its availability within depth. For sandbanks, in particular, detailed knowledge of their internal architecture is crucial for the accurate estimation of the resource reserves. Moreover, the hydrodynamics and sediment dynamics of these areas should be diagnosed in order to assess (predict) the morphodynamic evolution and the physical impacts of aggregate extraction. In addition, ecological information should be acquired in order to identify vulnerable species and habitats. Finally, although data availability will vary significantly, according to location and distance from the coast, the information detail needs to be sufficiently high, to ensure a realistic initial evaluation of any potential impacts.

Multicriteria resource maps, as presented in Figure 2., can assist in the selection of optimal locations for MA extraction, within the (often predefined) concession zones. These maps can integrate information on: (a) detailed sediment grain size distribution; (b) thickness of the targeted sediment deposit; (c) bedform distribution, shape/size, asymmetry and dynamics; and (d) areas of diagnosed/predicted erosion and deposition. Similarly, seabed mobility studies (e.g. Velegrakis *et al.*, 2007) can be used as an input to the decision-making process. Erosion/deposition rates can also be modelled, or derived from historical charts and maps. In the latter case, historical changes in sediment volume and sandbank elevation can be established providing erosional/depositional rates and regional patterns of sand movement (Brampton, Evans, and Velegrakis, 1998; Gao and Collins, 1995).

Detailed spatial and temporal information on ecological functioning is difficult to acquire and integrate, but is important within the context of the protection of sensitive or valuable habitats, communities or species. For soft-substratum areas of the shelf, there is likely a strong link between the nature and dynamics of the physical and biological environment; as such, recent developments in modelling tools may enable the mapping of ecologically important zones on the basis of abiotic parameters alone (e.g. Van Lancker and Foster-Smith*,* 2007). This approach has been demonstrated for the Belgian Continental Shelf, where the nature of macrobenthic communities was predicted successfully, on the basis of the median grain size and fine material (silt-clay) percentage in the sediment (Degraer *et al.*, in press). Biological/ecological valuation criteria (e.g. Derous *et al.*, 2007) can be applied then, to obtain maps establishing the ecological value of shelf environments (Derous *et al.*, in press). Such ecological maps, together with resource maps (Van Lancker *et al.,* 2007b) and the results of more detailed, targeted research can provide an ideal basis for any spatial planning initiative (e.g. Maes *et al.*, 2007). The data can be used to establish quantitative parameters, which can serve as inputs to decision-support systems, guiding the planning and management of future extraction activities (e.g. Calewaert *et al.,* 2007; Schrijvers *et al.*, 2007). In Table 4., the knowledge/data needs and the tools and innovation, required to establish the necessary framework for an improved sustainable management of MA deposits are summarised.

Details on the morpho-sedimentary and biological environment are, nowadays, increasingly derived from very high-resolution acoustic surveys (for an overview of seabed mapping techniques in environmental monitoring and management, see Boyd *et al.* (2006) and Mesh Project (2007)). Nevertheless, targeted ground-truthing of the remote-sensed information will remain an important component, in order to: (a) calibrate the acoustic imagery and improve automated seabed classifications; and (b) establish quantitative relationships between the physical and biological environment to be used in diagnostic and predictive modelling. Hydro-sediment dynamic observations (at least over a tidal cycle), using high frequency acoustical (e.g. acoustic doppler velocimeters and current profilers, acoustic backscatter sensors), optical (e.g. optical backscatter sensors) or electromagnetic devices, together with detailed information on sediment grain size and bedform dynamics, should be considered against the outputs of morphodynamic modelling. Moreover, the results should be evaluated against extraction data to distinguish between natural and anthropogenic seabed dynamics. The significance of any impacts can be further assessed using long-term predictive modelling tools (for an overview, see Idier *et al.*, this volume).

The scientific framework of such an investigation can be managed ideally in a GIS environment, allowing simplified integrations of spatially diverse data sets. However, the availability of relevant data in an appropriate spatial and temporal resolution and the inherent uncertainties in the diagnosis and prediction of the dynamics of the marine environment remain a continuous challenge.

The management of MA activities is a complex exercise, requiring robust cost-benefit analyses and holistic, science-based practical approaches, as well as effective transfer of knowledge between scientists, managers and policy-makers. The communication and fine-tuning of the various management needs should be considered within appropriate frames of reference (e.g. Van Koningsveld and Mulder, 2004), which contain key elements such as the formulation of: (a) strategic objectives, expressing the long-term management vision and policy; and (b) operational objectives, describing how the strategic objectives will be achieved.

Environmental monitoring

Environmental monitoring of the extraction sites should be able to document whether unacceptable impacts are evident or conditions that will lead to the development of such impacts are already in place (for an overview of monitoring guidelines/practices, see Fredette *et al.* (1990) and Posford Duvivier Environment and Hill (2001)) As such, monitoring schemes should provide clearly interpretable information on whether a threshold of an adverse condition has been, or is likely to be reached. On this basis, decisions can be made on the continuation, modification or closure of MA extraction sites. ICES (2003) has put forward a number of questions that should be answered in a successful monitoring programme: *(a) what are the environmental concerns that the monitoring programme seeks to address?; (b) what measurements are necessary to identify the significance of a particular effect?; (c) what are the most appropriate locations at which to take samples or observations for assessment and what is their natural variation?; (d) how many measurements are required to produce a statistically sound programme?; and (e) what is the appropriate frequency and duration of monitoring?*

Answering these questions requires the acquisition/analysis of quantitative information at various spatial and temporal scales (e.g. Collins and Balson, 2007). The present investigation has demonstrated that intensive, concentrated monitoring is required to detect in detail the morphological, sedimentary and ecological dredging-related impacts. A critical part of the assessment is the evaluation of these effects, against the background of the natural dynamics of the seabed. This approach requires systematic monitoring of the wider areas of the extraction sites, albeit at a lower spatial resolution. However, robust monitoring programmes may become very 'labour intensive'; the Belgian experience has shown that, even in the case of relatively high temporal resolution surveying (e.g. 4-5 times/year), it is difficult to establish statistically significant trends in sediment volumes/morphology (Norro *et al.,* 2006). Baseline information is crucial, as, in its absence, impact assessments are likely to remain inconclusive (Van Lancker *et al.,* this volume). It must be noted also that the establishment of practical and efficient monitoring practices require rigorous quality control (e.g. through regular reporting and publishing in peer-reviewed journals) and continuous fine-tuning.

Extensive or intensive dredging?

An important issue in MA extraction is related to whether extraction should be procured extensively, i.e. with a high spatial spread of the extraction activities, or intensively, i.e. focussed on relatively small areas of the seabed. Ideally, the former option would imply reduced severity of the environmental impacts and increased potential for site recovery from a physical and biological viewpoint; however, these benefits should be considered against the increased requirements for information gathering and environmental monitoring. In comparison, the Kwinte Bank investigation has shown that focussing on small areas of the seabed may result in the development of enduring morphological features, which are also related to long-term changes in the sedimentary and ecological properties.

It must be noted that the intensive dredging of the Kwinte Bank has involved, mostly, dredging vessels with an average capacity of less than 5,000 m^3, reflecting the availability of the vessels presently in service and the economics of MA exploitation, which constrain the extraction site's water depth and distance from the coastline (e.g. Bate *et al.*, 1997; Posford Duvivier, 2000). In response, both to the increasing general demand (driven by large beach nourishment or land reclamation projects) and stricter regulations on the exploitation of land-won aggregates (e.g. Radzevicius *et al.,* this volume, and Velegrakis *et al.*, this volume) future resource developments are envisaged to occur in deeper waters (e.g. Bate *et al.*, 1997). Anticipating these needs, dredging vessel capacities have recently increased substantially (in some cases up to 46,000 m^3 (www.jandenul.com)). However, deeper offshore sedimentary environments (including the offshore sandbanks) are much less dynamic and, as such, their recovery potential is reduced. Therefore, strategies and practices involving the exploitation of deeper water resources should be formulated carefully.

CONCLUSIONS

The Kwinte Bank investigation has shown that the MA extraction, focussing on the upper part (crown) of the bank, has had significant environmental impacts, the most important being the formation of a substantial depression. Within the depression, the sedimentary character of the seabed was found to differ from that of the remainder of the bank's crown and its characteristics resembled more to those of the adjacent swale. Bedforms and their dynamics showed also evidence of change. Following cessation of extraction activities in 2003, the bank morphology remained remarkably stable, with no significant additional effects being observed either on the bank itself or on the adjacent coast. The formation of the depression led to changes in the hydrodynamic and sediment dynamic regimes, which appear to hamper the regeneration of the depression, at least in the short-term. In comparison, predictive modelling of the medium- to long-term evolution of the bank showed a slow recovery of the bank's morphology. However, as the sources of appropriate material, necessary for the infill of the depression, are limited in the area and with the general erosive trend of the Flemish Banks, it is unlikely that natural regeneration processes will counterbalance the effects of the extraction. Finally, sand extraction appears to have created a 'locally-different' habitat on the Kwinte Bank, with adaptation of the benthic fauna; nevertheless, the change has not been found significant, at least on the scale of the sandbank system.

As non-renewable sediment resources are likely to be targeted increasingly for extraction, efficient and sustainable resource use is required. Such an approach relies upon detailed field information and appropriate mapping and modelling approaches within a long-term perspective. The Kwinte Bank investigation, although site-specific, may assist in the formulation of general guidelines for minimising environmental effects. It is suggested that the setting of clear and quantifiable criteria is a necessary prerequisite in the planning/design of MA concession zones, the efficient management of MA extraction and the planning of effective environmental monitoring schemes. Such criteria are related to considerations on: (a) resource location (i.e. water depth and distance from the coast); (b) the nature and thickness of the targeted sedimentary deposits; (c) bank morphodynamics; (d) sediment dynamics at regional and extraction site spatial scales; (e) biology and ecology; and (f) extraction practices.

The Kwinte Bank investigation has demonstrated that intensive, concentrated monitoring is required to identify the morphological, sedimentary and ecological impacts related to the dredging activities. A critical part of the assessment is the evaluation of these effects, against the background of the natural dynamics of the seabed; thus, baseline information is crucial, as, in its absence, impact assessments are likely to remain inconclusive. Finally, the jury is still out on whether MA extraction activities should follow an extensive (i.e. widespread) or an intensive (i.e. concentrated in small areas) model, as both of these models has pros and cons.

ACKNOWLEDGEMENTS

Fieldwork undertaken on the Kwinte Bank was a joint research initiative between the Belgian Science Policy project Marebasse ('Management, Research and Budgeting of Aggregates in Shelf Seas related to End-users', contract EV/02/18A) and the EU-RTN FP5 project EUMARSAND (contract HPRN-CT-2002-00222). Repeated sediment sampling formed part of the Belgian Science Policy project SPEEK (EV/02/38A). The Management Unit of the Mathematical Model of the North Sea and Scheldt Estuary (MUMM) approved ship time onboard the Belgian oceanographic vessel R/V *Belgica* and provided additional instrumentation and logistical support. The Flemish Institute of the Sea (VLIZ) granted ship time on the R/V *Zeeleeuw*. The captains, officers and crew of the above research vessels are acknowledged warmly for their support. The Fund for Sand Extraction, FPS Economy, SME's, Self-employed and Energy (Brussels, Belgium) is acknowledged for the supply of historical data, multibeam data, expertise and the approval of the use of the multibeam echosounder on the R/V *Belgica*. This publication will contribute also to the MESH project (Mapping European Seabed Habitats, http://www.searchmesh.net), which received European Regional Development Funding through the INTERREG III B Community Initiative (http://www.nweurope.org). Richard Soulsby, Ad Stolk and Jan Mulder are thanked for their constructive comments as reviewers, which improved the overall quality of the manuscript.

LITERATURE CITED

Bate, R.; Velegrakis, A.F.; Brand, C.; Collins, M.B., and Nunn, A., 1997. Deep water and inshore aggregates exploitation. *Research Report for the Countryside Council of Wales*, Green Balance, 91p.

Bellec, V.; Van Lancker, V.; Degrendele, K.; Roche, M., and Le Bot, S., this volume. Geo-environmental characterization of the Kwinte Bank in relation to sand extraction. *Journal of Coastal Research.*

Boers, M., 2005. Overview of historical pits, trenches and dump sites on the NCS. *In:* Van Rijn, L.C.; Soulsby, R.L.; Hoekstra, P., and Davies, A.G. (Eds.), SANDPIT*: Sand Transport and Morphology of Offshore Sand Mining Pits. Process knowledge and guidelines for coastal management.* End document May 2005, EC Framework V Project No. EVK3-2001-00056, Aqua Publications The Netherlands, H-1 - H-9.

Bonne, W., 2003. *Benthic copepod communities in relation to natural and anthropogenic influences in the North Sea*. Gent, Belgium: University of Gent, Ph.D. thesis, 289 p.

Bonne, W., this volume. Macrobenthos characteristics and distribution during recovery within a depression created by sand extraction on a subtidal sandbank. *Journal of Coastal Research*.

Boyd, S.E.; Limpenny, D.S.; Rees, H.L., and Cooper, K.M., 2005. The effects of marine sand and gravel extraction on the macrobenthos at a commercial dredging site (results 6 years post-dredging). *ICES Journal of Marine Science*, 62, 145-162

Boyd, S.E.; Coggan, R.A.; Birchenough, S.N.R.; Limpenny, D.S.; Eastwood, P.E.; Foster-Smith, R.L.; Philpott, S.; Meadows, W.J.; James, J.W.C.; Vanstaen, K.; Soussi, S., and Rogers, S., 2006. The role of seabed mapping techniques in environmental monitoring and management. *Sci. Ser. Tech Rep*., Cefas Lowestoft, 127, 170 p.

Brampton, A.; Evans, C.D.R., and Velegrakis A.F., 1998. *South Coast Mobility Study*, CIRIA PR 65, London. 219 p.

Brière, C.; Roos, P.C.; Garel, E., and Hulscher, S.J.M.H., this volume. Modelling the morphodynamic effects of sand extraction from the Kwinte Bank, Southern North Sea. *Journal of Coastal Research.*

Calewaert, J.-B.; Maes, F.; Lymbery, G.; Engelen, G.; Van Lancker, V.; Douvere, F.; Vanaverbeke, J.; Collins, M.; Mink, E., and Elliott, M., 2007. Conclusions and recommendations, pp. 251-305. In: Calewaert, J.-B and Maes, F. (Eds.), *Science and Sustainable Management of the North Sea: Belgian case studies*. Gent, Academia Press, 326p

Campbell, T.J.; Andrews, J.; Finkl, C.; Benedet, L., and Dean, R., 2003. *Locating and evaluating sand for beach nourishment projects*. Coastal Sediments '03. "Crossing Disciplinary Boundaries". The Fifth International Symposium on coastal Engineering and Science of coastal Sediment Processes. Clearwater Beach, Florida (USA): May 18-23, 2003.

Collins, M.B.; Shimwell, S.J.; Gao, S.; Powell, H.; Hewitson, C., and Taylor, J.A., 1995. Water and sediment movement in the vicinity of linear banks: the Norfolk Banks, southern North Sea. *Marine Geology*, 123, 125-142.

Collins, M.B. and Balson, P.S., 2007. Coastal and shelf sediment tranport: an introduction, pp 1-5. In: Balson, P.S. and Collins, M.B.. *Coastal and Shelf Sediment Transport*. Geological Society of London, Special Publication 274, 162 p.

Degraer, S.; Verfaillie, E.; Willems, W.; Adriaens, E.; Vincx, M., and Van Lancker, V. (in press). Habitat suitability modelling as a mapping tool for macrobenthic communities: An example from the Belgian part of the North Sea. *Continental Shelf Research.*

Degrendele, K.; Roche, M.; Schotte, P.; Van Lancker, V.; Bellec, V., and Bonne, W., this volume. Morphological evolution of the Kwinte Bank central depression before and after cessation of aggregate extraction. *Journal of Coastal Research.*

Deleu, S.; Van Lancker, V.; Van den Eynde, D., and Moerkerke, G., 2004. Morphodynamic evolution of the kink of an offshore tidal sandbank: the Westhinder Bank (Southern North Sea). *Continental Shelf Research*, 24, 1587-1610.

Derous, S.; Agardy, T.; Hillewaert, H.; Hostens, K.; Jamieson, G.; Lieberknecht, L.; Mees, J.; Moulaert, I.; Olenin, S.; Paelinckx, D.; Rabaut, M.; Rachor, E.; Roff, J.; Stienen, E.; Van Der Wal, J.T.; Van Lancker, V.; Verfaillie, E.; Vincx, M.; Weslawski, J.M., and Degraer, S., 2007. A concept for biological valuation in the marine environment. *Oceanologia,* 49(1), 99-128.

Derous, S.; Courtens, W.; Deckers, P.; Deneudt, K.; Hostens, K.; Moulaert, I.; Paelinckx, D.; Rabaut, M.; Roff, J.; Stienen, E.; Van Lancker, V.; Verfaillie, E.; Vincx, M., and Degraer, S., in press. Biological valuation: Guidelines for a transparent and generally applicable protocol for the marine environment. *Aquatic Conservation: Marine and Freshwater Ecosystems*.

Desprez, M., 2000. Physical and biological impact of marine aggregate extraction along the French coast of the Eastern English Channel. Short and long-term post-dredging restoration. *ICES Journal of Marine Science*, 57, 1428-1438.

De Groot, S.J., 1996. The physical impact of marine aggregate extraction in the North Sea. *ICES Journal of Marine Science* 53, 1051-1053.

De Moor, G., 2002. Évaluation de la morphodynamique sous-marine en Mer du Nord méridionale au cours de la période 1985-1995 (Evaluation of sea-floor sediment dynamics in the Flemish Banks (southern North Sea) between 1985 and 1995). *Géomorphologie: Relief, Processus, Environnement*, 2, 135-150.

Dyer, K.R. and Huntley, D.A., 1999. The origin, classification and modelling of sand banks and ridges. *Continental Shelf Research*, 19, 1285-1330.

Fredette, T.J.; Nelson, D.A.; Clausner, J.E., and Anders, F.J., 1990. Guidelines for physical and biological monitoring of aquatic dredged material disposal sites. Dredging Operations Technical Support Program. Technical Report D-90-12, US Army Corps of Engineers, US Army Engineer Waterways Experiment Station, Vicksburg, MS, 29 pp. + Annexes.

Gao, S. and Collins, M.B., 1995. On the physical aspects of the 'design with nature' principle in coastal management. *Ocean & Coastal Management*, 26(2), 163-175.

Gao, S.; Collins, M.B.; Lanckneus, J.; De Moor, G., and Van Lancker, V., 1994. Grain size trends associated with net sediment transport patterns: an example from the Belgian Continental Shelf. *Marine Geology*, 121, 171-185.

Garel, E., this volume. Tidally-averaged currents and bedload transport over the Kwinte Bank, Southern North Sea. *Journal of Coastal Research*.

Giardino, A.; Van den Eynde, D. and Monbaliu, J., this volume. Wave effects on the morphodynamic evolution of an offshore sand bank. *Journal of Coastal Research*.

HOOGEWONING, S.E. and BOERS, M., 2001. *Fysische effecten van zeezandwinning*. Report RIKZ-2001.050, RIKZ, Den Haag, The Netherlands. In Dutch.

ICES Advisory Committee on the Marine Environment, 2003. Annex 2: ICES guidelines for the management of marine sediment extraction. *ICES Cooperative Research Report* 263, 210-215.

IDIER, D.; HOMMES, S.; BRIÈRE, C.; ROOS, P.C.; WALSTRA, D.J.R.; KNAAPEN; M.A.F., and HULSCHER, S.J.M.H., this volume. Morphodynamic models used to study the impact of offshore aggregate extraction: a review. *Journal of Coastal Research.*

JENNES, M.I. and DUINEVELD, G.C.A., 1985. Effects of tidal currents on chlorophyll a content of sandy sediments in the southern North Sea. *Marine Ecology-Progress Series*, 21, 283-287.

KAISER, M.J. and SPENCER, B.E., 1996. The effects of beam-trawl disturbance on infaunal communities in different habitats. *Journal of Animal Ecology,* 65, 348-358.

KENNY, A.J. and REES, H.L., 1994. The effects of marine gravel extraction on the macrobenthos: Early post-dredging recolonization. *Marine Pollution Bulletin,* 28(7), pp.442-447.

KENNY, A.J. and REES, H.L., 1996. The effects of marine gravel extraction on the macrobenthos: Results 2 years post-dredging. *Marine Pollution Bulletin,* 32(8/9), 615-622.

KENNY, A.J.; REES, H.L.; GREENING, J., and CAMPBELL, S., 1998. The effects of gravel extraction on the macrobenthos at an experimental dredge site off North Norfolk, UK (results 3 years post-dredging). *ICES CM1998/V:14*, 1-7.

LE BOT, S.; VAN LANCKER, V.; DELEU, S.; DE BATIST, M., and HENRIET, J.P., 2003. *Tertiary and Quaternary geology of the Belgian Continental Shelf*. Scientific Support Plan for a Sustainable Development Policy. SPSD II North Sea. Brussels: PPS Science Policy publication D/2003/1191/12, 75p.

MACKIE, A.S.Y.; JAMES, J.W.C.; REES, E.I.S.; DARBYSHIRE, T.; PHILPOTT, S.L.; MORTIMER, K.; JENKINS, G.O., and MORANDO, A., 2006. *The Outer Bristol Channel Marine Habitat Study*. BIOMÔR Reports 4: 495 p., map and DVD-ROM.

MAES, F.; CALEWAERT, J.-B.; SCHRIJVERS, J.; VAN LANCKER, V.; VANHULLE, A.; VANDENABEELE, P.; VERFAILLIE, E.; DEROUS, S.; VOLCKAERT, A.; DEGRAER, S., and DE WACHTER, B., 2007. Chapter 6: GAUFRE: towards a spatial structure plan for the sustainable management of the Belgian part of the North Sea, pp177-250. In: CALEWAERT, J.-B and MAES, F. (Eds.), *Science and Sustainable Management of the North Sea: Belgian case studies*. Gent, Academia Press, 326pp.

MCCAULEY, J.E.; PARR, R.A., and HANCOCK, D.R., 1977. Benthic infauna and maintenance dredging: a case study. *Water Research*, 11, 233-242.

MESH PROJECT. *MESH Guide to Habitat Mapping*, JNCC, Peterborough (UK). Available online at: (http://www.searchmesh.net).

MORTON, J.W., 1977. Ecological effects of dredging and dredge spoil disposal: a literature review. *Techn. papers U.S. Fish and Wildlife Service* 94, 33p.

NEWELL, R.C.; SEIDERER, L.J., and HITCHCOCK, D.R., 1998. The impact of dredging works in the coastal waters; a review of the sensitivity to disturbance and subsequent recovery of biological resources on the sea bed. *Oceanogr. Mar. Biol. Ann. Rev.*, 36, 127-178.

NORRO, A.; PICHOT, G.; PISON, V., and OZER, J., 2006. Bidimensional approach to the volumetric evolution of an exploited sandbank. ICES *Journal of Marine Science*, 63(1), 176-186.

PATTIARATCHI, C. and COLLINS, M.B., 1987. Mechanisms for linear sandbank formation and maintenance in relation to dynamical oceanographic observations. *Progress in Oceanography*, 19, 117-176.

PETERSON, C.H. and BISHOP, M.J., 2005. Assessing the Environmental Impacts of Beach Nourishment. *BioScience,* 55(10), 887-896.

POINER, I.R and KENNEDY, R., 1984. Complex patterns of change in the macrobenthos of a large sand bank following dredging. *Marine Biology*, 78(3), 335-351.

POSFORD DUVIVIER, 2000. *Bristol Channel Marine Aggregates: Resources and Constraints*. Posford Duvivier Draft Final Report, C1366 to the Welsh Office.

POSFORD DUVIVIER ENVIRONMENT and HILL, M.I., 2001. *Guidelines on the impact of aggregate extraction on European marine sites*. Countryside Council for Wales (UK Marine SACs Project), Peterborough, 126p.

POULOS, S.E. and BALLAY, A., this volume. Grain size trend analysis for the determination of non-biogenic sediment pathways at the Kwinte Bank (Southern North Sea), in relation to sand abstraction. *Journal of Coastal Research*.

QUEENSLAND, 2005. *Moreton Bay Sand Extraction Study. Summary of Findings*. Queensland Government, Environmental Protection Agency, Queeensland Park and Wildlife Service, Brisbane (Au), 16p.

RADZEVIČIUS, R.; VELEGRAKIS, A.F.; BONNE, W.; KORTEKAAS, S.; GAREL, E.; BLAŽAUSKAS N., and ASARIOTIS, R., this volume. Marine aggregate extraction: regulation and management in EU Member States. *Journal of Coastal Research*.

RIBBERINK, J.S., 1989. *Zeezandwinnng. Onderbouwend rapport: milieu effectrapportage RON, discussienota kustverdediging*, Technisch rapport 10, *Report H825*, WL|Delft Hydraulics, Delft, The Netherlands. In Dutch.

ROOS P.C., 2004, *Seabed pattern dynamics and offshore sand extraction*, Ph.D. Thesis, ISBN 90-365-2067-3, University of Twente, The Netherlands, 166p.

SCHRIJVERS, J.; SCORY, S.; SUTTON, V.; DEROUS, S.; POLET, H.; VOLCKAERT, A.; CALEWAERT, J.-B., and MAES, F., 2007. Chapter 5: BALANS: Policy system thinking for sustainable management, pp137-176. *In*: CALEWAERT, J.-B and MAES, F. (Eds.), *Science and Sustainable Management of the North Sea: Belgian case studies*. Gent, Academia Press, 326p.

SMITH, D.B., 1988. Stability of an offset kink in the North Hinder Bank. *In*: DE BOER, P.L. VAN GELDER, A. and NIO, S.D. (Eds.), *Tide-Influenced Sedimentary Environments and Facies*. Dordrecht-Boston-Lancaster-Tokyo: D. Reidel Publ. Comp., pp65-78.

SOLOMON, S.; QIN, D.; MANNING, M.; CHEN, Z.; MARQUIS, M.; AVERYT, K.B.; TIGNOR, M., and MILLER, H.L.E., 2007. *IPCC, 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, (Cambridge, United Kingdom and New York, NY, USA) Cambridge University Press, 996p.

THRUSH, S.F.; J.E. HEWITT, V.J.; CUMMINGS, P.K.; DAYTON, M.; CRYER, S.J.; TURNER, G.A.; FUNNELL, R.G.; BUDD, C.J.; MILBURN, and WILKINSON, M.R., 1998. Disturbance of the marine benthic habitat by commercial fishing: impacts at the scale of the fishery. *Ecol. Appl.*, 8, 866-879.

TRENTESAUX, A.; STOLK, A., and BERNE, S., 1999. Sedimentology and stratigraphy of a tidal sand bank in the southern North Sea. *Marine Geology*, 159, 253-272.

VANAVERBEKE, J.; BELLEC, V.; BONNE, W.; DEPREZ, T.; HOSTENS, K.; MOULAERT, I.; VAN LANCKER, V., and VINCX, M., 2007. *Study of post-extraction ecological effects in the Kwintebank sand dredging area (SPEEK).* Final report. Scientific Support Plan for a Sustainable Development Policy, SPSDII. Part 2 Global Change, Ecosystems and Biodiversity. Brussels: Belgian Science Policy, 91p.

VAN CAUWENBERGHE, C., 1971. Hydrografische analyse van de Vlaamse Banken langs de Belgische kust. *Het Ingenieursblad*, 40(19), 563-571.

VAN DALFSEN, J.A.; ESSINK, K.; TOXVIG MADSEN, H.; BIRKLUND J.; ROMERO, J., and MANZANERA, M., 2000. Differential response of macrozoobenthos to marine sand extraction in the North Sea and the Western Mediterranean. *ICES Journal of Marine Science,* 57(5), 1439-1445.

Van den Eynde, D.; Giardino, A.; Portilla, J.; Fettweis, M.; Francken, F., and Monbaliu, J., this volume. Modelling the effects of sand extraction on the sediment transport due to tides on the Kwinte Bank. *Journal of Coastal Research.*

Van der Veer, H.W.; M.J.N. Bergman and Beukema, J.J., 1985. Dredging activities in the Dutch Waddensea: effects on macrobenthic infauna. *Netherlands Journal of Sea Research,* 19, 183-190.

Van Hoey, G.; Degraer, S., and Vincx, M., 2004. Macrobenthic community structure of soft-bottom sediments at the Belgian Continental Shelf. *Estuarine, Coastal and Shelf Science*, 59(4), 599-613.

Van Lancker, V, 1999. *Sediment and morphodynamics of a siliciclastic near coastal area, in relation to hydrodynamical and meteorological conditions: Belgian continental shelf*. Unpublished Ph.D. Thesis, Universiteit Gent, Gent, 194 p.

Van Lancker, V.; Bonne, W.; Velegrakis, A., and Collins, M.B., this volume. Aggregate extraction from tidal sandbanks: is dredging with nature an option? Introduction. *Journal of Coastal Research.*

Van Lancker, V. and Foster-Smith, B. (2007). How do I make a map?, pp. 1-77. In: MESH Project. *MESH Guide to Habitat Mapping*, JNCC, Peterborough (UK). Available online at: (http://www.searchmesh.net).

Van Lancker, V.; Deleu, S.; Bellec, V.; Du Four, I.; Verfaillie, E.; Fettweis, M.; Van Den Eynde, D.; Francken, F.; Monbaliu, J.; Giardino, A.; Portilla, J.; Lanckneus, J.; Moerkerke, G., and Degraer, S., 2007a. Chapter 4: MAREBASSE (Management, research and budgeting of aggregates in shelf seas related to end-users): Bridging gaps towards other disciplines and end-users, pp83-136. *In:* Calewaert, J.-B and Maes, F. (Eds.), *Science and Sustainable Management of the North Sea: Belgian case studies*. Gent, Academia Press, 326p.

Van Lancker, V.; Du Four, I.; Verfaillie, E.; Deleu, S.; Schelfaut, K.; Fettweis, M.; Van den Eynde, D.; Francken, F.; Monbaliu, J.; Giardino, A.; Portilla, J.; Lanckneus, J.; Moerkerke, G., and Degraer, S., 2007b. *Management, research and budgetting of aggregates in shelf seas related to end-users (Marebasse). Final Scientific Report*. Belgian Science Policy, 125p.

Van Moorsel, G., 1994. *The Klaverbank (North Sea), geomorphology, macrobenthic ecology and the effect of gravel extraction*. Bureau Waardenburg bv, Culemborg, NL, Rep. 94, 24, 65 p.

Van Rijn, L.C.; Soulsby, R.L.; Hoekstra, P., and Davies, A.G. (Eds.), 2005. SANDPIT: *Sand Transport and Morphology of Offshore Sand Mining Pits. Process knowledge and guidelines for coastal management*. End document May 2005, EC Framework V Project No. EVK3-2001-00056, Aqua Publications The Netherlands.

Van Koningsveld, M. and Mulder, J.P.M., 2004. Sustainable Coastal Policy Developments in the Netherlands. A Systematic Approach Revealed. *Journal of Coastal Research,* 20(2), 375-385.

Velegrakis, A.F.; Collins, M.B.; Bastos, A.C.; Paphitis, D. and Brampton, A., 2007. Seabed sediment transport pathways investigations: review of scientific approach and methodologies, pp. 127-146. *In*: Balson, P.S. and Collins, M.B.. *Coastal and Shelf Sediment Transport*. Geological Society of London, Special Publication 274, 162p.

Velegrakis, A.F.; Ballay, A.; Poulos, S.; Radzevicius, R.; Bellec, V., and Manso, F., this volume. European marine aggregates resources: Origins, usage, prospecting and dredging techniques. *Journal of Coastal Research.*

Verfaillie, E.; Van Lancker, V., and Van Meirvenne, M., 2006. Multivariate geostatistics for the predictive modelling of the surficial sand distribution in shelf seas. *Continental Shelf Research* 26(19), 2454-2468.

Verwaest, T. and Verelst, K., 2006. *Effect bodemverlaging Kwintebank op kustveiligheid* (model 765/20). Memo van resultaten. Advies Waterbouwkundig Laboratorium. Borgerhout (B): Waterbouwkundig Laboratorium, 14p. In Dutch.

Wellmer, F. and Becker-Platen, J., 2002. Sustainable development and the exploitation of mineral and energy resources: a review. *International Journal of Earth Sciences*, 91(5), 723-745.

Journal of Coastal Research	SI	51	165-172	West Palm Beach, Florida	Summer 2010

Aggregate resources and extraction in the Baltic Sea: an Introduction

Klaus Schwarzer

Christian-Albrechts Universität Kiel,
Institute of Geosciences,
Coastal and Continental Shelf Research
Olshausenstrasse 40, 24118 Kiel. GERMANY
kls@gpi.uni-kiel.de

ABSTRACT

There is no water body within the European Union which is surrounded by more countries than the Baltic Sea; likewise no water-body is more diverse regarding geological, environmental and ecological conditions. In response to postglacial development, there is isostatic uplift in the northern part of the Baltic Sea with rates of up to 9 mm/year; the southern part is sinking, at rates up to 2 mm/year. Crystalline rocks in the area of uplift and soft glacial and postglacial deposits in the area of sinking result in erosion and coastal retreat along the southern Baltic Sea coastline, whilst the northern countries are gaining land. Additionally, the marine resources of raw materials such as sand, gravel and stones are of limited extent and volume in the most south-westerly and southerly part of the Baltic Sea, due to the late glacial and Holocene development. Such conditions, combined with the predicted sea level rise, will lead to an increasing demand of aggregate resources in the future due to a higher demand for shore protection measures, as "soft" solutions like beach and dune nourishment are favoured in many countries. At the same time, restrictions due to EU and national directives are increasing, limiting the number of resources which can be used. This introduction gives both, an overview about the environmental conditions of the Baltic Sea which are controlling the availability of sand and gravel resources and as well a short summary about the exploitation and use of sand and gravel in the countries surrounding the Baltic Sea.

ADDITIONAL INDEX WORDS: *Baltic Sea, sand and gravel extraction, aggregate resources, Holocene coastal evolution*

INTRODUCTION

Since the trading route of the Hanseatic Lounge, which was established in 1250, the Baltic Sea stands for the exchange of culture, goods and knowledge. This was interrupted only by the "Cold War", separating the eastern and western world for more than 40 years. The political separation, which finished at the end of the last century, led to different developments regarding the demand, exploitation and use of mineral resources from and below the seafloor. Such resources are of limited extent and volume in the Baltic Sea.

Mismanagement of the extraction of sand and gravel resources may cause unacceptable consequences for society and the environment (Boyed *et al*., 2004; HELCOM, 1999). Hence, it is important to aim at sustainable development, whereby dredging is carried out, but with maximum consideration for the needs of nature protection; at the same time ensuring societal benefits from the extraction of the raw material. For this reason, it is necessary to improve our knowledge of the real extent, volume and quality of the resources, likewise to adapt extraction procedures to the development of new techniques, knowledge, laws and guidelines, to ensure minimum impacts on marine habitats.

Sedimentary deposits of economic importance such as sand, gravel, stones and boulders are resources of limited extent and volume; they are either non-renewable or they renew very slowly. Knowledge of the physical characteristics of the seafloor is essential for the identification, delimitation and exploitation of marine resources. Locating sand and gravel mining areas and a sustainable exploitation approach requires a profound knowledge of the palaeogeographic and geological evolution of an area, the spatial extent of the raw material resources and the environmental conditions and consequences, during and after extraction. For beach nourishment and land reclamation, sometimes in connection with harbour construction, extraction of material from offshore is the only environmentally - and economically - realistic alternative. Geological mapping using state of the art mapping technology (side-scan sonar, multibeam, 3-D seismic), is an appropriate approach to explore offshore resources; this enables the accurate delineation of deposits of the required quality.

Within the European Union there is no water body which is surrounded by more countries than the Baltic Sea (Figure 1). Likewise no water-body is more diverse regarding geological, environmental and ecological conditions. All riparian countries of the Baltic Sea have some offshore sand and gravel resources at their disposal, even Sweden in its southern part (Harff *et al*., 2004a; HELCOM, 1999). In some countries, mining is on-going today, due to the increasing demand for aggregates for industrial use, construction purposes and especially coastal defence. This paper provides a short introduction to the evolution of the Baltic Sea, with information in relation to sand and gravel resources; these have been exploited from the Baltic Sea for more than a century (Nielsen *et al*., 2004), but exploitation became very modest until the beginning of the 1980ties (Dybern and Fonselius, 1981).

THE BALTIC SEA

The Baltic Sea is a non-tidal intracontinental shelf sea with a free connection to the North Sea through the Kattegat and Skagerrak (Figure 1). It is the second largest brackish water body in the world, comprising an area of 412,560 km², a volume of 21,631 km³, extending 1,300 km in

DOI: 10.2112 / SI51-015.1 received 21 February 2008; accepted in revision 21 April 2008.

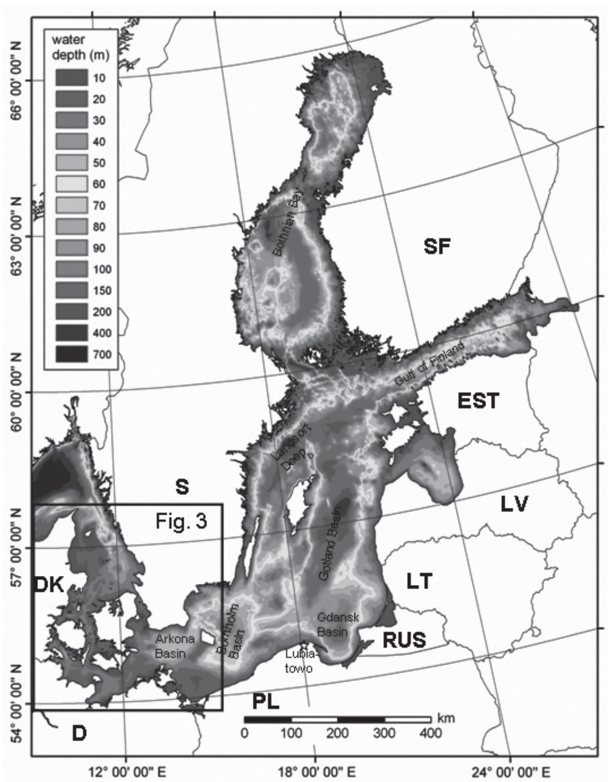


Figure 1. Bathymetry of the Baltic Sea (based upon data abstracted from SEIFERT, TAUBER and KAYSER, 2001).

S – N direction (54° - 66°), 1,000 km in E – W direction (10° - 30°) and has a maximum width of approximately 300 km. Various values ranging between 52 m (HELCOM, 1990) and 55 m (HARFF *et al*., 2005), are given for the average depth of the Sea; the deepest part, Landsortdeep, is 460 m in depth. The bathymetry is controlled by the presence of sills and deep basins, which developed during the last glacial period. These basins increase in size from west to east (Mecklenburg Bight, 25 m deep; Arkona Basin, 45 m deep; Bornholm Basin, 100 m deep; Gotland Basin, 250 m deep).

Geological development

During the last glacial maximum, approx. 21.000 years[1] ago (FLEMING *et al*., 1998), the world's continental shelves were widely exposed to sub-aerial processes. Their subsequent flooding was at its highest rates between 15,000 and 7,000 years ago; then was followed by a pronounced retardation during the last 7,000 years. Due to this relatively short time-span, the continental shelves contain presently a lot of relict features, which are inherited from past glacial times (EMERY, 1968; ROY *et al*., 1994). Typical examples in the higher latitudes are till, deposited by glaciers, and river valleys, which are sometimes deeply incised in the shelf sequences, due to the formerly lower-lying sea-level. The veneer of marine sediments, deposited since the post-glacial flooding, is on many shelf platforms still relatively thin, e.g. the German part of the North Sea, where it does not exceed a few metres (ZEILER, FIGGE and SCHULZ-OHLBERG, 2000) or is even absent, except in areas of high sediment input, e.g. adjacent to river mouth systems or within deep basins.

[1] When not explicitly mentioned all data are given in conventional ^{14}C dates.

The northern and central parts of the sub-surface of the Baltic Sea are dominated by crystalline rocks and Palaeozoic sediments. The whole south-eastern to south-western part, the coastal areas of Latvia, Lithuania, Russia, Poland, Germany and Denmark, are built up of Quaternary deposits (WINTERHALTER et al., 1981), mainly of Weichselian age, with only a few exceptions, e.g. parts of Rügen Island (Germany) or Møns Klint (Denmark), where cretaceous deposits have been pushed by the last glaciation. This observation is at least consistent for the upper layers exposed in shallow waters and at the coastlines.

The basin of the Baltic Sea was carved out over the past 2.4 million years, by several ice advances; of these, the latest formed the specific geomorphological shape of the basins, bays and coastal areas, on a larger spatial scale. The distances between the different ice-marginal lines of the latest ice advance, increase from west to east. Between these ice-marginal lines, melt-water sediments (composed of silt, sand and gravel) have been deposited. As such, the amount of sand and gravel below the veneer of the modern, post-littorina sediment increases from west to east.

Glacio-isostatic movement and climatically-controlled eustatic sea level fluctuations have caused transgressions and regressions in the Baltic Sea and its precursors, during the Holocene development. From the early to middle Holocene, the Baltic Sea underwent 4 evolutionary stages: Baltic Ice Lake; Yoldia Sea; Ancylus Lake and Littorina Sea (Figure 2) (BJÖRK, 1995; ERONEN *et al*., 2001 and LAMPE, 2005), experiencing alternating fresh-, brackish- and marine water conditions as a result of the interaction of uplift rates and changes in relative sea level. Based upon the modelling of large scale palaeo-coastline changes, since the onset of the Littorina transgression 8000 BP the sea-level in the northern part has declined significantly; in some areas by more than 200 m (CATO, 2004). This pattern has been resulted in a regression, out-weighting by far the southern transgression. According to MEYER and HARFF (2005) the aerial extent of the Baltic Sea has diminished by approximately 30 % whilst the volume has decreased from 47,000 km^3 to 22,000 km^3, or by 47 %.

In response to glacio-isostatic rebound, the northern part of the Baltic Sea is dominated still by an uplift relative to the present sea level, with rates up to 9mm/year in Bothnian Bay (MÖRNER, 1977; HARFF *et al*., 2005); in the southern part, subsidence rates of up to 2 mm/year occur (MEYER and HARFF, 2005). Such subsidence generally causes erosion and coastal retreat, along the whole of the southern Baltic Sea coastline, from Denmark via Germany, Poland, the Kaliningrad area, Lithuania to parts of Latvia, as these coastal areas consist of an alteration of cliffs and lowlands, built up of soft glacial and postglacial deposits, with only the few exceptions of the chalk-cliffs of Jasmund, Arkona and Møns Klint (Figure 3).

Environmental conditions

For the ecosystem of the Baltic Sea, the deep basins are not the most important; rather the two sills, the Drodgen Sill in the Øresund, with a depth of only 7 m below sea level and the Darss Sill between Gedser Rev and Fischland-Darss, with a depth of 18 m below sea level (Figure 1). These sills control the water exchange with the North Sea (JACOBSEN, 1980). Such exchange is not continuous, but depends strongly upon westerly storms, resulting in oxygen-rich North Sea water inflow into the Baltic Sea basin; this, 73 % takes place via the Darss sill, whilst the remainder is controlled by the Drodgen Sill.

The ratio between the Baltic Sea surface and the drainage area is 1:4, the annual freshwater input (rainfall and river discharge) amounts to 660 km^3/year and the brackish water discharge is 950 km^3/year, which is compensated by 475 km^3/year of North Sea water inflow (BJÖRCK, 1995). The difference in the balance is due to evaporation. Therefore the Baltic Sea is dominated by an estuarine circulation. A distinct stratification of the water body with a pronounced halocline and pycnocline leads to oxygen depletion in the deepest parts of the basins where regularly anoxic conditions predominate.

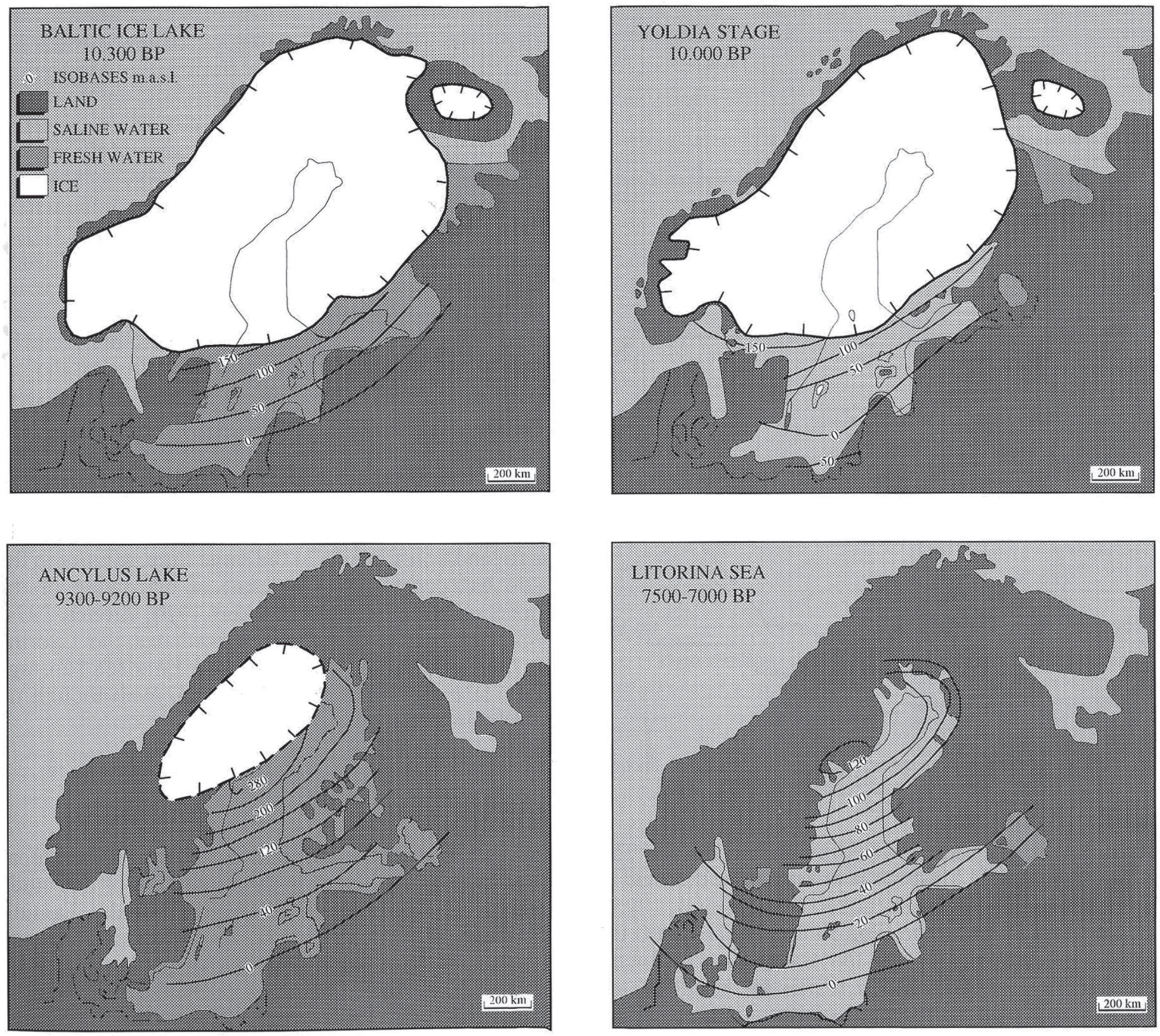


Figure 2. The development of the Baltic Sea during the late- and post-glacial (from ERONEN *et al*., 2001).

Besides the vertical stratification of the water-body, there is also a strong salinity gradient from full marine conditions in the Skagerrak area to only approx. 3 – 5 ‰ in Bothnian Bay and the Gulf of Finland; this influences strongly the faunal and floral distribution within the entire Baltic Sea. As the Baltic Sea extends up to 66° N, it is affected also by different climatic zones. Sea ice develops in the northern and north eastern parts (e.g. the Gulf of Finland has an ice cover of up to 100 days/year), which is dominated by continental climate. The southern and southwestern parts are mostly free of ice, even during the wintertime. However, several times since 1742 the entire Baltic Sea, including its southwestern part, has been covered with ice (HELCOM, 2007; TINZ, 1995).

Wave conditions and sediment transport in shallow coastal waters depend upon exposure to the main wind and wave direction. Within this context, the southern Baltic Sea coast is exposed to both north easterly and westerly winds. For comparison, within the western Baltic Sea (Germany and Denmark) where fjords and bays are common (Figure 3), the most effective wind direction inducing coastal currents and sediment mobilisation varies considerably; it includes all directions, even south for some stretches of the Danish coastline. However, no long term-trend in increasing storminess indices over southern Scandinavia has been observed (HELCOM, 2007).

Large sections of the German Baltic Sea coastline are retreating, at an average rate of 0.2 – 0.3 m/year and maximum rates of up to 1.5 m/year (SCHWARZER *et al*., 2003). East of Rügen Island (Figure 1) the coastline turns towards a formation which looks as if equilibrium conditions between erosion and accumulation predominate; however even here coastal retreat dominates. Approximately 70 % of the coastline of the

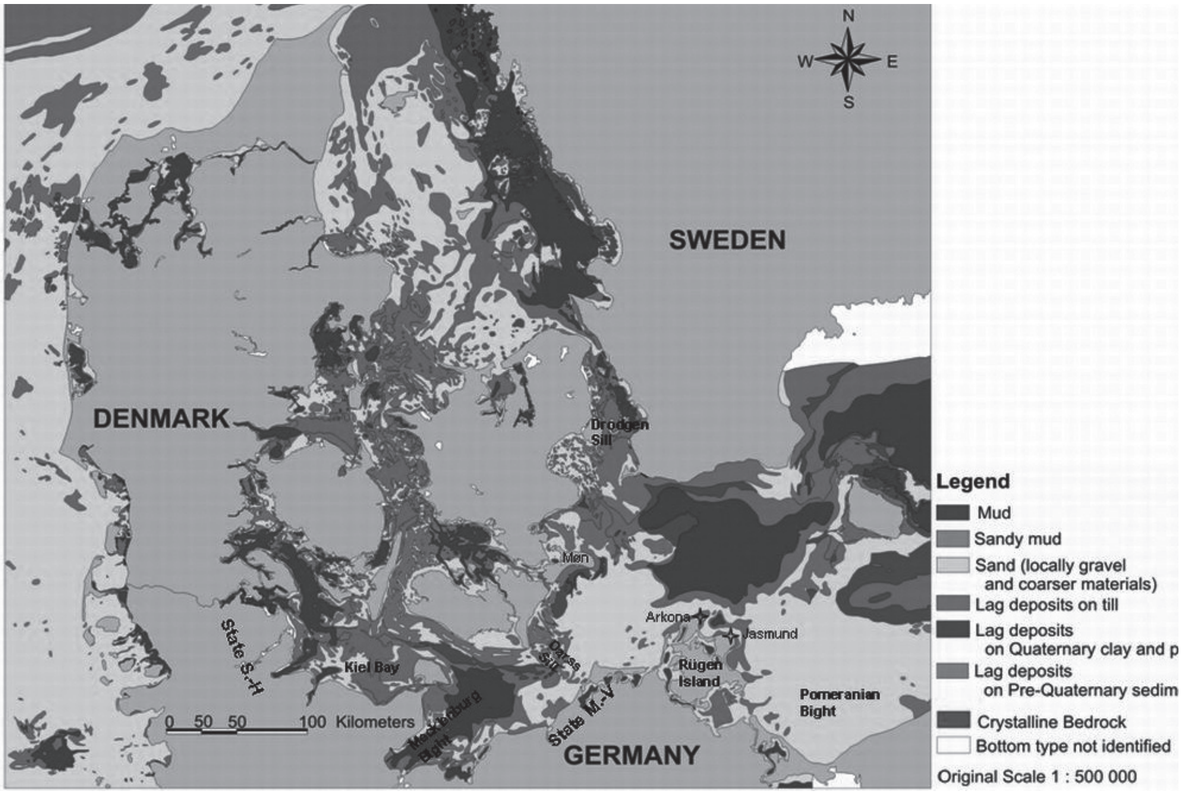


Figure 3. Seabed sediments around Denmark, the German part of the Baltic Sea and parts of the Polish coast. Source: Hermansen, B. and Jensen, J.B. 2000.

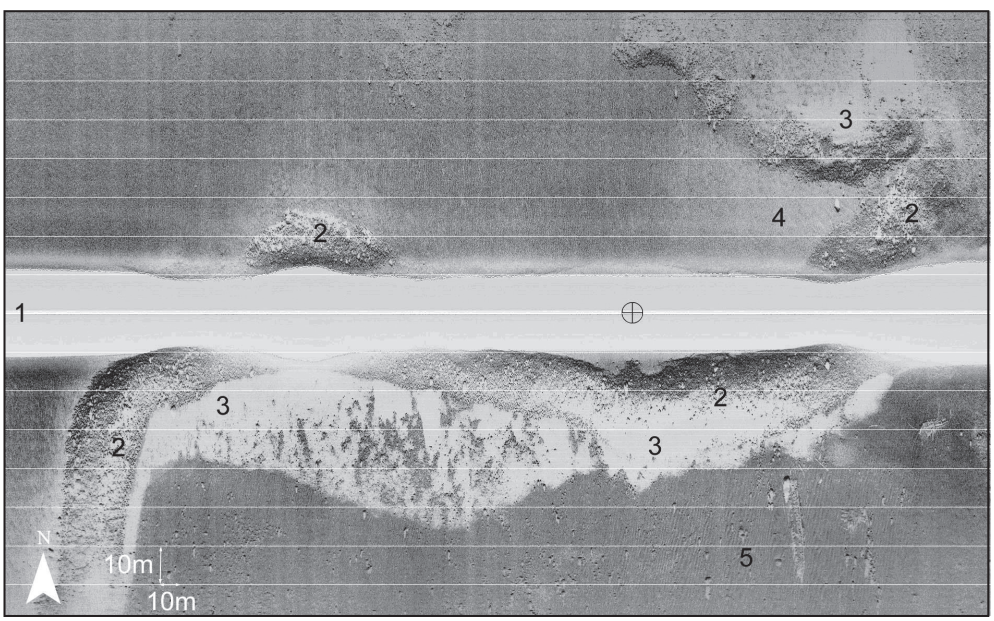


Figure 4. Side-scan image from Adlergrund / Baltic Sea (54° 44,433' N, 14° 17,533' E). To get a better impression about the relief, there is no slant range correction of the image. 1 – water-column, 2 – ridges, 3 – acoustic shadow, 4 – sand, 5 – wave induced ripples (Feldens, Diesing and Schwarzer, 2007).

Table 1. *Offshore aggregate resources and present mining activities of the countries surrounding the Baltic Sea. Resources are given in m³ ·106 (* data taken from HELCOM, 1999, ** Kramarska et al., 2004, ***Nielsen et al., 2004, +M.-V. = State Mecklenburg-Vorpommern, Germany).*

Country	Poland	Latvia	Lithuania	Estonia	Russia (Kaliningrad and St. Peters-burg region)**	Finland	Sweden	Denmark***	Germany
Aggregate Material	Gravel: 280 Sand: 35	No activity*	No activity*	No activity*	Gravel and sand 400 (33.4+)	< 0,5*	No activities since 1992*	Gravel: 300 Sand: 2510	Gravel: 11.0 Sand: 14.5 (**only M.-V.)

state Mecklenburg-Vorpommern, extending from Mecklenburg Bay to Odra Bay (Figure 3), is under retreat permanently (Harff *et al*., 2004a). According to HELCOM (2007), 74% of the Polish coast is presently under erosion, but coastal defence structures have only been erected along 26 % of the coast. Along parts of the Latvian coast, cliff erosion has increased from an average of 0.5 – 0.6 m/year over the past 60 years, to 1.5 – 4 m since 1980/81. All of this response is related to the isostatic / neotectonic sinking, sea level rise, frequency of storm surges and the geological architecture of the coastal areas. As such, it requires continuous replacement of the eroded material to maintain a stable coastline in those areas where settlements, different kinds of infrastructures and/or industrial use predominate.

Natural sediment sources within the region are active cliffs and sediment, abraded from the seafloor (Schrottke, 2001). In many cases, the amount of sediment supplied by seafloor abrasion is underestimated, sometimes completely neglected. Depending upon the composition of the Quaternary deposits and the exposure to the main wind- and wave direction, such sediment supply can be of the same order of magnitude as that e.g., from a 10 m high retreating cliff (Schrottke and Schwarzer, 2006). However, in many cases even this is not sufficient to stabilize the coastline.

No precise information is available on wave conditions in the open Baltic Sea, but some measurements are available from the research station in Lubiatowo (Figure 1), which was established in 1974 and belongs to the Polish Academy of Sciences - Institute of Hydroengineering. Records from this research station indicate a maximum wave-height H_{max} of 7.4 m (Paplinska-Swerpel, 2003) and a maximum wave length of around 80 m. During those NE-storm conditions, the depth of incipient sediment movement induced by waves (Wright, 1995) extends down to a water depth of approximately 40 m.

Aggregate resources

Compared to other marine environments in particular to the tidally dominated North Sea, the surficial sediment distribution in the non-tidal Baltic Sea is much more heterogeneous; it is patchy on both, small and large spatial spatial scales (Figure 3). This observation is confirmed by different maps, either covering the whole Baltic Sea (Winterhalter *et al*., 1981) or just localised areas (Emelyanov, Tauber, and Lemke, 1993; Gelumbauskaite *et al*., 1999; Hermansen and Jensen, 2000; Tauber and Lemke, 1995; Tauber, Lemke and Endler, 1999 and Uscinowicz and Zachowicz, 1994). The deep basins (Figure 1) function as sinks for fine grained sediment (silt and clay), whilst sandy material is deposited in the more shallow areas. Relict sediment remains, where till or other glacial deposits pinch out at the seafloor (Figure 4) where they are directly influenced by waves.

Dredged material in the Baltic Sea result from both: a) non-renewable fossil resources like glaciolimnic deposits or deposits from a former stage of the Baltic Sea (Bellec, Diesing and Schwarzer, this volume; Manso *et al*., this volume and Schwarzer, Diesing and Trischmann, 2000); or b) material which originates from coastal erosion or seafloor abrasion, which is transported and re-deposited in shallow marine areas (Kortekaas *et al*., this volume, and Schwarzer *et al*., 2003).

Sand and gravel deposits in the southern part of the Baltic Sea (the offshore areas belonging to Denmark, southern Sweden, Germany, Poland and the Kaliningrad area) have formed mainly as the result of post-glacial erosion and selective transport and deposition processes of glacial and partly postglacial deposits, reflecting the geological settings and the prevailing hydrodynamic conditions. Many of these deposits are of fossil origin and, therefore, non-renewable. They consist of glacio-fluvial deposits, fossil beach ridges and submerged coastal planes, which developed during the former stages of the Baltic Sea (Nielsen *et al*., 2004 and Schwarzer, Diesing and Trischmann, 2000).

Although the sediment distribution is affected strongly by the subsurface geology, a depth-dependent overall zonation of surface deposits can be found (Seibold *et al*., 1971). In the southwestern and southern Baltic Sea, coarse-grained lag deposits form a thin veneer (a few decimetres) on top of till deposits, in water depths of 5 to 15 m along the coasts and on the submarine sills and shoals. These sediments result directly from the abrasion of the underlying till deposits. Material with grain sizes within the range of sand is removed by wave- and current action, leaving the coarser constituents behind (Swift *et al*., 1971; Tauber, Lemke and Endler, 1999). Lag deposit areas are often found to be surrounded by well-sorted fine to medium sands. Apart from the immediate proximity of the coast and abrasion platforms, these sand veneers are relatively thin, for example only 0.5 to 2 m in Kiel Bay (Seibold *et al*., 1971) and inner Mecklenburg Bay. Significant amounts of marine sediments are found within the deeper basins and channels of the Baltic Sea, where fine-grained, organic-rich sediments (mud) accumulate (Lemke, 1998; Werner *et al*., 1987). Depending on the water depth, the grain-size decreases from coarse to fine silt while the content of organic matter increases up to 10 – 15 % (Winterhalter *et al*., 1981).

Exploitation

In the western Baltic Sea, sand, gravel, stone and even boulder exploitation (Karez and Schories, 2005) has lasted for more than a century (Nielsen *et al*., 2004). For all kinds of usage the most important parameter is grain size; others such as the mineral composition are of minor importance and as such their analyses are mostly not carried out. Gravel is used mainly by the concrete industry; however, sand is used predominantly for coastal protection works, only minor proportions are being used by the glass industry. Natural restrictions regarding exploitation are the water depth, the thickness of mud cover and the distance of the resources from the coast. Around the Baltic Sea, Denmark is the leading extractor and supplier of marine aggregates to other countries, followed by Germany. Minor quantities are dredged in Finland and the St. Petersburg area of Russia (Table 1). No activities are reported from Lithuania, Latvia, Estonia and the Kaliningrad region (Nielsen *et al*., 2004).

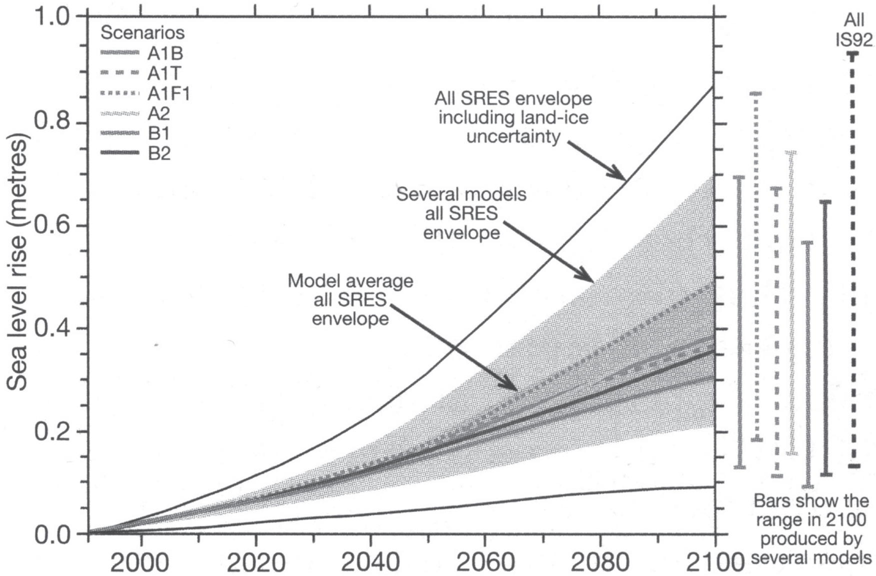


Figure 5. Projected global sea level response related to global climate change in the 21st century as presented in the IPCC Third Assessment Report. Taken from "Climate Change in the Baltic Sea Area, HELCOM Thematic Assessment in 2007" (HELCOM, 2007).

Probably the largest known resource of sand and gravel in the Baltic Sea is the NE – SW elongated shoal "Rønne Bank – Adler Ground" (Figures 1and 3), with a potential volume of 1.5 billion m³ of sand and gravel (Nielsen *et al*., 2004), of which 2000 · 10^6 m³ are located in Danish waters. This shoal extends 60 km from the Bornholm coast, into German territorial waters. Extraction is carried out here to support the Danish, Swedish and German market; it is still on-going but has decreased recently from 700,000m³/year to 250,000m³/year. However, the total volume dredged in the Danish Baltic Sea territories is about 1.5 – 2.0 x 10^6 m³ (Nielsen *et al*., 2004).

The amount of sand and gravel resources located in coastal waters off Mecklenburg Vorpommern (Figure 3) amounts to 25.5 x 10^6 m³ (Table 1) of which 31 % have been exploited until 2004 (Harff *et al*., 2004b). In Poland, from 1990 – 2000, 10.9 x 10^6 m³ of sand and gravel were exploited from the Baltic Sea; this approximates to 1 x 10^6m³/year (Kramarska *et al*., 2004). Approximately 33 x10^6 m³ of sand and gravel exist in the eastern Gulf of Finland; of this, 45% were mined for building in the St. Petersburg and Leningrad districts (Mosakalenko *et al*., 2004). The dredging areas are established partly in shallow waters, within a water depth of only 6 m. According to Cato (2004), only 17 % of the Swedish Baltic Sea territories are well mapped. However due to uplift, the highest postglacial shoreline in Sweden is found at an altitude of 286 m above the present sea level: Therefore a huge amount of sand and gravel of former marine origin is found on land at various altitudes (Cato, 2004) and can be mined there. In the past, the demand for marine extraction was not very high; since 1992 there have been no offshore dredging activities offshore Sweden.

CONCLUSIONS

The Baltic Sea is a very 'young' marine environment, which is extremely diverse compared to other oceans regarding geological prerequisites, physical forcing of sediment mobility and environmental conditions. Due to its young geological history and the on-going uplift / subsidence processes, the surface sediment distribution and the upper part of the subsurface, which are of interest as an economic deposit, are very patchy; they are mainly of Quaternary origin. In part, they are primary deposits, such as the gravel sediments in Tromper Wiek (Bellec, Diesing, and Schwarzer, this volume), which is the most shallow extraction site in the southwestern Baltic Sea, located in water depth of only 8 m, at a distance of approximately 2 km from the coastline. Partially in some areas deposits are renewing continuously in response to active coastal transport processes (Kortekaas *et al*., this volume). In the eastern Gulf of Finland (Kurort District St. Petersburg, Figure 1) deposits formed by wave and current activities, actually are found in water depths of only 3 – 5 m. These deposits have a sediment dynamic linking to beach sands and as such their mining is endangering the coastline (Moskalenko *et al*., 2004).

In addition to the risk assessment of aggregate extraction, there are legal and administrative restrictions, e.g. the EU Water Framework and Habitat Directive, together with national laws and restrictions, which differ from country to country. Other conflicts of interest regarding the exploitation of marine mineral resources result from the identification as military exercise areas, archaeological sites, shipping lanes or spawning grounds (Czybulka and Bosecke, 2006).

For the subsiding southern and southwestern parts of the Baltic Sea in particular there might be an increasing demand of sand for beach nourishment in the future; this is related to increasing erosion and coastal retreat, because of the predicted sea level rise (HELCOM, 2007). As these are the areas which have the most limited amount of natural, marin mineral resources due to their Pleistocene and Holocene development, and where shore protection is favoured to be carried out only with natural material, some problems might occur here. In the northern uplift section, where sea level rise is not yet a problem, the available resources are sufficient and dredged material is only used for construction purposes; as such offshore aggregate dredging is not yet identified as a problem. However, by the year

2100, many regions currently experiencing a relative fall in sea level would instead have a rising relative sea level (Figure 5). For example, the past trend of a lowering mean sea level in the Gulf of Finland would not continue in the future because the accelerated rise in global average sea level will balance the land uplift. The combination of high sea levels induced by storm surges, ice-free seas, and unfrozen sediments would enhance erosion and the transport of sediments (HELCOM, 2007).

In summary it is important for each society to maintain environmentally - and economically - sound raw material management, to ensure the fully sustainable exploitation of offshore resources.

ACKNOWLEDGMENTS

This study was carried out in the framework of EUMARSAND ("European marine Sand and Gravel Resources: Evaluation and Environmental Impact of Extraction"), contract HPRN-CT-2002-00222. I thank Ralf Otto Niedermeyer, State Agency for Environment, Nature Protection and Geology of Mecklenburg-Vorpommern, Michael Collins, National Oceanography Centre, Southampton and an anonymous reviewer for review comments and suggestions to improve this paper. Their comments and advice are very much appreciated.

LITERATURE CITED

Bellec, V.; Diesing, M., and Schwarzer, K., this volume. Late Quaternary evolution of gravel deposits in Tromper Wiek, southwestern Baltic Sea. *Journal of Coastal Research*.

Björk, S., 1995. A review of the history of the Baltic Sea, 13,0 – 8,0 Ka BP. Quaternary International, 27, 19 – 40.

Boyed, S.E.; Cooper, K.M.; Limpenny, D.S.; Kilbride, H.L.; Rees, H.L.; Dearnaley, M.P.; Stevenson, J.; Meadows, W.J., and Morris, C.D., 2004. Assessment of the re-habilitation of the seabed following marine aggregate dredging. *Sci. Ser. Tech. Rep*., CEFAS Lowestoft, 121-154.

Cato, I., 2004. Marine Mineral Deposits within the Swedish EEZ. - Exploration, Exploitation and Sustainable Development. *Zeitschrift für Angewandte Geologie*, 2, 147 – 158.

Czybulka, D. and Bosecke, T., 2006. Marine Protected Areas in the EEZ in light of international and European Community law – Legal basis and aspects of implementation. *In*: Nordheim, H. von; Boedeker, D. and Krause, J.. *Progress in Marine Conservation in Europe*, pp. 27 – 46.

Dybern, B.I. and Fonselius, S.H., 1981. Pollution. *In*: Voipio, A. *The Baltic Sea*. Elsevier Oceanography Series, 30, 351-375.

Emery, K.O., 1968. Relict sediments on continental shelves of world. - American Association of Petroleum Geologists Bulletin, 52 (3): 445 – 464.

Emeljanov, E.; Neumann, G., and Lemke, W., 1993. *Bottom Sediments of the Western Baltic*. Baltic Sea Research Institute (IOW) and St. Petersburg P.P. Shirshov Institute of Oceanology RAS, Atlantic Branch.

Eronen, M.; Glückert, G.; Hatakka, L.; Vande Plassche, O.; Van Der Plicht, J., and Tantala, P., 2001. Rates and Holocene isostatic uplift and relative sea-level lowering of the Baltic in SW Finland based on studies of isolation contacts. *Boreas*, 30(81), 445-464.

Feldens, P.; Diesing, M., and Schwarzer, K., 2007. Concertina eskers on the seafloor near Adler Grund (Southern Baltic Sea). TERRA NOSTRA – Schriften der GeoUnion Alfred-Wegener-Stiftung, 2007/1-2, 80-81.

Fleming, K.; Johnston, P.; Zwartz, D.; Yokoyama, Y.; Lambeck, K., and Chappell, J., 1998. Refining the eustatic sea-level curve since the Last Glacial Maximum using far- and intermediate-field sites. *Earth and Planetary Science Letters*, 163, 327-342.

Gelumbauskaite, L.Y.; Grigelis, A.; Cato, I.; Repecka, M., and Kjellin, B.,1999. LGT Series of Marine Geological maps No.1. SGU Series of Geological Maps Ba No. 54.

Harff, J.; Emelyanov, E.M.; Schmidt-Thomé, M. and Spiridonov, M., 2004a. Mineral Resources of the Baltic Sea – Exploration, Exploitation and Sustainable Development. *Zeitschrift für Angewandte Geologie*, Sonderheft 2, 227 p.

Harff, J.; Bobertz, B.; Granitzki, K.; Lemke, W., and Wehner, K., 2004b. Sand and gravel deposits in the South-Western Baltic Sea, their utilisation and sustainable development. *Zeitschrift für Angewandte Geologie*, Sonderheft 2, 111–122.

Harff, J.; Lampe, R.; Lemke, W.; Lübke, H.; Lüth, F.; Meyer, M., and Tauber, F., 2005. The Baltic Sea – A Model Ocean to Study Interrelations of Geosphere, Ecosphere, and Anthroposphere in the Coastal Zone. *Journal of Coastal Research*, 21(83), 441-446.

HELCOM, 1990. Second periodic assessment of the state of the marine environment of the Baltic Sea, 1984 – 1988. General Conclusions. *Baltic Sea Environment Proceedings*, No. 35A, 35 p.

HELCOM, 1999. Marine Sediment Extraction in the Baltic Sea – *Status report Baltic Sea Environmental Proceedings*. No. 76, 33 p.

HELCOM, 2007. Climate Change in the Baltic Sea Area – HELCOM Thematic Assessment 2007. – *Baltic Sea Environmental Proceedings*. No. 111, 49 p.

Hermansen, B., and Jensen, J.B., 2000. Digital Sea Bottom Sediment Map around Denmark. *Danmark og Groenlands Geologiske Undersoegelse Rapport*, 68.

Jacobsen, T.S., 1980. Sea Water Exchange of the Baltic – Measurements and Methods. National Agency of Environmental Protection, Copenhagen, 1-71.

Karez, R. and Schories, D., 2005. Die Steinfischerei und ihre Bedeutung für die Wiederansiedlung von *Fucus vesicolosus* in der Tiefe. *Rostocker Meeresbiologische Beiträge*, 14, 95–107.

Kortekaas, S.; Bagdanaviciute, I.; Gyssels, P.; Huerta, J.M.A., and Héquette, A., this volume. Assessment of the effects of marine aggregate Extraction on the Coastline: An example from the German Baltic Sea coast. *Journal of Coastal Research.*

Kramarska, R.; Masloska, M.; Uscinowicz, S., and Zachowicz, J., 2004. Review of Marine Sand and Gravel Resources in the Polish Exclusive Economic Zone of the Baltic Sea. Exploration, Exploitation and Sustainable Development. *Zeitschrift für Angewandte Geologie*, 2, 125–134.

Lampe, R., 2005. Lateglacial and Holocene water-level variations along the NE German Baltic Sea coast: Review and new results. *Quaternary International*, 133-134; 121-136.

Lemke, W., 1998. Sedimentation und paläogeographische Entwicklung im westlichen Ostseeraum (Mecklenburger Bucht bis Arkonabecken) vom Ende der Weichselvereisung bis zur Litorinazeit. *Meereswissenschaftliche Berichte*, 31, 156 p.

Manso, F.; Radzevicius, B.; Blažauskas, N.; Balay, A., and Schwarzer, K., this volume. Nearshore dredging in the Baltic Sea: Conditions after cessation of activities and assessment of regeneration. *Journal of Coastal Research*.

Meyer, M. and Harff, J., 2005. Modelling Palaeo Coastline Changes of the Baltic Sea. *Journal of Coastal Research*, 21(3), 598-609.

Mörner, N.A., 1977. Post and present uplift in Sweden: Glacial isostasy, tectonism and bedrock influence. *Geol. Fören*. 29, 48-54.

Moskalenko, P.E.; Zhamoida, V.A.; Manuilov, S.F., and Spiridonov, M., 2004. The geological Structure, History of Geological Development and Potential Mineral Resources of the Eastern Gulf of Finland. Exploration, Exploitation and Sustainable Development. *Zeitschrift für Angewandte Geologie*, 2, 135-145.

Nielsen, P.E.; Jensen, J.B.; Binderup, M.; Lomholt, S., and Kuipers, A., 2004. Marine Aggregates in the Danish sector of the Baltic Sea: Geological setting, exploitation potential and environmental assessment. *Zeitschr. f. Angewandte Geologie*, 2, 87–108.

Paplińska-Swerpel, B., 2003. Sea Wave Measurements and Modelling in the South Baltic Sea. Summer School-*Workshop* Coastal Zone '03. Institute of Hydroengineering of the Polish Academy of Sciences, 65–80.

Roy, P.S.; Cowell, P.J.; Ferland, M.A. and Thom, B.G., 1994. Wave-dominated coasts. *In*: Carter, R.W.G. and Woodroffe, C.D. (eds.). *Coastal Evolution. Late Quarternary shoreline morphodynamics*, pp. 121 – 186.

Schrottke, K., 2001. Retreat dynamics of Schleswig-Holstein's cliff-coasts with special regard to submarine abrasion and residual sediment mobility. *Report Inst. of Geosciences*, 16, 168p.

SCHROTTKE, K. and SCHWARZER, K., 2006. Mobility and transport of residual sediments on abrasion platforms in front of active cliffs (Southern Baltic Sea). *Journal of Coastal Research,* Special Issue, 39, 459–464.

SCHWARZER, K.; DIESING, M., and TRISCHMANN, B., 2000. Nearshore facies of the southern shore of the Baltic Ice Lake – example from Tromper Wiek (Rügen Island). Baltica, 13, 69-76.

SCHWARZER, K.; DIESING, M.; LARSON, M.; NIEDERMEYER, R.-O.; SCHUMACHER, W., and FURMANCZYK, K., 2003. Coastline evolution at different time scales. Examples from the southern Baltic Sea (Pomeranian Bight). *Marine Geology*, 194, 79-101.

SEIBOLD, E.; EXON, N.; HARTMANN, M.; KÖGLER, F.C.; KRUMM, H.; LUTZE, G.F.; NEWTON, R.S., and WERNER, F., 1971. Marine Geology of Kiel Bay. *In*: MÜLLER, G. (ed.), *Sedimentology of parts of Central Europe*. Guidebook. *VIII. Int. Sediment. Congress* 1971, pp. 209-235.

SEIFERT, T.; TAUBER, F., and KAYSER, B., 2001. *A high resolution spherical grid topography of the Baltic Sea*. Baltic Sea Science Congress (2nd ed.), Stockholm, Poster #147, www.io-warnemuende.de/iowtopo.

SWIFT, D.J.P.; STANFORD, R.B.; DILL, C.E. JR. and AVIGNONE, N.F., 1971. Textural differentiation during erosional retreat of an unconsolidated coast, Cape Henry to Cape Hatteras, Western North Atlantic shelf. *Sedimentology*, 16. 221 – 250.

TAUBER, F. and LEMKE, W., 1995. Map of sediment distribution in the Western Baltic Sea (1 : 100.000), sheet: Darss. Deutsche Hydrographische Zeitschrift, 47, 3, 171-178.

TAUBER, F.; LEMKE, W., and ENDLER, R. 1999. Map of sediment distribution in the Western Baltic Sea (1:100,000), Sheet Falster - Møn. - *Deutsche Hydrographische Zeitschrift*, 51 (1): 5-32; Hamburg.

TINZ, B., 1995. Untersuchungen der Eisverhältnisse der Ostsee und deren Zusammenhang mit Klimaschwankungen. Spezialarb. Gr. Klimaforsch. Humboldt-Universität zu Berlin 10, 1–65.

USCINOWICZ, S. and ZACHOWICZ, J., 1994. Geological map of the Baltic Sea bottom. Polish Geological Institute, Branch of Marine Geology (1991–1992) Wydawnictwa Geologiczne. (1992–1994) Wydawnictwo Kartograficzne Polskiej Agencji Ekologicznej S.A.

WERNER, F.; ERLENKEUSER, H.; GRAFENSTEIN, U.v.; MCLEAN, S.; SARNTHEIN, M.; SCHAUER, U.; UNSÖLD, G.; WALGER, E. and WITTSTOCK, R., 1987. Sedimentary records of benthic Processes. *In*: RUMOHR, J.; WALGER, E. and ZEITSCHEL, B. (eds.). *Seawater-Sediment Interactions in Coastal Waters*. Lecture Notes on Coastal and Estuarine Studies, 13, 162–262.

WINTERHALTER, B.; IGNATIUS, H.; AXBERG, S., and NIEMISTÖ, L., 1981. Geology of the Baltic Sea. *In:* VOIPIO, A (ed.), *The Baltic Sea*, 1–121.

WRIGHT, L.D., 1995. Morphodynamics of inner continental shelves. Boca Raton: CRC Press, 241 p.

ZEILER, M.; FIGGE, K., and SCHULZ-OHLBERG, J., 2000. Mobile Sand Deposits and Shoreface Dynamics in the Inner German Bight (North Sea). *Marine Geology*, 170, 363-380.

Journal of Coastal Research	SI	51	173-186	West Palm Beach, Florida	Summer 2010

Late Quaternary Evolution of Gravel Deposits in Tromper Wiek, South-western Baltic Sea

Valérie Bellec[1*], Markus Diesing[2], and Klaus Schwarzer[2]**

[1] Ghent University
Renard Centre of Marine Geology
Krijgslaan 281, s. 8
B-9000 Gent, Belgium

[2] Christian-Albrechts Universität Kiel,
Institute of Geosciences, Coastal and
Continental Shelf Research
Olshausenstrasse 40, 24118 Kiel. Germany

[*] Present address:
Geological Survey of Norway
Leiv Eirikssons vei 39
7040 Trondheim, Norway
valerie.bellec@ngu.no

[**] Present address:
Centre for Environment, Fisheries and
Aquaculture Science
Remembrance Avenue
Burnham-on-Crouch, Essex
CM0 8BQ, United Kingdom

ABSTRACT

The Late Quaternary history of the Baltic Sea is marked by a complex sequence of glacial, lacustrine and marine phases (late Pleistocene, Baltic Ice Lake, Yoldia Lake, Ancylus Lake, Littorina Sea). Boomer data, acquired in October 2004, permitted to improve the knowledge of the late Quaternary geological evolution of Tromper Wiek, a semi-enclosed bay, located in the north-eastern part of Rügen Island. The sedimentary deposits can be subdivided in 6 seismic units (U1 to U6). The upper part of the lowest unit (U1) corresponds to Pleistocene till. Channels incise the top of this till (surface S2), probably created during the first drainage of the Baltic Sea during the Late Glacial. Subsequent channel filling (U2) occurred in two phases beginning with chaotic deposits, probably fluviatile of origin, followed by graded deposits. This filling was stopped by an erosive period with the formation of surface S3, showing channels at the same location as S2. The facies of the channel filling (U3 and U4), during a second phase, is similar to the first one, but resembles a prograding sediment body, intercalated between the two units in the shallower part. U3 shows a bar-shaped deposit at its top. The facies of U4 is very similar to a barrier/back-barrier facies similar to the facies of unit U5, partly composed of gravel. The deposits of U6 correspond to the post-Littorina Sea deposits.
The presence of gravel is linked to coastal cliffs, in which chalk layers, pushed up by glaciers, alternate with sections of till and meltwater deposits and with submarine outcrops of till. Gravel deposits are present in unit U5. They are strongly linked to the presence of a barrier. Four of the six units show a barrier facies (U2, U3, U4 and U5); gravel deposits could be present inside all of these units and would represent a larger deposit than estimated previously.

ADDITIONAL INDEX WORDS: *Baltic Sea, coastal evolution, barrier development, marine resources.*

INTRODUCTION AND AIM OF THE STUDY

Gravel-dominated coastal deposits occur in several places where sediment supply and wave energy favour the accumulation of coarse debris in the littoral zone. The presence of rocky cliffs, submarine outcrops and tectonic setting (e.g. raised gravel beaches, associated with co-seismic uplift, such as in New Zealand (Berryman *et al.*, 1992; Wellman, 1967), favour these deposits (Davies, 1972; Orford, Forbes, and Jennings, 2002). Moreover, there is a latitudinal control (>40° N and S) on the common occurrence of gravel deposits in continental shelves and shore zones (Davies, 1972; Hayes, 1967), which correspond to periglacial deposits (Church and Ryder, 1972). On storm wave-dominated coasts gravel originates mainly from glacigenic deposits (Carter *et al.*, 1987; Forbes and Taylor, 1987; Forbes and Syvitski, 1994).

The coastline of the Southwestern Baltic Sea (from Denmark via Germany to Poland) consists of an alternation of Pleistocene cliffs and lowlands, where the cliffs are composed mainly of till, partly of meltwater deposits or older material, pushed-up by advancing ice during the last glaciations. Most of these cliffs are under erosion with an average retreat of approximately 30 cm/year (Schwarzer, 2003).

Exploration and exploitation of offshore mineral resources have been carried out in the former German Democratic Republic since the seventies (Harff *et al.*, 2004; Jürgens, 1999; Lemke *et al.*, 1998; Lemke, Schwarzer, and Diesing, 2002). Extraction has been carried out by means of anchor hopper dredging in depths of up to -9 m mean sea level (msl). As a result, the sea bottom is covered with furrows and pits with diameters between 20 to 50 m and depths of up to 6 m below the sea bed (Diesing, 2003; Diesing *et al.*, 2004; Klein, 2003; Kubicki, Manso, and Diesing, 2007; Manso *et al*, this volume). Our study area is situated in the northwestern part of Tromper Wiek (Figure 1) where the seafloor is dominated by gravel. The aim of this paper is to improve the knowledge of the geological setting of the study area and especially to understand the geological development of gravel resources.

DOI: 10.2112 / SI51-016.1 received 14 January 2007; accepted in revision 15 January 2008.

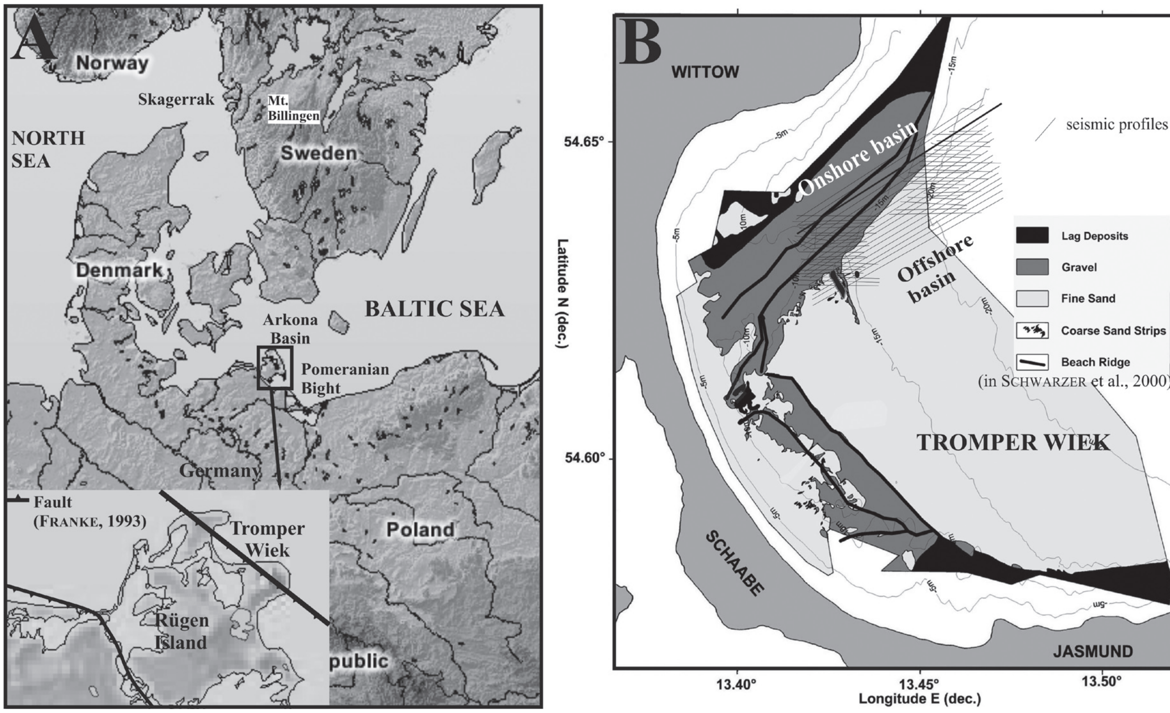


Figure 1. Localisation of Tromper Wiek. A- General map; B- Localisation of the seismic profiles and geological interpretation of the sea bottom (modified from Schwarzer et al., 2000).

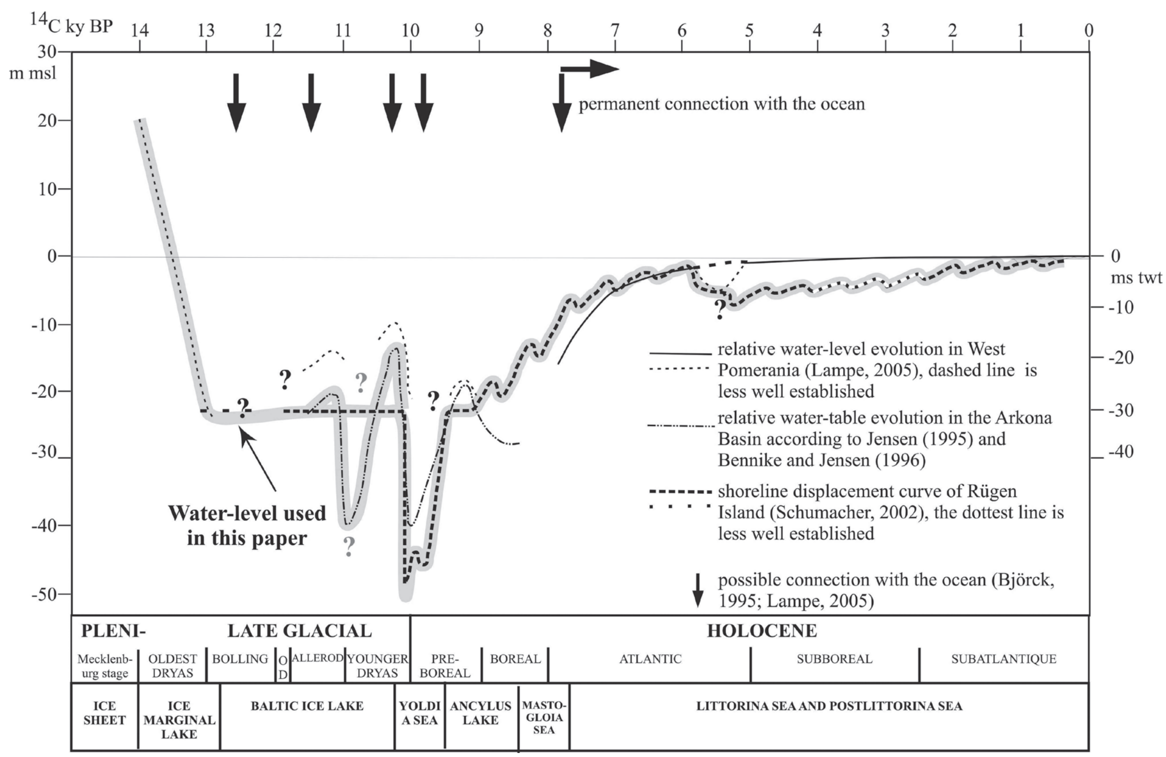


Figure 2. Water-level changes close to the study area (modified from Lampe, 2005). In grey: water-level, as used in this paper.

Table 1. *Baltic Sea stages (adapted from Lampe, 2005). The transgressive stages noted Rügen 1 to Rügen 7 are derived from Schumacher and Bayerl (1999). WL: water-level.*

Baltic Sea stages	Date 14C (ky BP)	Possible evolution of the water-level	Events
Post-Littorina	0		
	1.5	Rügen 7	
	3-2	Rügen 6	4-0 ky: only tectonic movements of minor importance
		Rügen 5	(Uscinowicz, 2002)
	5.8	Abrupt regression	6-5 ky: regression phase? Neotectonic movements?
	6	Much slower rise	
Littorina Sea		Rügen 3	7-6 ky: temporary increase of the uplift
	7.3-7.2	Rügen 4 then WL fall of ~1m	Depth: -2 m (Janke and Lampe, 2000)
		WL fall (from –6 to –7.5 m)	Flooding of the Danish Strait – Depth: -15 m
	7.8	Rapid rise (Lemke, 1998)	
Ancylus Lake	7.8		Connection with the ocean
	8-7.3	WL rise (Rügen 2)	8-7 ky: decrease of the rate of uplift
	9.2-8.8	Sudden WL fall after 8.8 ky	Regression (32 m below wl, Lemke et al., 1998)
	9.5	Rapid rise (Rügen 1)	
Yoldia Lake	9.5		
	9.9		Temporary link to the ocean
	10.3		
Baltic Ice Lake	10.3	WL drop of 25 m	Connection with open ocean-drainage. Start of the early
		WL rise	Holocene incision phase on the mainland (Janke, 1978).
			Late-glacial Lake transformed into a delta or river plain.
			Melt-water pulse (Fairbanks, 1989) - Subglacial drainage,
	11.5	WL drop of 5-10 m	channel incisions.
	12.5		14-11 ky: main uplift (Uscinowicz, 2002)
	13.5-13	WL rise	Connection with the ocean

GEOLOGICAL HISTORY OF THE BALTIC SEA AND STUDY AREA

The Baltic Sea is an almost non-tidal water body with only one narrow connection (Skagerrak) to the North Atlantic via the North Sea. Its history is controlled by isostacy, eustasy and resulting connections to the North Sea, for distinct periods during the Late Pleistocene and early Holocene (Björk, 1995). Therefore its evolution is marked by lacustrine and marine phases, resulting in four stages: Baltic Ice Lake, Yoldia Sea, Ancylus Lake and the Littorina Sea (Figure 2, Table 1) (Björck, 1995; Duphorn *et al.*, 1995; Lampe, 2005). Below, a description of the evolution of the Baltic Sea is given, with an indication of conventional radiocarbon years.

During the pleniglacial (Figure 2), the water-level was high in Pomerania, between 3 and 25 m above the mean sea level (Janke, 2002b). Here, the late Pleistocene history of the Baltic Sea started with the retreat of the active ice from Rügen Island and the Pomeranian Bight around 14 ky BP (Görsdorf and Kaiser, 2001; Kramarska, 1998; Lagerlund *et al.*, 1995; Uscinowicz, 1999). With the opening of several, probably subglacial drainage channels at Mt. Billingen app. 11.2 ky BP, the water-level dropped to at least –25 m msl and extensive river erosion occurred. During the Younger Dryas, the water level rose again from -40 to -20 m msl (Lampe, 2005) leading to the full development of the Baltic Ice Lake (Table 1). The reopening of a drainage pathway at Mt. Billingen, due to the retreat of the Scandinavian ice sheet around 10.3 ky BP, caused a drop of the water table to about -40 m (Björck, 1995). The early Holocene marine incision phase Yoldia Sea started (Janke, 1978), but due to rapid uplift of Scandinavia the closure of the connection to the open ocean followed 9.5 ky BP (Table 1). The Ancylus Lake period began with a water level rise reaching a maximum highstand of –18 m msl (Lampe, 2005; Lemke, 1998; Lemke *et al.*, 1999), similar to the level of the Baltic Ice Lake. This highstand was followed by a water level fall during the second half of the Ancylus Lake period. The first phase of the following Littorina Sea is marked by a rapid water level rise between 7.8-6 ky BP. Since then, the water level had fluctuated within a range of a few meters between –5 m msl and the present water level (Schumacher and Bayerl, 1999). After 5 ky BP, the water level almost reached its modern position (Figure 2). Water level lowstands occurred at the end of Dryas 1, at the Yoldia Sea stage and the regression of the Ancylus Lake (Table 1).

Rügen Island was reached by the Littorina transgression about 7.2 ky BP (Janke, 2002; Lampe *et al.*, 2002) and shows a strongly undulating shoreline displacement curve with up to 17 regression and transgression phases (Schumacher, 2002). This island, a former archipelago comprising more than a dozen larger and smaller Pleistocene islands, connected by barrier and spit development during the younger Holocene (Duphorn *et al.*, 1995, Janke, 2002), is an uplifted area with rates of 0.24 mm/yr for the north-eastern part (Schumacher, 2002). Kolp (1979) and Dietrich and Liebsch (2000) have shown the presence of a hinge line of zero isostatic uplift, which stretches from the southern Zingst peninsula to Usedom Island, separating an uplifted (Rügen Island) from a subsiding area (southwestern Baltic Sea, e.g. bays of Wismar, Lübeck and Kiel). The strong regression between 6-5 ky BP has been related to an uplift of 6 m between 7-5 ky BP (Schumacher and Bayerl, 1999; Schwarzer, Diesing, and Trieschmann, 2000) and as a land upheaval on Rügen Island of 8 m (Schumacher, 2002). The age of this uplift fits to the age of the uplift of the Pomeranian Bight shoreline around 5.8-5 ky BP (Janke and Lampe, 2000).

Tromper Wiek is a semi-enclosed bay located in the north-eastern part of Rügen Island between the cliffs of Wittow and

Jasmund (Figure 1). The cliffs are connected by a 12 km long Holocene barrier named Schaabe, which developed after the Littorina Transgression (Duphorn *et al.*, 1995; Schumacher and Bayerl, 1999). The cliffs, with a maximum height of 118 m at Jasmund, are characterized by a complicated pattern of glacio-tectonically uplifted Late Cretaceous chalk and Pleistocene deposits subdividing the chalk units (Herrig and Schnick, 1994). The chalk is soft and weakly cemented, inheriting black flint concretions (Janke, 2002; Schnick, 2002). The waters off Jasmund and Wittow are characterized by a steep bathymetric gradient which continues in the north-western part of Tromper Wiek where the water depth increases rapidly from -12 to -18 m msl (Stephan *et al.*, 1989).

The latest result of sediment distribution patterns in this bay (Figure 1B) can be found in Schwarzer, Diesing, and Trieschmann (2000). Lag deposits occur in front of Wittow and Jasmund cliffs. They situate the gravel deposit, which is located in front of Wittow cliff and Schaabe barrier between –8 and –14 m msl. This deposit shows prominent morphological ridges composed of well-rounded pebbles and cobbles up to 25 cm in diameter. Shallower than -10 m some till crops out. Fine sand is located in front of Schaabe spit between –10 and –14 m msl. Muddy fine sand and sandy mud occurs in deeper parts of Tromper Wiek.

Jensen (1992); Jensen *et al.* (1997); Lemke *et al.* (1998); Lemke, Schwarzer, and Diesing (2002) have identified five seismostratigraphic units (E1 to E5) in the western Baltic Sea and the area around Rügen. An uppermost till (E1) was incised by late glacial channels, probably filled with glacio-lacustrine sediments (E2) of the early Baltic Ice Lake stage. A thick sedimentary complex (E3) covered these deposits during the final phase of the Baltic Ice Lake. The boundary separating E2 and E3 corresponds to a major discontinuity. At least in Tromper Wiek E3 is subdivided into E3a and E3b. E3a corresponds to an associated beach ridge - lagoon system and E3b is interpreted to be either of fluvial or coastal origin, deposited during the lowstand of the Yoldia Sea. E4 was deposited in the deeper central part of the bay during the final phase of the Yoldia stage and in the beginning phase of the Ancylus Lake. The maximum highstand of the Ancylus Lake was around -18 m msl. It was followed by a regression to about 30 m msl. Unit E5 is a brackish marine mud, which reflects recent sedimentation.

In the shallower part of Tromper Wiek, an inner basin is characterised by lagoonal deposits of E3a which are covered by gravelly beach ridges. Further offshore, towards the central part of Tromper Wiek, the till surface dips steeply, reaching a level of more than –40 m msl and delimiting an outer basin created by former ice (Lemke, Schwarzer, and Diesing, 2002).

METHODS

The Uniboom is an electro-acoustic sound converter producing a broad frequency band of acoustic pulses (0.5 to 15 kHz) emitted vertically into the water column (Atzler, 1995). The boomer acoustic source is mounted on a catamaran and towed behind the ship. The sound signal is reflected from boundaries between different layers/structures within the sedimentary sequence, consisting of different impedances. Reflected signals are received by a streamer, additionally towed behind the ship, close beneath the sea surface. This signal is tuned in a receiver and transferred to analogue and digital acquisition units. Processing of the digital data consists of bandpass filtering, stacking and the adjustment of a time varied gain (TVG). Very-high resolution seismic profiles are interpreted according to seismo-stratigraphy principles (Posamentier *et al.*, 1992; Posamentier, Jervey, and Vail, 1988; Vail *et al.*, 1977; Van Wagoner *et al.*, 1988). Originally developed for low resolution seismics, it can also be applied for high to very-high resolution seismic (e. g. Browne, 1994; Chiocci, Orlando, and Tortora, 1991; Cirac *et al.*, 1997; Lericolais, Berné, and Fenies, 2001).

Limitations in the quality of the seismic profiles, due to bad weather conditions during the surveys, complicate partly the interpretation of the data into different seismostratigraphic units.

RESULTS

Several seismic units (U1 to U6) are present on the seismic profiles (Figures 3 to 7). They are bounded by high amplitude and often strongly erosive surfaces S2-S6. These units essentially correspond to the filling of two basins. The first one, in the shallower part of the bay, would correspond to a lagoonal facies (Lemke, Schwarzer, and Diesing, 2002) and is located between –13 to –20 ms twt (app. –10 to –15 m msl) behind the gravel barrier (Schwarzer, Diesing, and Trieschmann, 2000) on our seismic profiles. Its maximum depth is about 20 ms (app. -15 m) twt (two-way travel time) in our study area. The second basin is situated offshore deeper than –24 ms twt (app. -18 m msl) (Figure 3) and is marked by a steeply dipping surface. The thickness of the sediment fill is more or less 25 ms twt (app. 20 m). Correlation between the two basins was achieved by comparing the seismic facies and the number of the seismic units above unit U1, occurring in the whole study area without interruption. The unit U1 dips steeply offshore where it delimits the offshore basin. The base of U1 is not accessible. Its upper part constitutes of indented reflections which form channels.

The base of the onshore (lagoonal) basin corresponds to an uneven high amplitude and to low to good continuity surface S2 which can be followed throughout the whole study area (Figures 3, 4 and 5). S2 shows channels right to the offshore boundary of the inner basin where it almost reaches the sea bottom. In this area, three channels show a general NW-SE strike and incise the substratum down to 36 ms twt (app. -27 m) (Figure 5). They are separated by interfluves shallower than 28 ms twt (app. 21-22 m h). The channels, which almost disappear at the boundary between the two basins, are filled by two different facies: the first one (U2a) is chaotic and evolves upwards into a second facies (U2b), which shows wavy parallel reflections (Figure 4). There is no clear reflection horizon visible between these two seismic facies.

Surface S3 shows similar characteristics as S2. It is an uneven high amplitude and good continuity surface showing channels. Nevertheless, the channels are generally smaller than the previous ones. The first deposits filling the channels (U3a) are composed of a chaotic facies with few parallel reflections on the interfluves. Another type of deposits (U3b) is only located in the westernmost area. Its base is quite tabular. The seismic facies corresponds to prograding reflections. U3b rapidly pinches out offshore. U3 shows a bar-shaped body in this upper part (Figure 6).

The amplitude of the surface S4 is variable, but its continuity is good (Figure 4). It erodes the top of unit U3. Unit U4 corresponds to the last filling of the channels formed by S2 and

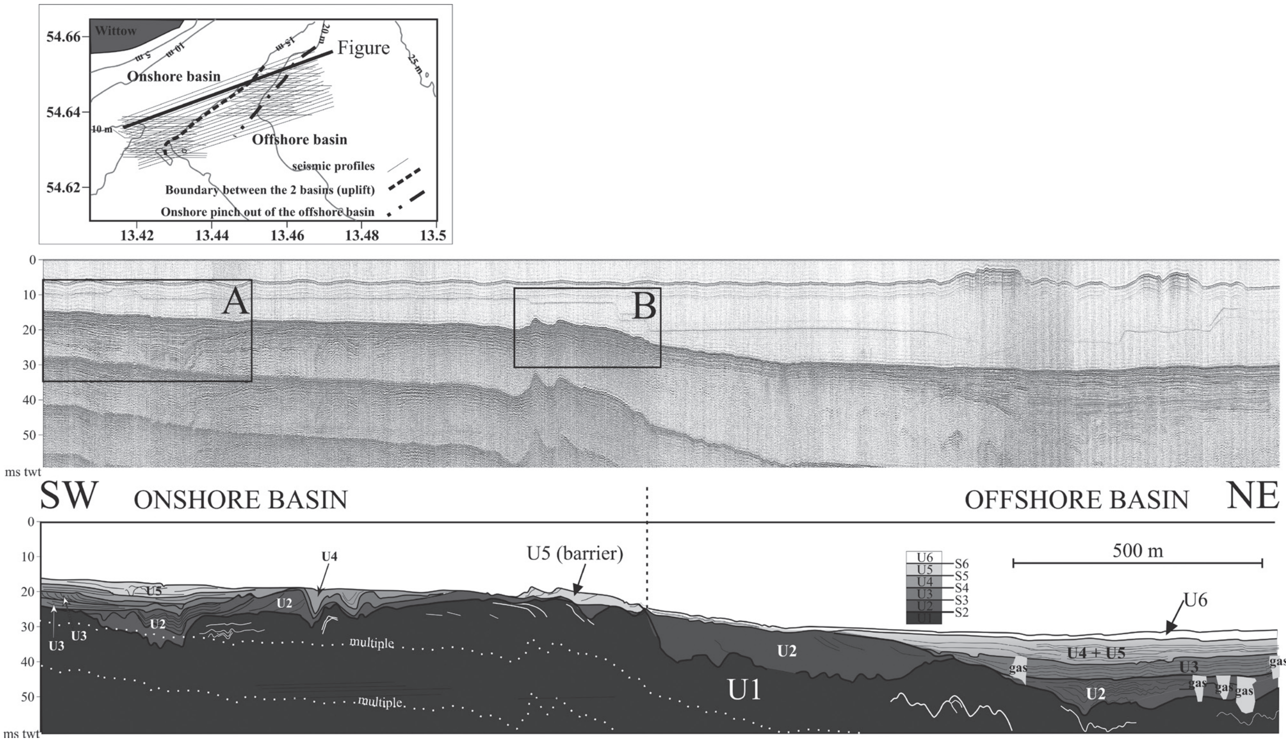


Figure 3. Boomer profile showing the different seismic units. See details A and B on Figure 4.

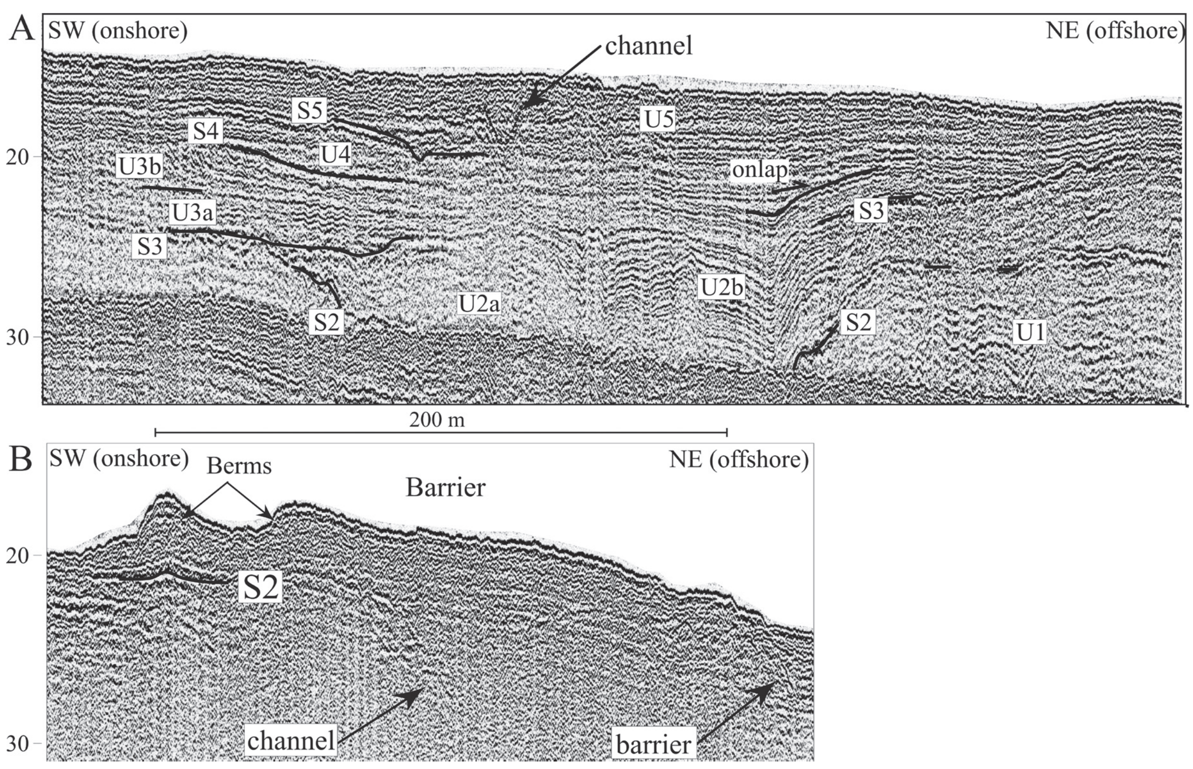


Figure 4. Details of the seismic profile displayed in Figure 3.

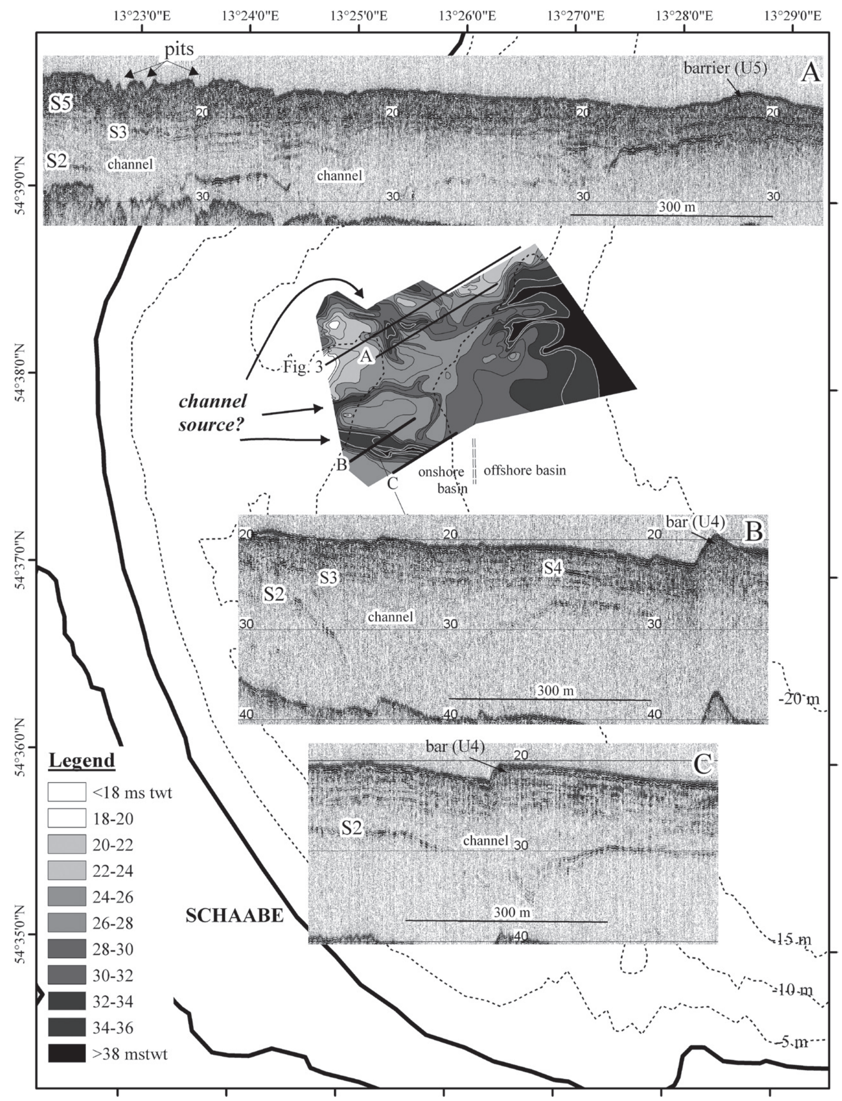


Figure 5. Isochrons of surface S2 and details of the seismic profiles.

onlaps on S4. Further south this unit shows a complex pattern of retrograding, prograding reflections and small channels with only a few milliseconds (twt) deep. An offshore bar-shaped body is present between the two basins, at the same place than the U3 bar-shaped body. Its facies is chaotic (Figure 6).

The upper surface S5 exhibits high amplitude and good continuity and can be followed almost throughout the inner basin (Figures 3, 4 and 7). It shows NW-SE oriented isochrons between 16 and 24 ms twt (app. -12 and -18 m) and a small E-W oriented channel of only a few milliseconds deep. It is covered by the high amplitude facies U5 which is composed of two units: a basin filling showing chaotic facies (U5a), prograding and retrograding reflections as well as channels of 3-4 ms twt which are very similar to the facies of U4, and a barrier-shaped body (U5b) which ends up the facies offshore. The steep slope of the ridges on the barrier (Figure 4) is directed towards the coast and the gentle slope towards the sea. This barrier facies is located exclusively in the shallow part of the bay where it shows a thickness of up to 6 ms twt (app. 4,5 m). The thicker parts are located on the barrier and in the shallowest area. The unit U6 is a thin layer (less than 1 m) of deposits, which is difficult to follow because it is mixed with the seafloor signal.

The seismic units U2, U3 and U4 reach the position of the outer ridges and U3 and U4 pinch out at the end of the ridge deposit. The thickness of each unit does not exceed 8 ms twt (app. 6 m), with a mean around 3-4_ms twt (app. 2-3 m).

Between the two basins, the till deposit U1 is bounded by the surface S2, covered by U2 in the northwest (Figures 3, 4 and 6). The facies of this unit shows channel filling in the north (U2a, Figure 4). Towards the southeast, prograding and retrograding reflections form a dome-shaped deposit (U2c) on S2 and sometimes cover the channels formed by this surface. Small channels are also present in the dome-shaped deposit. U2c was gently eroded by the formation of S3, except on its top

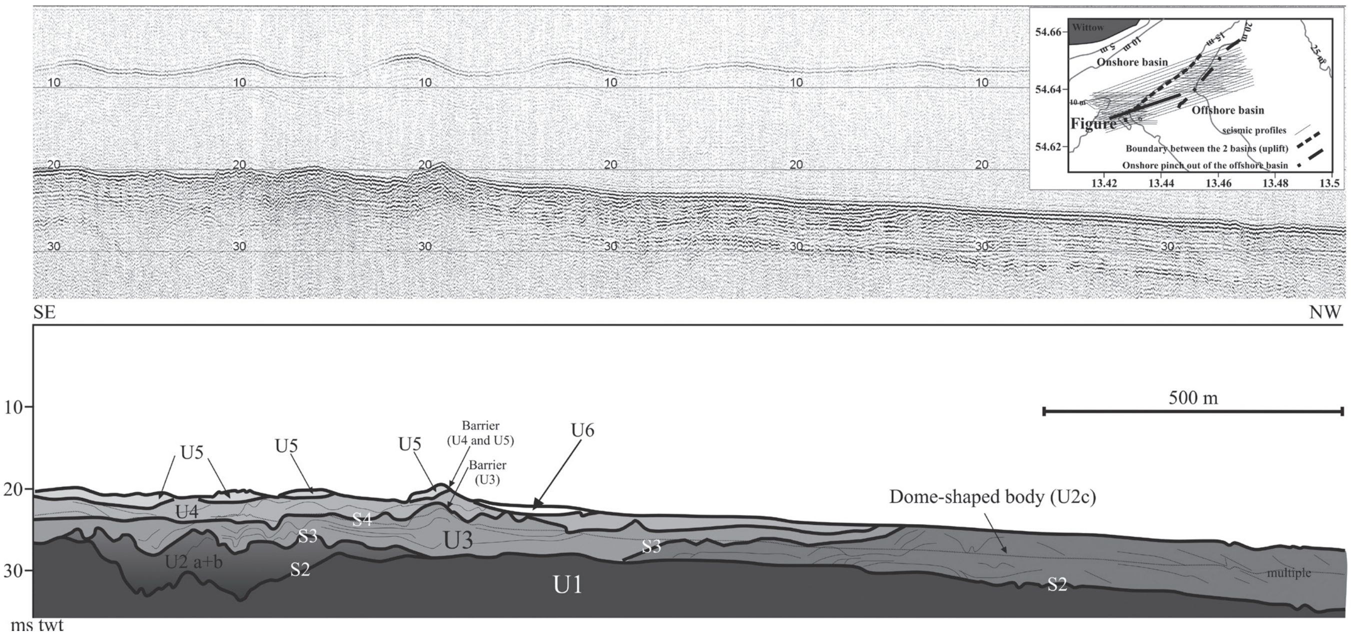


Figure 6. Boomer profile showing the interfluve between the two basins.

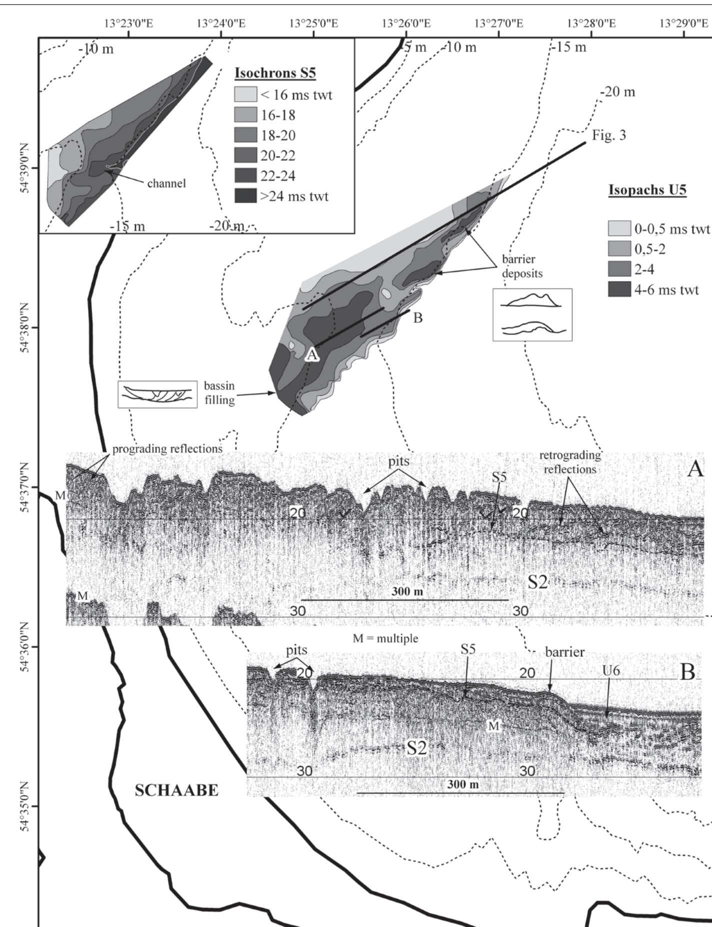


Figure 7. Isochrons and isopachs of S5 and U5 and seismic profiles details.

where the erosion was stronger and probably younger than the formation of S3, as U3 deposits are only present on each side of the dome-shaped deposit (Figure 6). U2 and U3 are covered by a thin layer composed of the younger unit U6, which thickens just at the foot of the barrier (app. 2-3 m thick), showing parallel reflections at this location.

Into the offshore basin (Figure 3), the uneven surface S2 also corresponds to the base of the basin, which dips offshore around 30 ms twt (app. 22 m). S2 shows channels of less than 5 ms twt (app. 3,5 m). S2 is covered by U2, which present similar seismic facies than in the onshore basin: the bottom deposit is chaotic and evolves upwards from wavy to more or less parallel reflections. S3 does not correspond to an uneven surface in the offshore basin. It corresponds to a planar surface with a medium amplitude and continuity, locally disturbed by gas presence. U3 presents high frequency parallel reflections. The upper surface S4 is quite horizontal with a high amplitude and continuity. It shows small channels of 2-3 ms twt deep (app. 1.5-2 m). The seismic facies of unit U4 also corresponds to high frequency parallel reflections. It is partly difficult to differentiate U5 from U4 in the offshore basin, as U5 could correspond to a part of facies U4. U6 is composed of parallel reflections and becomes thicker offshore, increasingly.

The thickness of the units is regular and corresponds to 8 ms twt (app. 6,5 m) for U2, about 5-7 ms twt (app. 4-5,5 m) for U3, 6-8 ms twt (app. 5-6,5 m) for U4 (plus U5?) and 1 to 3 ms twt (app. 1-2,5 m) for U6.

DISCUSSION AND INTERPRETATION

History of the Western Part of Tromper Wiek

Comparing the results with previous investigations on land, (Hoffmann, Lampe, and Barnasch, 2005; Schumacher and Bayerl, 1999) and inside Tromper Wiek (Lemke *et al.,* 1998; Lemke, Schwarzer, and Diesing, 2002; Schwarzer, Diesing, and Trieschmann, 2000), the upper part of the unit U1 corresponds to Pleistocene till (unit E1 in Lemke *et al.*, 1998; Lemke, Schwarzer, and Diesing, 2002; Table 2). In fact, these authors indicate that the surface of the uppermost till is characterised by a high relief and channel-like depressions with the surface dipping steeply towards the central part of Tromper Wiek, as is the case for surface S2.

After the last glacial maximum about 18.5 ky BP (Lambeck *et al.,* 2000), during the Ice Sheet and the Ice Marginal Lake periods, the melting of the ice led to an opening of the Baltic Sea towards the North Sea (Lampe, 2005). The water-level dropped more than 40 m, which probably initiated the formation of the channels bounded by S2 (Figures 8A and 8B). Channels generally form during water-level fall, but can also be formed due to melt-water pulses or subglacial draining. There were two important water-level falls due to the drainage of the Baltic Ice Lake. The first one (drainage at 13 ky BP, Figure 2) occurring in the Baltic Sea was combined with a melt-water pulse, as the ice retreat on Rügen Island is situated about 14 ky BP (Görsdorf and Kaiser, 2001; Kramarska, 1998; Lagerlund *et al.*, 1995; Uscinowicz, 1999), and so could lead to the formation of the more important channels, bounded by surface S2. Between about 13 and 10 ky BP, the water-level had been more or less stable, around -20 to -25 m msl (Schumacher, 2002) or rose up to a few meters on Rügen Island considering the water-level evolution in the Arkona basin or in west Pomerania (Bennike and Jensen, 1996; Jensen, 1995; Lampe, 2005). The three channels, present in Figure 4, incise from 26-28 ms twt (19-21 m msl) down to more than 36 ms twt (27 m msl). Therefore a water-level around 20-25 m msl probably allowed the filling of the channels (U2, Figure 8C). Unit U2 was deposited in two steps during the water-

Table 2. *Comparison between the seismic units of* Lemke *et al. (1998) and those in this paper.*

Lemke *et al.*, 1998			This paper	
Seismic units	**Sediment type**	**Age**	**Seismic units**	**Supposed Age**
E1: Till	hyp: grey, partly clayey, chalk fragments	Pleistocene	U1	Pleistocene
Channel surface		Late glacial	S2 (channel)	~13 ky (drainage)
E2: channel filling, glacio-lacustrine sequence	hyp : Silty to sandy material	Early Baltic Ice Lake stage	U2	Baltic Ice Lake
Major unconformity			S3 (channel)	~11.5 ky (drainage)
E3 : E3a: ………………. E3b (below 35 m depth): fluvial or coastal	 Thick silt then olive grey, fine laminated silt ………….. Silty fine sand	Baltic Ice Lake Upper part: ~10.1-10.5 ky …………. From ~10.3 ky	 U3? U4? U5? U5?	Baltic Ice Lake to Yoldia Sea
E4: fresh water lake deposit	Below -34 m: grey silts	Base: ~9.6 ky Ancylus Lake	U5 ? U6?	Ancylus Lake
E5	Olive grey sandy mud	Post-Littorina	U6	Post-Littorina Sea

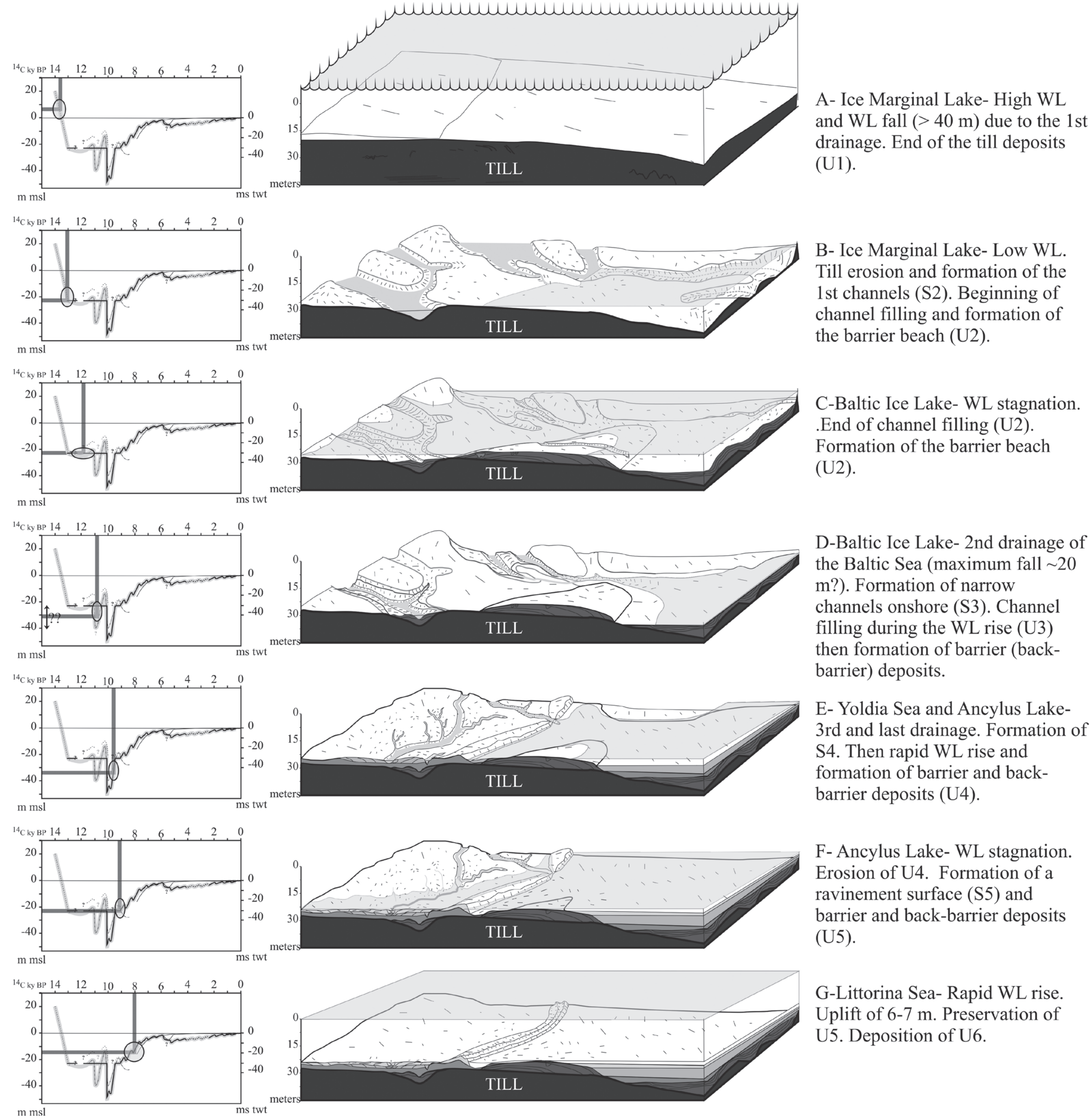


Figure 8. Deposition model of the 6 seismic units, interpreted from the boomer profiles. WL: water-level.

level stagnation after 13 ky BP (Figure 8C). The lowest unit (U2a) shows a chaotic facies, which might represent the final melt water deposits, composed of heterogeneous and/or coarse material. The unit above (U2b) shows alternating wavy bedded reflections, following the underlying relief. This generally gives evidence of more homogeneous and/or finer deposits. This wavy facies is very similar to the E2 facies mentioned in Lemke, Schwarzer, and Diesing (2002) where the authors also indicate that the seismic facies represents silty to sandy material. They interpret E2 as a glacio-lacustrine sequence formed immediately after the final deglaciation of the area. In front of the offshore basin, a dome-shaped body (U2c, Figure 6) seems to correspond to a barrier beach, formed during or after the filling of the channels since their deposition. It should indicate a stabilisation of the water-level around 20-25 m msl for a duration which is sufficient to create these deposits. This

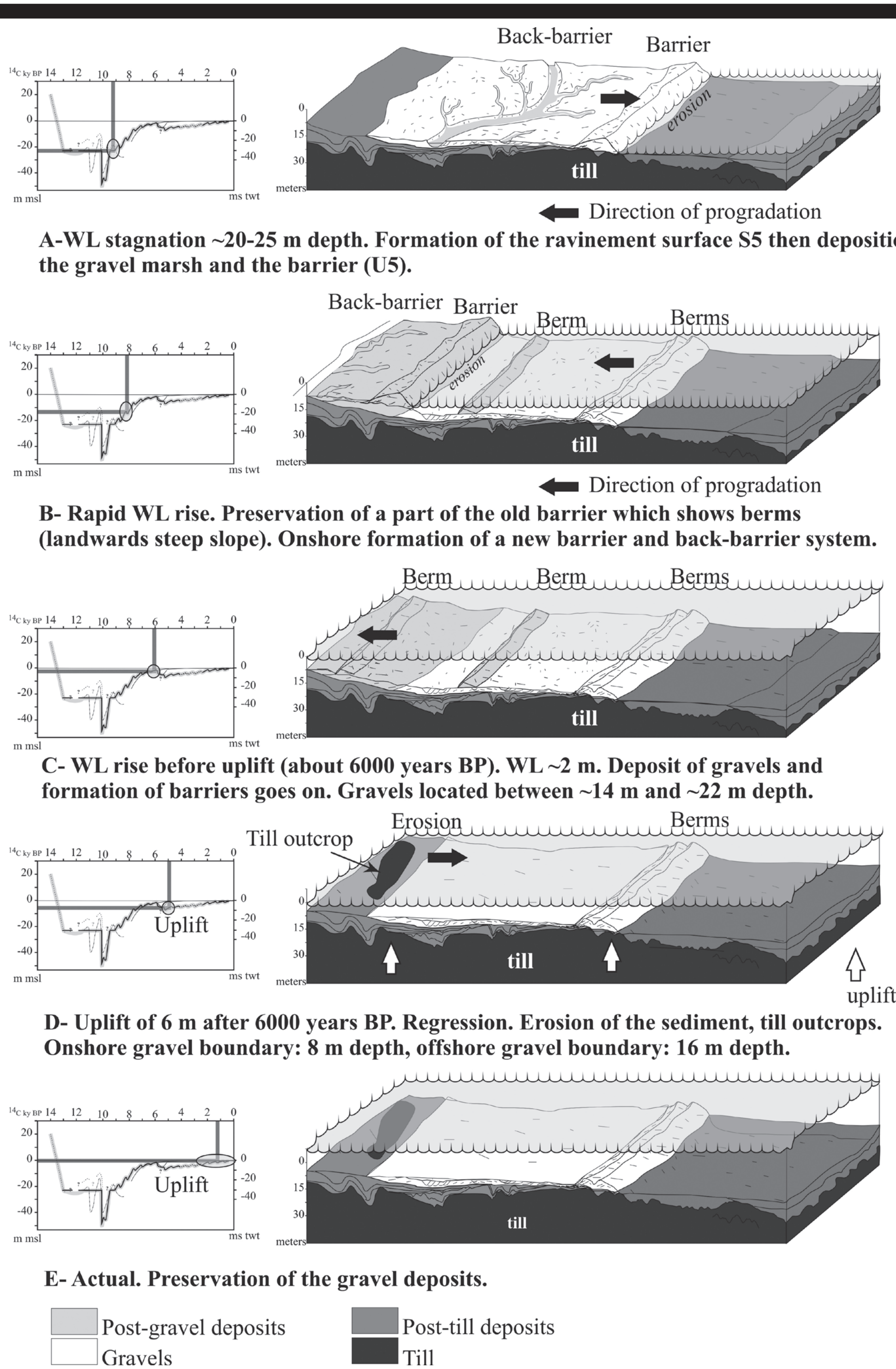


Figure 9. Model of gravel barrier deposits in Tromper Wiek. WL: water-level.

meets the water level curves for Rügen Island, presented by Schumacher (2002) and the position around 20-25 m depth of the channels (S2). In the offshore basin, the initial filling of the channels consists of similar facies.

The formation of the second set of channels, located in the onshore basin (surface S3, Figure 8D), should be due to the second important drainage of the Baltic Ice Lake around 11 ky BP present on the water-level curves of the Arkona basin or the west Pomerania (Bennike and Jensen, 1996; Jensen, 1995; Lampe, 2005) (Figure 2). When forming this surface S3, a part of the beach barrier, located offshore, was eroded. S3 seems to correspond to the boundary between the units E2 and E3 which is mentioned in Lemke, Schwarzer, and Diesing (2002); Schwarzer, Diesing, and Trieschmann (2000). Moreover, these authors indicate that E3, corresponding to the seismic unit of U3, was deposited prior to 10.3 ky BP.

More in detail, the lowermost deposits of U3 in the channels look similar to the facies of U2, i.e. heterogeneous and/or coarse deposits (U3a). The facies above is different and corresponds to a small prograding deposit (U3b). Normally, this indicates sediment input during a constant water-level. As it is only located in the west part of the profile (Figures 3 and 4), it could be formed due to local conditions, e.g. progradation of the channel wall. U3 deposits do not show a large beach barrier facies as U2c. Nevertheless, a deposit similar to a barrier is present downstream of U2c (Figure 6). Lemke, Schwarzer, and Diesing (2002); Schwarzer, Diesing, and Trieschmann (2000) also indicate that this unit is correlated with a barrier-lagoon system in the central part of Tromper Wiek, where the barriers are composed of gravel. A barrier is also present in our study area. So the barrier-lagoon system probably extended towards the north. Nevertheless, in our study area the gravel deposits do not correspond to U3, but to the younger unit (U5). Therefore there should have been several periods of gravel deposition with a shift of the centre of deposition towards the north.

A third erosive surface is indicated by S4. This surface could have been formed during the last drainage after 10.3 ky BP. Onlaps, which are characteristic for a transgressive facies, are present on S4 (Figures 4 and 8E). As such, U4 is a transgressive facies which should have been formed during the first part of the water-level rise about 10-9.5 ky BP. The channel-filling continued as well, as also the construction of the barrier which is already present in U3. A back-barrier/lagoon facies is present also (Figure 6).

About 9.5 ky BP, the speed of the water-level rise slowed down and remained stable at a level of 23-25 m msl, which is about 10 m below the back-barrier system. Nevertheless, if we consider an uplift of 6 m after 7 ky BP, then the gravel deposits would have been located around 16-20 m msl, which was the depth of the shoreface 9.5 ky BP ago (Figure 9A). The shape of the gravel confirms this fact, as observations by scuba divers revealed that these ridges are composed of well-rounded pebbles and cobbles of up to 25 cm in diameter (Schwarzer, Diesing, and Trieschmann, 2000).

The water-level stagnation may have favoured the formation of a wave erosion surface (S5) at the top of U4 (Figures 8F and 9A). Due to stable water-level conditions during several centuries, a barrier, larger than the former ones, had been developed. Behind this barrier, a facies similar to the U4 facies has been deposited. The U5 deposit is oriented parallel to the barrier (Figure 7). U5 would correspond to a barrier and a back-barrier facies with channels alternating interfluves showed by retrograding or prograding reflections.

The next water-level rise, after 9 ky BP, was likely relatively fast. Due to the very coarse material, the gravel deposits were preserved partly. Nevertheless, the barrier was probably in part eroded due to its shallow water location, and its morphology evolved in a berm system (steep slope shifted landwards; Figure 9B). The deposition of gravel probably decreased quickly with increasing water depth. No gravel is present on the actual coast, below -15 m msl. New systems of barriers and berms might have formed on the gravel deposits (Figure 9C). Prior to the uplift approximately 5-7 ky BP, the gravel deposits were probably located in 22 m water-depth. The onshore boundary is more difficult to establish, but, by comparison with the actual depth, it was likely in approximately 15 m water-depth. Uplift raised Rügen Island with about 6 m (Schumacher and Bayerl, 1999; Schwarzer, Diesing, and Trieschmann, 2000). Then the gravel deposits were located between 8 and 16 m msl, which is the actual depth (Figure 9D and E). Due to the very coarse granulometry of the barrier sediments, it was mostly preserved.

The last unit, U6, is a thin cover of fine sand, which represents the actual sedimentation onshore. Offshore, it can be subdivided in several sub-units, which have probably recorded the oscillations of the water-level since 9000 years BP (Figure 8G). This unit probably corresponds to the unit E5 of Schwarzer, Diesing, and Trieschmann (2000), which shows typical deposits of the post-Littorina brackish marine Baltic Sea.

Gravel deposits: Barrier and back-barrier facies

We found a barrier facies in four of the six units (U2, U3, U4 and U5), generally in their upper part/top. In our study area, a back-barrier/lagoon facies is present in two units (U4 and U5) and other investigations (Lemke, Schwarzer, and Diesing, 2002; Schwarzer, Diesing, and Trieschmann, 2000) showed the presence of a lagoon in E3/U3 in the central part of Tromper Wiek. Two of these units crop out on the sea floor (U3 in the central part of Tromper Wiek and U5 in our study area) showing barriers composed of gravely sediments with a northwest-southeast orientation for U3 and a northeast-southwest orientation for U5.

The with gravel built-up unit U5 is intensively dredged, showing pits of up to a few m deep (Diesing, 2003) (Figure 7). The thickness of the gravel unit (U5) reaches 6 ms twt on our seismic profiles (about 5 m thick) (Figure 7). U5 spreads over more than 3500 m in a NE-SW direction and from about 300 m (in the north) to more than 1000 m (in the south) in a NW-SE direction.

It is possible that each of these units (U2, U3, U4 and U5) shows gravel deposits on their upper part, especially in the barrier facies. That means that the total gravel deposit is probably much more spread than the gravel deposits on the sea bottom shows.

Generally, there are two sources of gravel: the seafloor itself and the erosion of the cliffs (Anthony, 2002; Caviola, 1997; Johnson, 1919; Orford, Forbes, and Jennings, 2002; Regnauld, Mauz, and Morzadec-Kerfourn, 2003; Schrottke, 2001). The gravel deposits formed when the water-level was about 15-20 m msl, considering the uplift of about 15-10 m modern msl. Moreover, the barrier deposit built during quite high and stable water-levels. If the seafloor was the only source of the gravel, we should find gravel deposits in the outer basin; this is not the case. So, the most probable source of the gravel deposits is the erosion of Wittow cliff, composed of chalk, meltwater sediments, boulder and clay, present close to our study area. This erosion is only possible when the water-level was about 15-20 m msl. Following, the cliff was eroded by wave and current action and supplied the gravel needed for the formation of the gravel deposits.

CONCLUSIONS

Six units (U1 to U6) have been identified in the western part of Tromper Wiek and are bounded by 5 surfaces (S2 to S6). U1 is attributed to the presence of Pleistocene till; its upper part was eroded by the formation of channels (S2), probably related to the water-level drop during the Late Glacial. The filling of these channels (U2) began by fluviatile sediments, which were later replaced with finer and homogeneous sediments. U2 shows a beach barrier facies deposited during or after the filling of the channel. The location of this barrier is slightly offshore of the modern barrier. The first reactivation of the channels (S3) occurred probably during the Baltic Ice Lake about 11 ky BP. Their filling (U3) is very similar to U2. At the top of U3, a barrier is found at more or less the same position as the actual barrier. Outside of the study area, investigations have shown that U3 is partly composed of gravel barriers. S4 corresponds to the last reactivation of the channels formed by S2 and could have been formed about 10 ky BP. The filling of the channels (U4) occurred during the Yoldia Sea and the Ancylus Lake. It is slightly different as it shows transgressive deposits and a barrier and back-barrier facies. S5 would be an erosional surface caused by waves as the water-level rise speed decreased. U5 also shows a barrier and a back-barrier facies similar to the U4 facies. This unit is nowadays dredged intensively, because of its high gravel content. Due to the uplift of 6 m about 5-7 ky BP, the gravel deposited originally around 15-20 m msl depth, which are the mean depth of the high water-level between 9 and 13 ky BP, are now at about 10-15 m msl. U6 would correspond to the last Littorina deposits.

Four of the six units (U2, U3, U4 and U5) show barrier deposits. The two units (U3 and U5), outcropping on the sea bottom, and showing a barrier, are composed of gravelly sediments. It is possible that the two others units (U2 and U4), showing a barrier, are also composed, at least partly of gravel. The gravel came from the erosion of the Wittow cliff during periods of high water-level. The volume of gravel resources can be more important than estimated before.

ACKNOWLEDGEMENTS

This study frames into the research objectives of the project EUMARSAND ("European Marine Sand and Gravel Resources: Evaluation and Environmental Impact of Extraction", contract HPRN-CT-2002-00222). The captain and the crew of the R.V. *Alkor* are thanked for their flexibility and assistance during the campaigns.

LITERATURE CITED

Anthony, E. J., 2002. Long-term marine bedload segregation, and sandy versus gravelly Holocene shorelines in the eastern English Channel. *Marine Geology*, 187(3-4), 221-234.

Atzler, R., 1995. Der pleistozäne Untergrundder Kieler Bucht und angrenzender Gebiete nach reflexionsseismischen Messungen. Berichte - *Reports. Geologisch-Paläontologisches Institut und Museum, Christian-Albrechts-Universität Kiel*, 70, 116 p.

Bennike, O. and Jensen, J. B., 1996. Late- and postglacial shore-level changes in the southwestern Baltic Sea. *Bulletin of the Geological Society of Denmark* 45, 27-38.

Berryman, K.R.; Hull, A.G.; Beanland, S.; Pillans, B., and Deely, J., 1992. Excursion to Cape Turakirae. *In*: IGCP 274 Programme and Abstracts, Annual Meeting, *WellingtonGeol. Soc. N. Z. Misc. Pub.*, 65A, pp. 64-69.

Björck, S., 1995. A review of the history of the Baltic Sea, 13.0-8.0 ka BP. *Quaternary International*, 27, 19-40.

Browne, I., 1994. Seismic stratigraphy and relict coastal sediments off the east coast of Australia. *Marine Geology*, 121, 81-107.

Carter, R.W.G.; Orford, J.D.; Forbes, D.L., and Taylor, R.B., 1987. Gravel barriers, headlands and lagoons: an evolutionary model. *Proc. coastal sediments '87. Am. Soc. Civ. Eng.*, 2, pp. 1776-1792.

Caviola, P., 1997. Coastal dynamics and impact of coastal protection works on the Spurn Head spit (UK). *Catena*, 30(4), 369-389.

Chiocci, F. L.; Orlando, L., and Tortora, P., 1991. Small-scale seismic stratigraphy and palaeographical evolution of the continental shelf facing the SE Elba island (Northern Tyrrenian Sea, Italy. *Journal of Sedimentary Petrology*, 61, 506-526.

Church, M. and Ryder, J.M., 1972. Paraglacial sedimentation: a consideration of fluvial processes conditioned by glaciation. *Geological Society of America Bulletin*, 83, 3059-3072.

Cirac, P.; Berné, S.; Lericolais, G., and Weber, O., 1997. Séquences de dépôt dans le Quaternaire terminal du plateau continental nord aquitain (océan Atlantique, France). *Bulletin de la Société Géologique de France*, 168(6), 717-725.

Davies, J. L., 1972. *Geographical variation in coastal development*. Edinbourgh: (eds.) Oliver and Boyd, 204 p.

Diesing, M., 2003. Die Regeneration von Materialentnahmestellen in der südwestlichen Ostsee unter besonderer Berücksichtigung der rezenten Sedimentdynamik. Kiel, Germany: University of Kiel, Ph.D. thesis, 158 p.

Diesing, M.; Schwarzer, K.; Zeiler, M., and Klein, H., 2004. Comparison of Marine Sediment Extraction Sites by Means of Shoreface Zonation. *Journal of Coastal Research* Special Issue 39, 783-788.

Dietrich, R. and Liebsch, G., 2000. Zur Variabilität des Meeresspiegels an der Küste von Mecklenburg-Vorpommern. *Zeitschrift für Geologische Wissenschaften*, 28, 615-624.

Duphorn, K.; Kliewe, H.; Niedermeyer, R.-O.; Janke, W., and Werner, F., 1995. Die deutsche Ostseeküste. *Sammlung geologischer Führer*, 88, 281p.

Fairbanks, R. G., 1989. A 17,000-year glacio-eustatic sea level record: Influence of glacial melting rates on the Younger-Dryas event and deep ocean circulation. *Nature*, 342, 637-641.

Forbes, D.L. and Taylor, R.B., 1987. Coarse-grained beach sedimentation under paraglacial conditions, Canadian Atlantic coast. *In*: FitzGerald, D.M and Rosen, P.S. (eds.), *Glaciated Coasts*. San Diego: Academic Press, pp. 51-86.

Forbes, D.L. and Syvitski, J.P.M., 1994. Paraglacial coasts. *In*: Carter, R.W.G. and Woodroffe, C.D. (eds.), *Coastal Evolution: Late Quaternary shoreline Morphodynamics*. Cambridge: Cambridge Univ. Press, pp. 373-424.

Franke, D., 1993. The southern border of Baltica—a review of the present state of knowledge. *Precambrian Research*, 64(1-4), 419-430.

Görsdorf, J. and Kaiser, K., 2001. Radiokohlenstoffdaten aus dem Spätglazial und Frühholozän von Mecklenburg-Vorpommern. *Meyniana*, 53, 91-118.

Hayes, M.O., 1967. Relationship between coastal climate and bottom sediment type on the inner continental shelf. *Marine Geology*, 5, 111-132.

Harff, J.; Bobertz, B.; Granitzki, K.; Lemke, W., and Wehner, K., 2004. Sand and Gravel Deposits in the South-western Baltic Sea, their Utilization and sustainable Development. *Zeitschrift für* Angewandte Geologie, 2, 111 – 122.

Herrig, E. and Schnick, H., 1994. Stratigraphie und Sedimentologie der Kreide und des Pleistozäns auf Rügen. Greifswalder Geowiss. Beiträge., Reihe A, 1, pp. 6 – 55.

Hoffmann, G.; Lampe, R., and Barnasch, J., 2005. Postglacial evolution of coastal barriers along the West Pomeranian coast, NE Germany. *Quaternary International*, 133-134, 47-59.

Janke, W., 1978. Schema der spät- und postglazialen Entwicklung der Talungen der spätglazialen Haffstauseeabflüsse. *Wissenschaftliche*

Zeitschrift der Universität Greifswald, Mathematisch-naturwissenschaftliche Reihe 27, pp. 39-41

Janke, W., 2002. Glacial and coastal geomorphology of eastern Rügen Island. *In*: Lampe, R. (ed.), *Greifswalder Geographische Arbeiten 27*, Ernst-Moritz-Arndt-Universität Greifswald, pp. 21-26.

Janke, W., 2002b. The development of the river valleys from the Uecker to the Warnow. *In*: Lampe, R. (ed.), *Greifswalder Geographische Arbeiten* 27, Ernst-Moritz-Arndt-Universität Greifswald, pp. 101–106.

Janke, W. and Lampe, R., 2000. Zu Veränderungen des Meeresspiegels an der vorpommerschen Küste in den letzten 8000 Jahren. *Zeitschrift für Geologische Wissenschaften*, 28, 585- 600.

Jensen, J.B., 1992. *Late Pleistocene and Holocene depositional evolution in the shallow waters near the Island of Mön, SE Danmark*. Copenhagen, Denmark: Geol. Surv. Denm, Ph.D. thesis, 160 p.

Jensen, J.B., 1995. A Baltic Ice Lake transgression in the southwestern Baltic: evidence from Fakse Bugt, Denmark. *Quaternary International* 27, 59-68.

Jensen, J.B.; Bennike, O.; Witkowski, A.; Lemke, W., and Kuijpers, A., 1997. The Baltic Ice Lake in the southwestern Baltic: sequence-, chrono- and biostratigraphy. *Boreas*, 26, 217–236.

Johnson, D.W., 1919. *Shore Processes and Shoreline Development*. New York: Wiley, 584 p.

Jurgens, U., 1999. Buried Quaternary channels in the southern Baltic Sea north of Rugen island, Germany: distribution and genesis. *Baltica*, 12, 43-48.

Klein, H., 2003. Investigating sediment re-mobilisation due to wave action by means of ADCP echo intensity data : Field data from the Tromper Wiek, western Baltic Sea. *Estuarine, Coastal and Shelf Science*, 58(3), 467-474.

Kolp, O., 1979. Eustatische und isostatische Veränderungen des südlichen Ostseeraumes. *Petermanns Geographische Mitteilungen*, 123, 177-187.

Kramarska, R., 1998. Origin and development of the Odra Bank in the light of geologic structure and radiocarbon dating. *Geological Quarterly,* 42(3), 277-288.

Kubicki, A.; Manso, F., and Diesing, M., 2007. Morphological evolution of gravel and sand extraction pits, Tromper Wiek, Baltic Sea. *Estuarine, Coastal and Shelf Science*, 71, 647 – 656.

Lagerlund, E.; Malmberg Persson, K.; Krzyszkowski, D.; Johansson, P.; Dobracka, E.; Dobracki, R., and Panzig, W.-A., 1995. Unexpected ice flow directions during the last Weichselian deglaciation of the south Baltic area indicated by a new lithostratigraphy in NW Poland and NE Germany. *Quaternary International*, 28, 127-144.

Lambeck, K.; Yokoyama, Y.; Johnston, P., and Purcell, A., 2000. Global ice volume at the Last Glacial Maximum and early Lateglacial. *Earth and Planetary Letters*, 181, 513-527.

Lampe, R., 2005. Lateglacial and Holocene water-level variations along the NE German Baltic Sea coast: review and new results. *Quaternary International*, 133-134, 121-136.

Lampe, R.; Janke, W.; Meyer, H.; Ziekur, R., and Schuricht, R., 2002. The Late glacial/Holocene evolution of a barrier spit and related lagoonary waters - Schmale Heide, Kleiner Jasmunder Bodden and Schmachter See/Rügen. *In*: Lampe, R. (ed.), *Greifswalder Geographische Arbeiten 27*, Ernst-Moritz-Arndt-Universität Greifswald, pp. 75-88.

Lemke, W., 1998. Sedimentation und paläogeographische Entwicklung im westlichen Ostseeraum (Mecklenburger Bucht bis Arkonabecken) vom Ende der Weichselvereisung bis zur Littorina transgression. Universität Greifswald, Habilitation thesis, 186 p.

Lemke, W.; Endler, R.; Tauber, F.; Jensen, J.B., and Bennike, O., 1998. Late- and postglacial sedimentation in the Tromper Wiek northeast of Rügen. *Meyniana*, 50, 155-173.

Lemke, W.; Jensen, J.B.; Bennike, O.; Witkowski, A., and Kuijpers, A., 1999. No indication of a deeply incised Dana River between Arkona Basin and Mecklenburg Bay. *Baltica*, 12, 66-70.

Lemke, W.; Schwarzer, K., and Diesing, M., 2002. Quaternary development of Tromper Wiek, Rügen Island. *Greifswalder Geographische Arbeiten*, 27, 61-67.

Lericolais, G.; Berné, S., and Fenies, H., 2001. Seaward pinching out and internal stratigraphy of the Gironde incised valley on the shelf (Bay of Biscay). *Marine Geology*, 175, 183-197.

Manso, F.; Radzevicius, R.; Blažauskas, N.; Balay, A., and Schwarzer, K., this volume. Nearshore dredging on the Baltic Sea. State after cessation of activities and regeneration assessment.

Orford, J D.; Forbes, D. L., and Jennings, S. C., 2002. Organisational controls, typologies and time scales of paraglacial gravel-dominated coastal systems. *Geomorphology*, 48(1-3), 51-85.

Posamentier, H.; Allen, G.; James, D., and Tesson, M., 1992. Forced regressions in a sequence stratigraphic framework: concepts, examples and exploration significance. *AAPG Bulletin*, 76, 1687-1709.

Posamentier, H.; Jervey, M., and Vail, P., 1988. Eustatic controls on clastic deposition I- Conceptual framework: Sea-level changes: An integrated approach. *In*: Wilgus, C.; Hastings, B.; Kendall, C.; Posamentier, H.; Ross, C.; Van Wagoner, J. (eds.). *Society of Economic Paleontologists and Mineralogists*, Special publication, 42, pp. 109-124.

Regnauld, H.; Mauz, B., and Morzadec-Kerfourn, M.-T., 2003 .The last interglacial shoreline in northern Brittany, western France. *Marine Geology*, 194(1-52), 65-77.

Schnick, H., 2002. The Jasmund cliff section. *In*: Lampe, R. (ed.). *Greifswalder Geographische Arbeiten 27*, Ernst-Moritz-Arndt-Universität Greifswald, pp. 69-74.

Schrottke, K., 2001. Rückgangsdynamik schleswig-holsteinischer Steilküsten unter besonderer Betrachtung submariner Abrasion und Restsedimentmobilutät. - Ber. - Rep., Inst. für Geowiss., Univ. Kiel, 16: 168 S.; Kiel.

Schumacher, W., 2002. Coastal evolution of the Schaabe spit and the shoreline displacement curve for Rügen Island. *In*: Lampe, R. (ed.), *Greifswalder Geographische Arbeiten 27*, Ernst-Moritz-Arndt-Universität Greifswald, pp. 55-60.

Schumacher, W. and Bayerl, K.-A., 1999. The shoreline displacement curve of Rügen Island (Southern Baltic Sea). *Quaternary International*, 56, 107-113.

Schwarzer, K., 2003. Coastline evolution on different time- and spatial scales driven by natural processes and anthropogenic impact – examples from the Baltic Sea. *In*: Pruszak, Z. (ed.), Gdansk: CEM-Centre for Environmental Engineering and Mechanics; Summer School-Workshop Coastal Zone, pp. 283 – 308.

Schwarzer, K.; Diesing, M., and Trieschmann, B., 2000. Nearshore facies of the southern shore of the Baltic Ice Lake - example from Tromper Wiek (Rügen Island). *Baltica*, 13, 69-76.

Stephan, W.; Wehner, K.; Seiler, M., and Stamm, C., 1989. Höffigkeitseinschätzung Kiessande. Ostseeschelf V; Vorratsberechnung Tromper Wiek. *Unpublished report*, Zentrales

Geologisches Institut, Berlin/Reinkenhagen, 47 p.

Uscinowicz**,** S., 1999.Southern Baltic area during the last deglaciation. *Geological Quarternary*, 43, 137-148.

Uscinowicz,S., 2002. Glacio-isostatic movements in the southern Baltic area. *In*: Second Conference of the IGCP-Project No. 464 "*Continental Shelves During the Last Glacial Cycle*", Sao Paulo, Abstract volume, pp. 89-91.

Vail, P. R.; Mitchum, R. M. Jr.: Todd, R.G.; Widmerij, J.W.; Thompson, S.; Sangree, J.B.; Bubb, J.N., and Hatelied, W.G., 1977. Seismic stratigraphy and global changes of sea-level. *In*: Payton, C. E. (ed.), *Seismic Stratigraphy-Applications to hydrocarbon exploration*. AAPG, Memory 26, pp. 49-212.

Van Wagoner, J. C.; Posamentier, H. W.; Mitchum, R. M.; Vail, P. R.; Sarg, J., F.; Loutit, T. S., and Hardenbol, J., 1988. An overview of the fundamentals of sequence stratigraphy and key definitions: Sea-level changes. An integrated approach. Wilgus, C.; Hastings, B.; Kendall, C.; Posamentier, H.; Ross, C., and Van Wagoner, J. (eds.), *Society of Economic Paleontologists and Mineralogists*, Special publication, 42, 39-45.

Wellman, H.W., 1967. Tilted marine beach ridges at Cape Turakirae. *New Zealand. J. Geosci.*, 10, 123-129.

Journal of Coastal Research	SI	51	187-194	West Palm Beach, Florida	Summer 2010

Nearshore dredging in the Baltic Sea: Condition after cessation of activities and assessment of regeneration

Faustino Manso[1*], Rolandas Radzevicius[2], Nerijus Blažauskas[3], Arnaud Ballay[4***] and Klaus Schwarzer[1]**

[1] Christian Albrechts University
Institute of Geosciences
Sedimentology, Coastal and Continental Shelf Research
Ludewig Meyn Strasse 10
D-24118 Kiel, Germany

[*] Present address:
Fugro-Geoteam AS
Address Hoffsveien 1C
0213 Oslo (Norway)
f.manso@fugro.it

[2] Department of Marine Sciences
School of Environment
University of the Aegean
University Hill
Mytilene 81100, Greece

[**] Present address: Department of Marine Research. Institute of Geology and Geography
Vilnius 03223, Lithuania

[3] Klaipeda University Coastal Research and Planning Institute
H.Manto 84,LT-92294, Klaipeda, Lithuania

[4] Department of Geography and Climatology
Faculty of Geology and Geoenvironment
National and Kapodistrian University of Athens
Panepistimioupolis, Zografou
15784 Athens, Greece

[***] Present address: EcoPlage
100 route de Clisson F44200
Nantes. France.

ABSTRACT

Using hydro-acoustic survey techniques (side-scan sonar and multibeam), high-resolution bathymetric and acoustic images (sonographs) of former marine aggregate extractions, from Tromper Wiek (Rügen Island, Baltic German Coast) were obtained. These data, together with ground-truthing (underwater video and seabed sediment samples) are used to describe the present condition of marks generated by mining, in terms of their morphology and superficial grain size distribution. Different features (pits and furrows), generated by different extraction techniques (anchor suction dredging and trailer hopper suction dredging, respectively) were detected at both of the study sites: Tromper Wiek 1 (sandy gravel seabed) and Tromper Wiek East (sandy seabed). Regeneration varies, depending upon the material extracted and the mining technique applied. In general, it is rapid during the first years following the extraction, becoming almost undetectable over a longer period of time. However, the marks are still detectable after more than 10 years, since they were generated.

ADDITIONAL INDEX WORDS: *Marine aggregates; dredging effects; regeneration; western Baltic Sea.*

INTRODUCTION

Marine aggregate dredging consists of transferring sediment, generally using powerful pumps on a suction pipe, from the seabed to the dredging vessel. Investigation into the physical impact generated by such activities has been undertaken previously (i.e. Boyd *et al.*, 2004; Dickson and Lee, 1973; Gajewski and Uscinowicz, 1993; and Price *et al.*, 1978); however, most of these studies have focused mainly upon tidally-dominated, sandy, areas of the seabed. The objective of this contribution is to describe the present state of former extraction sites in a non-tidal area, where the sediments are mainly relict. For the investigation, high-resolution hydro-acoustically-based approaches were used. These will permit: 1) evaluation of the results of dredging operations, in terms of the morphology and superficial grain size distribution; and 2) the investigation of trends and processes related to the evolution of the area. Subsequently, regeneration rates can be established through the comparison with previous datasets; this will provide an indicator of the suitability of these extractions, in the long-term.

The Baltic Sea can be considered as being "sediment starved", due to the low input of material. As such, the regeneration of marine aggregate extraction sites extends over longer periods of time, in comparison to more active areas (Diesing *et al.*, 2006). During the early phase of dredging operations in the Baltic Sea, the vessel was stationary, or anchored, whilst the dredge pipe excavated the seabed. Material was often screened onboard, with the unwanted fractions (undersize or oversize) being returned immediately to the overlying waters. This technique, "anchor" or "static" dredging, generated deep pits on the seabed. Elsewhere, previous studies have evaluated the recovery of such pits, over several years, in gravelly substrates (Dickson and Lee, 1973); over a year, in the case of pits in channels associated with high current velocities (Van Der Veer, Bergman, and Beukema, 1985). In order to minimise the impacts on the seabed, dredging marine aggregates has evolved towards "trailer (suction) hopper" dredging. In this case, the lower end of the suction pipe is trailed slowly (at around 1-2 knots) across the seabed. Such an approach generates long shallow furrows.

DOI: 10.2112 / SI51-017.1 received 14 January 2007; accepted in revision 27 February 2008.

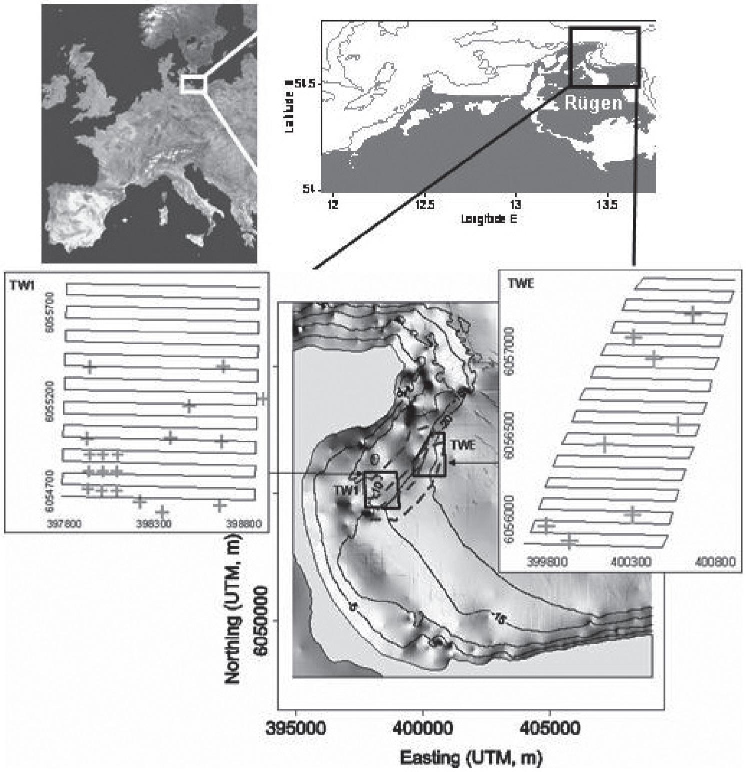


Figure 1. Location of the study area, within Europe and the Baltic Sea. In the Tromper Wiek image, the dashed lines correspond to the overall extent of the areas commissioned for dredging; solid lines to the zones of interest selected for the present study. The grids followed for the data acquisition are also presented, together with the location of the specific sites for which detailed data sets are investigated (grey crosses).

The study area

The study was undertaken within Tromper Wiek, a semi-enclosed bay located to the NE of Rügen Island (Figure 1). Tidal currents are hardly discernable (the tidal range is a few cm). Although wind driven currents may have some significance, the waves are the most important hydrodynamic agent for sediment mobility. The bay is located east of a spit, between two headlands (Figure 1). Due to this coastal configuration, Tromper Wiek is exposed only to waves from the 0-90° quadrant, with a maximum fetch of about 90km. Throughout the year, westerly winds dominate. High waves are only generated during the late winter and early spring (February to May), when strong easterly to northeasterly winds prevail (Mohrholz, 1998).

Various sedimentological environments on the seabed, ranging from gravel to mud, are associated with several extraction sites, located close to each other; here, different materials are extracted. For the purpose of this study, two sites were selected for investigation (not under exploitation presently): Tromper Wiek 1 (TW1); and Tromper Wiek East (TWE). At Tromper Wiek 1, 231.000m^3 of gravel has being extracted, in water depths ranging between 9 and 14m, from 1988 to 1999-2000. At Tromper Wiek East, sand has been extracted from water depths of around 20 m, on two occasions: in 1989 (151.000m^3); and in 2000 (104.000m^3) (Diesing *et al.*, 2006).

In order to facilitate establishing the effects related to dredging activities, the present study has focused upon locations, from the commissioned areas, where the extraction of material was most intense (Zeiler *et al.*, 2004).

DATA ACQUISITION AND ANALYSIS

Multibeam and side-scan sonar data were collected, simultaneously, onboard *RV Littorina* (IfM-GEOMAR) in 2003. The survey lines were designed in such a way as to ensure data overlapping, in relation to the swath width of instruments. The vessel speed was set at 5 knots. Due to technical problems, ground-truthing (seabed grab samples and underwater video) was performed in October 2004, onboard *RV Alkor* (IfM-GEOMAR).

Multibeam Data

The multibeam unit was a hull-mounted L3 ELAC NAUTIC SEABEAM 1185 (126 beams, emitting pulses at 180 kHz). Measurements were carried out in water depths of between 9 and 20m. To ensure full coverage of the seafloor, at all depths, the beams were set at 150º; this permitted a swath width of 7.5 times the working depth. The resolution of the multibeam (ranging from 0.26 to 0.52m) depends upon the ensonified area, which can be computed on the basis of the width of the emitted beams (1.5ºx1.5º) and the water depth (from 10 to 20m). Utilising this equipment, two different datasets have been acquired: bathymetry and sonographs, based mainly upon the amplitude of the backscattered signal (Fish and Carr, 2001).

Following sound velocity and water level calibration, the data were processed using HDP-Edit® (Elac Nautik®). 3D editing with Fledermaus®6.1.4b-pro (IVS 3D®) was undertaken to correct artefacts caused by MRU (motion reference unit) calibration problems. Subsequently, data from the outer beams were rejected, due to interferometric noise. Data were visualised using Surfer 8® (Golden Software®) and Fledermaus®6.1.4b-pro.

Data from the German Hydrographic Service, BSH (acquired in 1999) was collected using a hull-mounted Atlas Hydrosweep MD (80 beams, emitting pulses of 50 kHz).

Side-Scan sonar Data

Side-scan sonar data were acquired using a dual frequency (100-500kHz) high-resolution side-scan sonar (Klein Assoc. Inc., USA, Model 595). The 500 kHz frequency (beam width 0.2°) was selected and the range was set at 50m. The side-scan sonar data were processed with a resolution of 0.25m, since an along-track resolution (mainly beam width dependent) of 0.2m and an across-track resolution (based of the pulse length) of 0.075m was computed. The side-scan sonar fish was fixed underneath a larger buoyancy fish, to maintain the system in a stable position, minimising the effect of ship motion (SCHWARZER *et al.*, 1996). The data were processed with the ISIS Sonar®6.06 software (Triton Elics®), performing corrections on the vessel speed, slant range, layback, time-varying gain and navigation. For visualisation Delphmap 2.9 (Triton Elics®), Erdas Imagine® and Surfer 8 (Golden software®) were used. Generally, in the case of shallow surveys, when comparing two side-scan sonar sonographs from the same area, various effects can generate fluctuation on the position of the features (up to few tens of metres) in relation to: positioning errors, due to rapid changes of position of the dGPS antenna; current-generated drifting of the towed sonar fish, etc.

Hydro-acoustic data implementation

Side-scan sonar and multibeam backscatter maps were used to estimate seabed nature, based on differences in reflectivity (as a backscattered signal) (BLONDEL and MURTON, 1997; FISH and CARR, 2001; and ROBINSON *et al.*, 1995). Higher reflectivity represents acoustically-hard material and is, in this study, darker on the imagery. On the basis of the higher geometrical accuracy of the multibeam backscatter map, compared with the side scan sonar mosaics, this multibeam backscatter was merged with the multibeam bathymetry. Still, the resolution of the side-scan sonar mosaics is higher.

Ground-truthing

Based upon the side-scan sonar mosaic and the underwater video (towed Mariscope MICRO underwater video system, with black and white CCD), sample sites were selected from

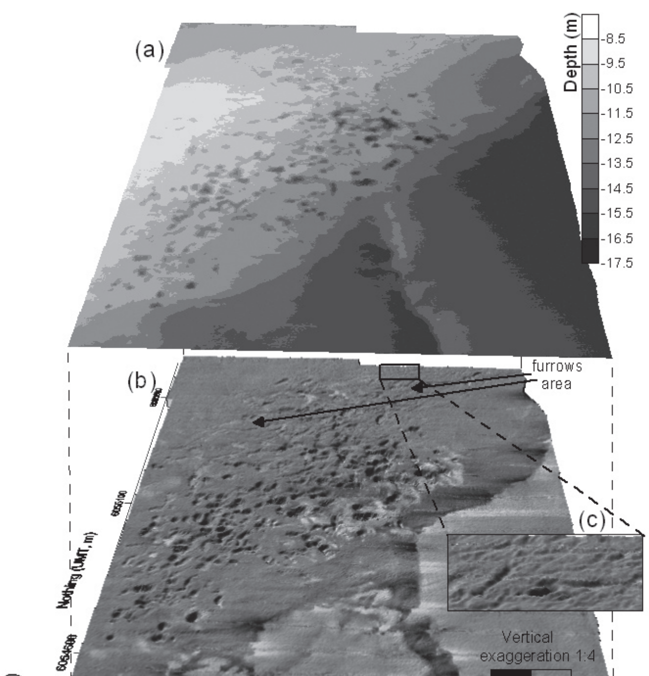


Figure 2. (a) bathymetric chart; (b) composite surface (multibeam bathymetry, merged with multibeam backscatter) of TW1. Detail of an area of furrows is presented in (c). Depths presented are relative to mean sea level.

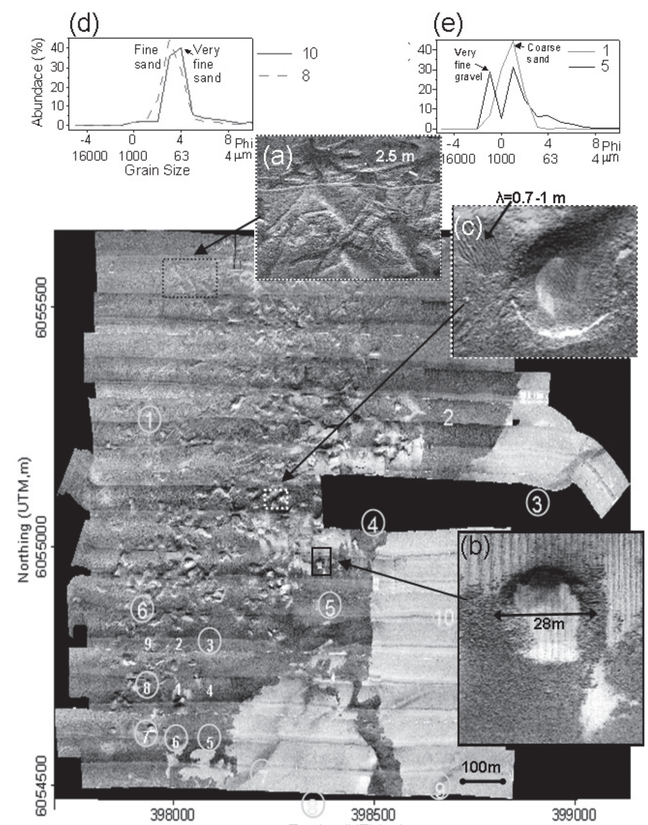


Figure 3. Side-scan sonar mosaic of TW1, with detailed images of relevant features ((a), (b), (c)). Numbers represent sample locations; only those shown by circles were recovered. The grain size distributions of undisturbed sediments from the low reflectivity (d) and high reflectivity (e) areas are presented.

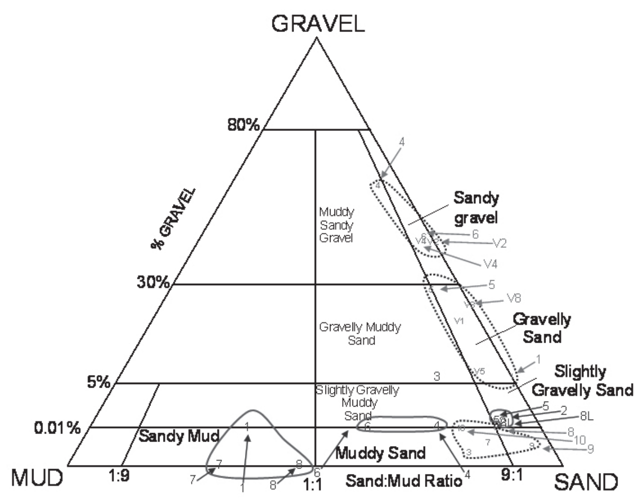


Figure 4. Ternary diagram of the gravel-sand-mud percentage of the samples from the study area. Dashed lines group TW1 samples, whist solid lines group TWE samples. V stands for the samples related with the small grid on the southwestern part of TW1 (see Figure 3.). L stands for the subsurface sample taken from TWE Sample 8 (Figure 6.).

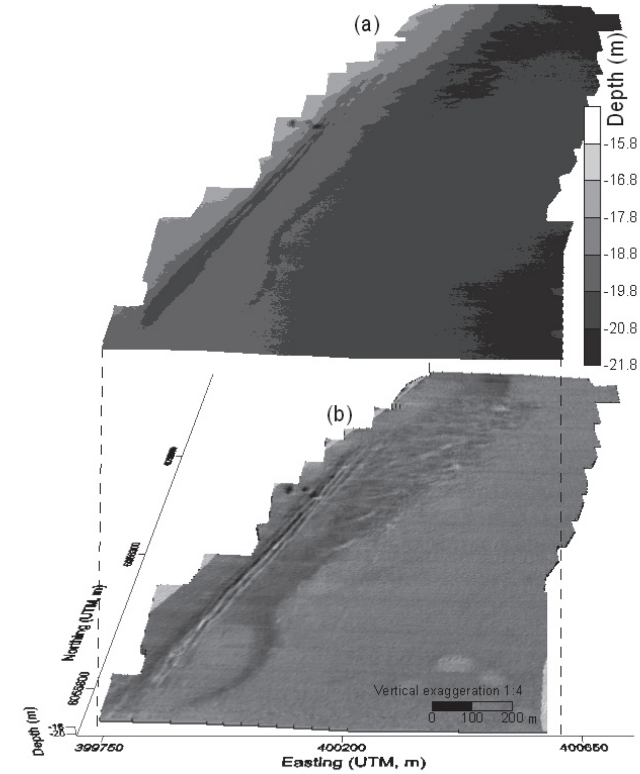


Figure 5. Bathymetric map (a), together with a composite surface (multibeam bathymetry merged with multibeam backscatter), of TWE (b).

representative locations, i.e. dredged 'impacted' and 'unimpacted' parts of the seabed. Seabed samples were collected using an 80 kg Van Veen grab (HELCOM standard). Samples were obtained from the upper 5-10 cm; at one station, two depth intervals (0-5 and 10-15 cm) were sampled to investigate granulometric changes, between the superficial and the underlying sediment deposits.

Grain size analysis

Sediment samples were analysed by combining the results of a Beckman Coulter LS 13320 laser diffraction particle analyser (fraction <2000 μm) and of dry sieving (fraction >2000 μm). For the very-coarse sediments, dry sieving was undertaken using sieves of 4000, 2800, 1400, 1000, 710, 500, 355, 250, 180, 125, 90 and 63 μm. All the grain size data were transposed into phi units, with a 1Φ interval. Based upon the logarithmic grain size distribution of the sediments, the mean grain size and sorting coefficient were calculated, according to the Folk and Ward method (1957). Calculations were performed using the GRADISTAT program (Blott and Pye, 2001).

RESULTS

Tromper Wiek 1 (TW1)

On the composite image of the Tromper Wiek 1 site, established using multibeam bathymetry and backscatter datasets (Figure 2), a sharp contact between two areas of different reflectivity is observed, partly because of a change in the slope of the seabed.

Furrows, generated by trailer suction hopper dredging, appear in the upper part of the image. However, the main features consist of abundant deep pits, generated by anchored suction dredging; around these, patches of lower reflectivity can be identified. In terms of reflectivity some horizontal artefacts (related to the tracks followed by the vessel) are visible; this pattern is related to the automatic gain of the multibeam attempting to adjust the signal, in response to the sharp changes in reflectivity of the different seabed materials. From the imagery, it appears that areas where dredging activities took place correlate with high reflectivity zones. In these zones, around 21% consists of pits, and 3% of furrows. The average size of the pits is 16±5.4m in diameter (on the basis of 47 measurements) and 1.7±1m in terms of the average water depth (on the basis of 82 measurements). The length of the furrows range between 15m and 290m, with an average width of 2.4±0.5m. A mosaic of the side-scan sonar tracks reveals the same general features, as observed on the multibeam backscatter map (Figure 3), i.e. sharp contact between areas of different reflectivity, including furrows (Figure 3a) and pits (Figure 3b).

This higher resolution image permits detailed features to be examined, such as the area of lower reflectivity around the pits (~32% of the total area). Looking into more detail, some observations can be made about the composition of the seabed, prior to the ground-truthing. On the high reflectivity area, lower reflectivity patches occur only around the pits, indicating their dredging-related origin. This finer material (associated with lower reflectivity) is related to the "undersize" particles spilled back to the water during dredging operations, as established during previous studies undertaken on the same area (Klein, 2003). The presence of ripples on the deeper part of the pits (Figure 3c), instead of the same material (in terms of reflectivity) observed on the unimpacted seabed, indicates that spilled material accumulates on these features. The wavelength of the ripples (0.7±0.15m) and their crestline orientation (from 45° NE, to 174° NW), have been computed, on

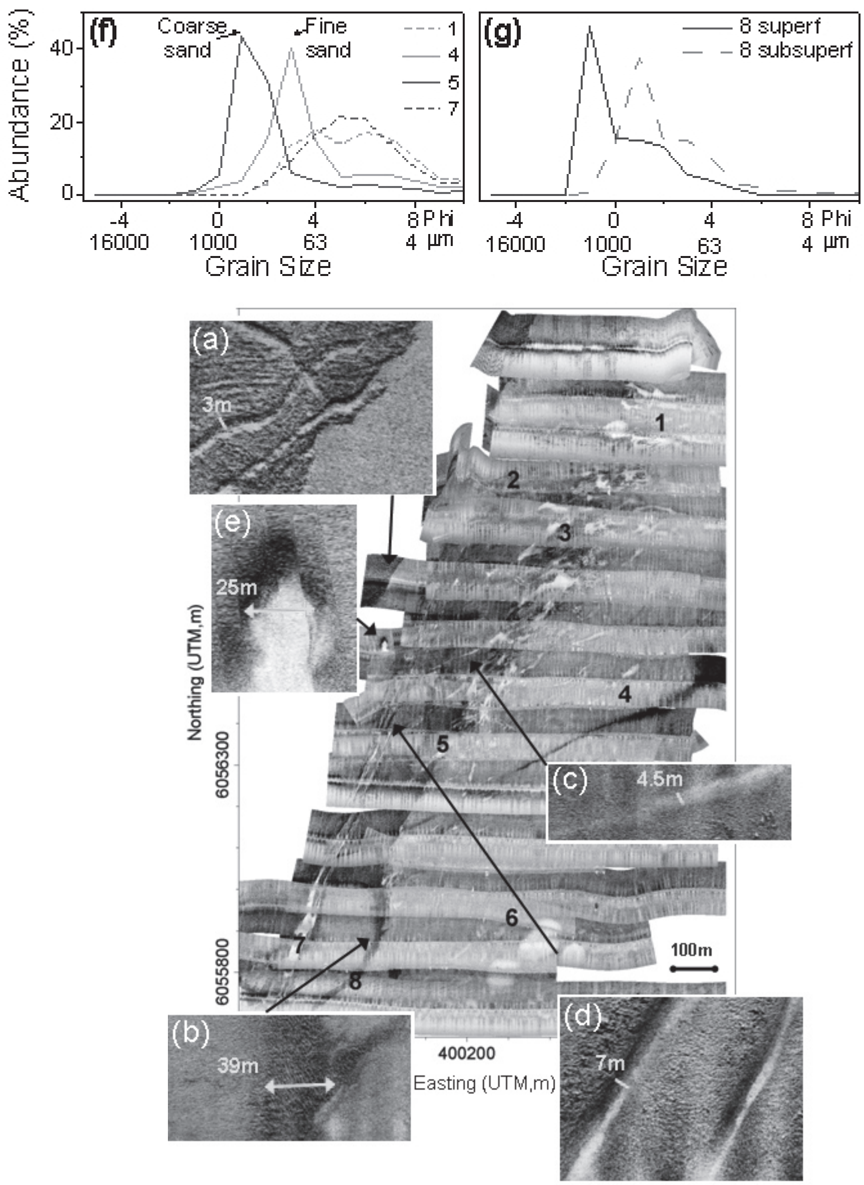


Figure 6. Side-scan sonar mosaic of TWE, with detailed images of relevant features ((a) to (e)). Numbers represent sediment sample sites. The grain size distribution of characteristic samples (f) and differences between superficial and subsurface samples (g) are also presented (see also, Figure 3.).

the basis of 89 measurements. Fourteen samples were collected from TW1 (Figure 3); 9 in the higher reflectivity zone and 5 in the area without dredging features, to characterise the lower reflectivity area. The superficial sediments vary from gravel to sand. On the basis of sonographs and ground-truthing, from each of the reflectivity areas, the relevant features and the superficial sediment distribution can be described. The studied surface area was 1.301.000m^2, within which the low reflectivity zone (~21% of the area) consisted of poorly sorted very fine sands; these increase in grain size (fine sand) in the vicinity of the higher reflectivity area (Figure 3d). The remainder of the area (~79%) is characterised by higher reflectivity; here poorly sorted sand and gravel (Figure 3e) occurs. Finally, the spilled material (lower reflectivity, around the pits) corresponds to coarse sand. Samples rich in spilled material showed a slight increase in their mud content (from 0.2% to 4.8%). To evaluate any trends regarding sediment composition, samples were plotted on the Folk ternary diagram (% gravel-sand-mud) (Folk, 1954; Figure 4). Three different groups were observed: sandy gravel from the undisturbed areas, showing high reflectivity; sand and muddy sand, from the lower reflectivity area; and an elongated group of gravelly sands, corresponding to the dredged areas. The more intense the impact of the extraction, the richer the samples are in finer-grained materials.

Tromper Wiek East (TWE)

The composite image of the Tromper Wiek East site shows a contact between two areas of slightly different reflectivities, i.e. higher in the west and lower in the east (Figure 5).

The sharp contact between gravel and sand, observed in TW1 (Figure 2), is also visible on the westernmost part of the area. Some diffuse furrows are observed within the northern part of the high reflectivity area. Crossing the area from SW to NW, some deep well-defined furrows appear, lying very close to each other. Depending upon the location, from 2 to 4 individual furrows, with a maximum width of 8m, 1.3km maximum length and 2.4 maximum depth, can be identified. Some pits appear also in the vicinity of the northern end of the deep furrows, with maximum diameters of 28.5m and maximum depths of 2.5m. The diffuse furrows were generated during the extractions taking place in 1989; more distinct furrows are seen in 2000 (Diesing, 2003). No side-scan sonar data are available from this area, from the 2003 survey. Nevertheless, given the low dynamics of this area (Diesing, 2003), another mosaic, generated from data collected in 2004, was used (Figure 6). In this sonograph, the same features as shown in the composite multibeam image are presented: the contact between gravel and sand (Figure 6a); the contact between the two areas with different reflectivity, where ripples are observed in the acoustically darker area (Figure 6b); the (1989) diffuse furrows (Figure 6c); the (2000) well-defined furrows (Figure 6d); and the pits (Figure 6e).

In order to correlate reflectivity with superficial grain size distribution, 8 samples were collected over this area; these were from undisturbed locations from each reflectivity zone, in the extraction sites and on the seabed surrounding the extraction sites (Figure 6). On the basis of these data, it can be established that the low reflectivity zone (~60% of the study area, i.e. 1.266.100m^2) corresponds to poorly sorted very fine sand; the remainder (~40%) with higher reflectivity, to poorly sorted medium sand (Figure 6f). Within the high reflectivity area, the newer furrows extend over roughly 9% of the area, showing superficial sediment finer than that of the surrounding seabed (poorly sorted, very coarse silt). The area covered by the older furrows, corresponding to very poorly sorted fine sand, could not be established (due to their diffuse profile). The effect of extraction on the superficial sediments can be detected also in relation to the mud content. On the undisturbed medium sand, the mud content is around 8%; in samples affected by dredging activities, this content is higher (~70% on the 2000 furrows; ~66% on the 1989 furrows).

Vertical grain size variations, observed on the subsamples from Station 8, indicate that the effects of dredging affect also the area surrounding the extraction sites. The superficial sample is associated with a grain size distribution, which is similar to that from the newer extraction site sample (Sample 7); it has high a mud content, but not as high as in the extraction area (~54% and ~70%, respectively). The sample from the underlying sediment presents a grain size distribution (poorly sorted, medium sand) and mud content (~7%), which lies within the same range as the undisturbed sediment from the high reflectivity area (Figures 6f and 6g).

On a ternary diagram (% gravel-sand-mud), the samples from TWE can be classified into 3 groups (Figure 4). Two of the groups relate to undisturbed sediments from the main areas, as observed on the sonographs: slightly gravelly sand, on the high reflectivity area (Samples 2, 5 and the sub-surface sample of Station 8); and slightly gravelly muddy sand, on the low reflectivity area (Samples 4 and 6). The third group, the sandy mud samples, are associated with sites impacted upon by dredging (Samples 1, 7 and 8); here, an increase in the mud content, coinciding with a decrease in the percentage of sand, is observed. The grain size distribution of Sample 3, located within a high reflectivity area, lies closer to that of the undis-

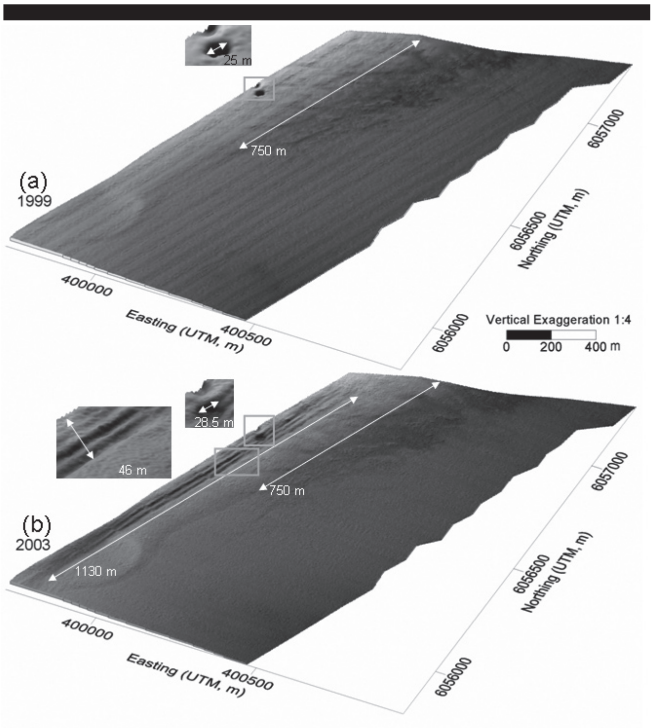


Figure 7. Multibeam surfaces derived from the 1999 (a) and 2003 (b) surveys: TWE. Details of some relevant features are also presented.

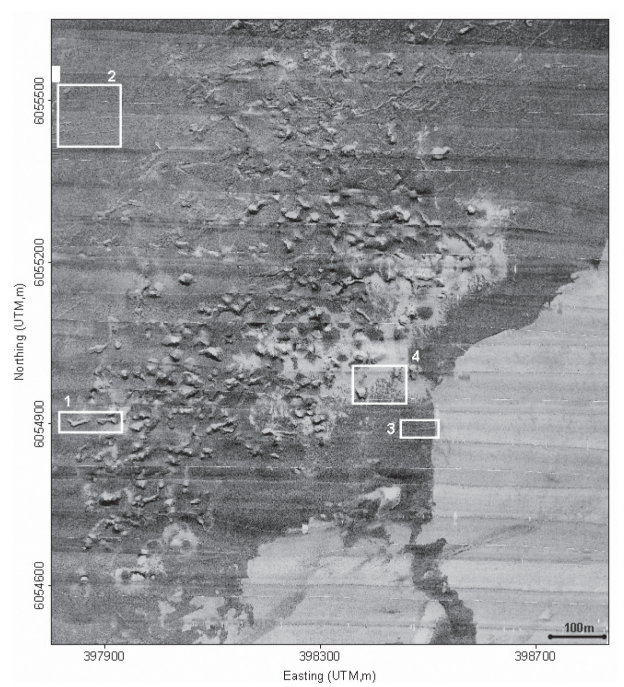


Figure 8. 2000 Mosaic of TW1. Note: the zones marked (1 to 4) are shown, in detail in Figure 9.

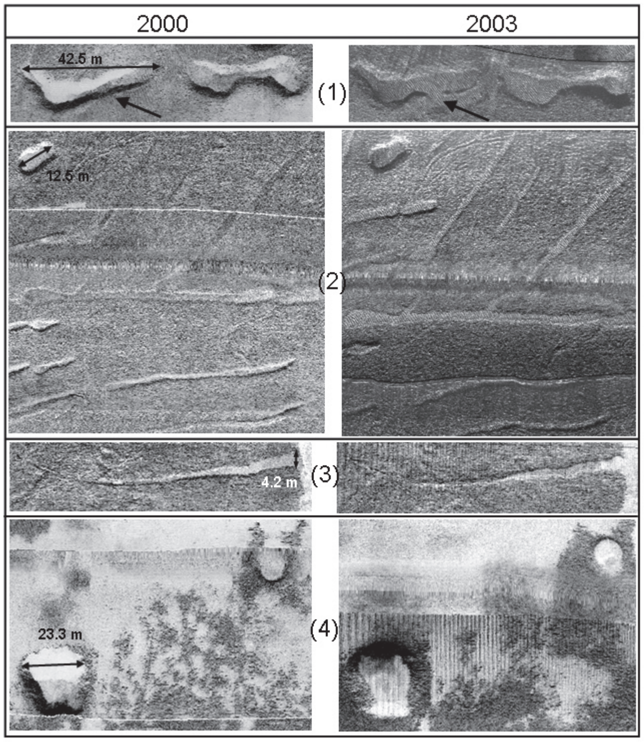


Figure 9. Comparison of the changes observed in some areas of TW1, from 2000 (first column) to 2003 (second column) (for locations, see Figure 8.).

turbed sediments, from the lower reflectivity area. An explanation of this effect will be discussed later.

Seabed Evolution along Dredging Sites

Datasets acquired within the framework of other projects, undertaken in 1999 and 2000, are compared now with the datasets available from 2003 and 2004. The seabed evolution along TWE is studied on the basis of multibeam bathymetry comparisons (Note: no backscatter information is available from the older dataset); TW1 by side-scan sonar, since no multibeam data are available.

Dredging mark evolution on a sandy seabed (TWE)

Figure 7 represents the multibeam surfaces of both the 1999 and 2003 surveys. Overall, both surfaces show the same features, except for the noise within the 1999 dataset and the deep, well-defined furrows, running parallel (from SW to NW) on the 2000 dataset (Figure 7). The diameter of the pit has increased between the two surveys, likely to be related to collapsing of the walls (Figure 7). No volumetric differences were calculated between the two surfaces, because of the noise of the 1999 dataset, due to calibration problems. Significant changes can be seen along the furrows; i.e. after 4 years, a maximum vertical variation exists of almost 2.5m.

Dredging mark evolution on a gravel seabed (TW1)

Dredging operations on TW1 were undertaken, continuously, from 1989 to 2000. The 2000 mosaic from TW1 (Figure 8) shows similar features to those of 2003.

Major differences can be observed within the pits (Figure 9), independent of their dimensions; this permits direct recognition of the various pits, after a 3 year period. Generally, there appears to be some correlation between the diameter and the depth of the pits: as a result, the potential for wall-collapsing will be higher in the case of the deeper pits; the smaller ones are more stable in their shape (Figures 8 and 9, Locations 1 and 2). Such an effect is even more marked on the furrows where, due to their shallow bathymetric profile, their edges remain highly stable. Further infilling within the furrows, by finer–grained sediments, is less intense (Figures 8 and 9, Location 2). Even infilling of furrows associated with the area of sand is not significant (Figures 8 and 9, Location 3). The main change observed is related to the area with spilled sand (Figures 8 and 9, Location 4). The surface area covered by this material decreases with time, remaining observable inside the pits. This corroborates the role of pits, as traps of such sediments (Diesing, 2003).

DISCUSSION

Results obtained from the hydro-acoustic surveys, for both study areas, reveal morphological features on the seabed, related to dredging activities. The effects of dredging can be detected also in the superficial sediment grain size distributions. Areas affected by dredging operations are associated with finer-grained sediments and a higher amount of mud, in relation to unimpacted areas; this has been observed previously, in other studies (Boyd *et al.*, 2004). On the gravel area, the finer-grained sediments are the result of the spilling of undersized material, during extraction. Such material is easily detectable on sonographs, as lower reflectivity patches around the pits themselves. On the area with sand, the extraction sites have revealed the presence of sandy-mud material, whilst the unimpacted sediment consists of slightly gravelly muddy sand. The mud content of the unimpacted sediment is around 8%, whilst it is around 66% at the older extraction sites (1989) and 70% on the more recent site (2000). Areas lying adjacent to the extraction sites have similar superficial sediment grain size distributions, together with slightly lower mud contents, than the directly-impacted zones.

In order to assess regeneration of the extraction sites, the dredging technique adopted and the nature of the material dredged are considered. No pit has been observed, within any of the datasets, in an advanced stage of regeneration, independent of the material dredged. The pits from the gravel area are associated with sharp edges, even though some of them were formed some 15 years before the present dataset was collected. Some refilling has occurred in response to accumulation of spilled sand, generating ripples in the craters, as cited previously (Boyd *et al.*, 2004). Likewise, the re-suspension and transport of material, around the pits, has been investigated elsewhere (Garel and Lefebvre, this volume; Klein, 2003;). Pits lying within a sandy seabed (TWE) are associated with more diffuse edges; this is related to "wall collapsing" effects, as described by other investigators (Boers, 2005). Furrows generated by trailing suction hopper dredging have been observed, in an advanced state of refilling, but only on the sandy beds. Furrows generated in the gravel part of the seabed are shown to remain almost constant in their expression, even when lying close to an area containing an abundance of finer-grained material.

Based upon the above observations, a change from anchor suction dredging to trailing hopper suction dredging appears to be an appropriate decision. In the case of the areas studied, the furrows show enhanced regeneration; as such, they impact less upon the environment, than the pits. Nevertheless, multiple dredging profiles, over the same transect, generate deeper features within the seabed, complicating their regeneration; this is the case of the 2000 extraction, from TWE. In relation to the extracted material, the dredging of the gravel areas of the seabed creates a deeper impact. Reworking of coarser-grained materials over the area follows a very slow pattern of recovery; this is corroborated by other studies (Garel and Lefebvre, this volume; Klein, 2003;).

CONCLUSIONS

(1) Hydro-acoustic survey techniques have generated detailed images of the seabed, where the morphology of areas of extraction can be described. In the case of Tromper Wiek, the impacts from anchor suction dredging (pits) and trailing hopper suction dredging (furrows) can be observed, in both of the areas studied. On the gravel area (TW1), deep pits and dredging-related spill material represent the main observable features. Over the sandy area (TWE), long and deep furrows are the main detectable features.

(2) Dredging activities can be identified also from information obtained from the grain size distribution of the superficial sediments. Dredged areas reveal a finer superficial grain size distribution and higher mud content, than the unimpacted areas. In some cases, this effect is detectable on the sonographs, due to the presence of spill material (e.g. after anchor suction dredging, on a gravel bed).

(3) Regeneration depends upon the adopted dredging technique and the nature of the dredged material. Pits remain more stable than furrows, indicating a higher impact of anchor suction dredging, in comparison with trailing hopper suction dredging. In relation to the type of dredged seabed material, representative marks on gravel areas are more stable than those on a sandy bed.

(4) Seabed evolution in the sandy gravel area, studied on the basis of sonographs, indicates high stability of the dredging marks. The main observed processes were collapsing of the pit walls and refilling by spilled sand.

(5) Seabed evolution in the sandy area, examined on the basis of multibeam bathymetry, shows that regeneration is rapid during the first years after the extraction; subsequently, this becomes hardly detectable, but marks are still visible, even after a decade.

ACKNOWLEDGEMENTS

Firstly, the authors would like to acknowledge the support provided by the EUMARSAND Research Training Network (HPRN-CT-2002-00222). We would like to thank also German Rodriguez, AZTI (San Sebastian, Spain), for undertaking the grain size analyses used in this study. Finally, the German Hydrographical Service (BSH) is acknowledged, especially Dr. M. Zeiler, for granting EUMARSAND to have access to their broad database. The multibeam dataset of 2000 was acquired as part of the project "Regeneration of aggregate extraction sites in the North Sea and Baltic Sea" (funded by the German Ministry of Education, Science and Technology).

LITERATURE CITED

Blondel, P. and Murton, B., 1997. *Handbook of Seafloor Imagery*. Willey & Sons, New York, 314p.

Blott, S.J. and Pye, K., 2001. Gradistat: A Grain Size Distribution and Statistics Package for the Analysis of Unconsolidated Sediments. *Earth Surface Processes and Landforms*, 26, 1237-1248.

Boers, M., 2005. *Effects of a deep sand extraction pit. Final report of the PUTMOR measurements at the Lowered Dump Site*. Rijkswaterstaat National Institute for Coastal and Marine Management (RIKZ), 87p+CD.

Boyd, S.E.; Cooper, K.M.; Limpenny, D.S.; Kilbride, R.; Rees, H.L.; Dearnaley, M.P.; Stevenson, J.; Meadows, W.J., and Morris, C.D., 2004. *Assessment of the re-habilitation of the seabed following marine aggregate dredging*. CEFAS Science Series. Technical Report, 121, 154p.

Dickson, R.R. and Lee, A., 1973. Gravel extraction: effects on seabed topography. *Offshore Services*, 6(6), 32-39.

Diesing, M., 2003. Regeneration von Materialentnahmestellen in der südwestlichen Ostsee unter besonderen Berücksichtigung der rezenten Sedimentdynamik. Kiel, Germany: (unpublished) University of Kiel, Ph.D. Thesis, 158pp.

Diesing, M.; Schwarzer, K.; Zeiler, M., and Klein, H., 2006. Comparison of Marine Sediment Extraction Sites by Means of Shoreface Zonation. *Journal of Coastal Research*, 2, 783-788.

Fish, J. P. and Carr, H. A., 2001. *Sound reflections*. Lower Cape Publishing. Orleans, MA, 272p.

Folk, R.L., 1954. The distinction between grain size and mineral composition in sedimentary rock nomenclature. *Journal of Geology*, 62(4), 344-359.

Folk, R.L. and Ward, W.C., 1957. Brazos River bar: a study in the significance of grain size parameters. *Journal Sedimentary Petrology,* 27, 3-26.

Gajewski, L. and Uścinowicz, S.Z., 1993. Hydrologic and sedimentologic aspects of mining aggregate from Stupsk Bank. *Marine Georesources and Geotechnology*, 11, 229-244.

Garel, E. and Lefebvre, A., this volume, Wave-induced Sand re-Suspension at Dredged Gravel Pits based upon Hydrodynamic Measurements (Tromper Wiek, Baltic Sea). *Journal of Coastal Research.*

Klein, H., 2003. Investigating sediment re-mobilisation due to wave action by means of ADCP echo intensity data: field data from the Tromper Wiek, western Baltic Sea. *Estuarine, Coastal and Shelf Science,* 58(3), 467-474.

Mohrholz, V., 1998. Transport and mixing processes in the Pomeranian Bight. Marine Science Reports, 33, 106p. (in German)

Price, W.A., Motyka, J.M., and Jaffrey, L.J., 1978. The effect of offshore dredging on the coastlines. *In: Proceedings of the 16th Coastal Engineering Conference*, 1347-1358.

Robinson, A.H.; Morrison, J.L.; Muehrcke, P.C.; Kimerling, A.J., and Guptill, S. C., 1995. *Elements of Cartography*, John Wiley & Sons, New York, 688p.

Schwarzer, K.; Ricklefs, K., And Schumacher, W. and Atzler, R., 1996 Beobachtungen zur Vorstranddynamik und zum Küstenschutz sowie zum Sturmereignis vom 3./4.11.1995 von dem Streckelsberg/Usedom. *Meyniana,* 48, 49-68.

Van Der Veer, H.W.; Bergman, M.J.N.; and Beukema, J.J., 1985. Dredging activities in the Dutch Wadden Sea: Effects on Macrobenthic Infauna. *Netherlands Journal for Sea Research*, 19, 183-190.

Zeiler, M.; Figge, K.; Griewatsch, K.; Diesing, M., and Schwarzer, 2004. Regenerierung von Materialentnahmestelln in Nord-und Ostsee. *Die Küste*, 68, 67-98.

Journal of Coastal Research	SI	51	195-204	West Palm Beach, Florida	Summer 2010

Wave-induced Sand re-Suspension at Dredged Gravel Pits based upon Hydrodynamic Measurements (Tromper Wiek, Baltic Sea)

Erwan Garel [1*] and Alice Lefebvre[1]**

[1] National Oceanography Centre, Southampton
European Way, Southampton
SO143ZH, United Kingdom

[*] Present address: CIACOMAR
University of Algarve
Avenida 16 de Junho
8700-311 Olhão
Portugal
egarel@ualg.pt

[**] Present address:
MARUM - Center for Marine Environmental Sciences
University of Bremen
Leobener Str.,
D-28359 Bremen, Germany

ABSTRACT

Gravel pits created by anchor hopper dredging may affect regional sediment transport patterns by trapping sediments. In turn, this may cause -or enhance- erosion at the adjacent coastline. Reliable assessment of such impacts requires a good understanding of the hydro-sediment dynamic processes acting at dredged pits. This paper examines the processes for sand re-suspension from pressure, current and turbidity data collected inside and outside a single dredged pit, in a non-tidal environment (Tromper Wiek, Baltic Sea). The data confirm the generally weak sediment dynamics in the area, with waves being the main hydrodynamic agent for sediment re-mobilization. Comparisons with historical data indicate a small number of sediment re-suspension events (<15%), over a 37 months-long period, without significant difference inside and outside the pit. Suspended sediment concentration profiles are predicted inside the studied pit by a simplistic model, tuned to over-estimate sediment re-suspension. The results suggest that the depth of the excavation should be very shallow (<1 m) for the bed material to be frequently extracted out by waves, and redistributed over the area. With pits up to 7 m-deep within the extraction zone, we conclude that a significant fraction of sediment is trapped over the long-term period (years).

ADDITIONAL INDEX WORDS: *dredging, suspended sediment concentration.*

INTRODUCTION

The volume of gravel extracted from the seabed has significantly increased since the 1980s, in response to growing demand of the market (ICES, 2001). Offshore gravel extraction is generally carried out by means of anchor suction dredging. The technique generates rounded craters on the seabed, typically 10-50 m in diameter and up to 10 m in depth. The unwanted fraction of (fine) material is screened onboard and dumped back into the sea. These operations may have negative effects upon the marine environment, including the benthic communities and sediment transport patterns (e.g. Boyd *et al.*, 2005; Kenny and Rees, 1996; Kortekaas *et al.,* this volume). Thus, in a number of countries, Environmental Impact Assessment (EIA) and Coastal Impact Studies (CIS) are required before granting licenses for extraction (Radzevičius *et al.*, this volume). With respect to sediment dynamics, dredging close to the shore may affect the coastal sediment budget by trapping fine sediments, and cause -or enhance- coastline erosion. A comprehensive understanding of the hydro- sediment dynamic processes acting at dredged pits is important to assess these harmful effects.

Recently, increasing attention has been put upon the hydrodynamic impacts and regeneration (refilling) processes of (dredged) sand trenches (e.g. the European projects PUTMOR (Boers, 2005) and SANDPIT (Van Rijn *et al.*, 2005)). These excavations present gentle internal slopes, and are surrounded by large amounts of sand. By contrast, dredged gravel pits

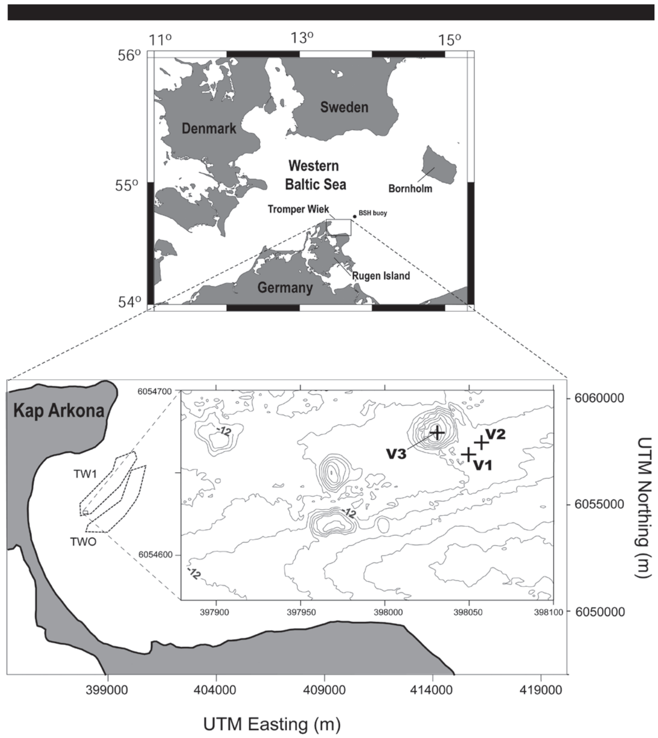


Figure 1. Location map of the studied area; insert: detail of the mooring zone (contour interval: 0.5m) with location of the ABLs. TW1: Gravel extraction site "Tromper Wiek 1"; TWO: sand extraction site "Tromper Wiek Ost".

DOI: 10.2112 / SI51-018.1 received 15 January 2007; accepted in revision 15 August 2007.

have steep walls, and sand is distributed in patches nearby the pits (due to the settling out of the fines during the screening process) (Kubicki, Manso, and Diesing, 2007). These differences in morphology and material availability imply distinct hydro-sediment dynamic conditions (e.g. flow structure and time-evolution) for both types of excavations.

The morphological changes and regeneration processes of dredged gravel pits have been the subject of several investigations, at the Tromper Wiek area (Baltic Sea) (Figure 1) (Diesing, 2003; Diesing *et al.,* 2006; Figge *et al.*, 2002; Klein, 2003; Kubicki, Manso, and Diesing, 2007; Zeiler *et al.*, 2004) However, apart from Klein (2003), no direct hydrodynamic measurements have been performed inside gravel dredged pits. In this paper, we present new hydrodynamic data collected in the same area, during a 4-days period which includes a storm event. Pressure, current and turbidity data, from both inside and outside a dredged gravel pit, are compared and discussed, in order to specify the processes responsible for fine material remobilization. In particular, we examine if some sand can be naturally extracted out of the pit due to the waves' action.

The organization of the paper is as follows. The first part describes the hydrodynamic and geological settings of the studied area. The next section presents the methods used to collect and process the data. In particular, a model to predict wave-induced bed shear stress is described. The results are provided in the following section. The subsequent discussion focuses on several points: firstly, we investigate the difference in suspended sediment concentration which has been observed inside and outside the studied pit; secondly, the relative number of sediment re-suspension events, over the long-term period, is characterized, based upon our records and historical data; next, we propose that sand is hardly extracted out of the pit by waves, on the basis of a simple sediment re-suspension model; additionally, we confirm that currents have no significant effect upon the upward diffusion of sand; at last, prior to conclude, we discuss the impact of dredged pits from a sediment transport perspective.

SETTING

Tromper Wiek is a semi-enclosed bay in the Western Baltic Sea, with low sediment dynamics intensity (Diesing, 2003) (Figure 1). Tidal currents are hardly discernable in this practically non-tidal environment (the tidal range is a few cm). Although wind driven currents may have some significance, the waves are the most important hydrodynamic agent for sediment mobility. The bay is located east of a spit, between two headlands, in the northern part of Rügen Island (Figure 1). Due to this coastal configuration, Tromper Wiek is exposed only to waves from the 0-90° quadrant, with a maximum fetch of about 90 km (Figure 1). Throughout the year, westerly winds dominate. High waves are only generated during the late winter and early spring (February to May), when strong easterly to northeasterly winds prevail (Mohrholz, 1998).

Sand and gravel extraction has been carried out at Tromper Wiek for many years (Figure 1). Within the gravel extraction site (Tromper Wiek 1), between 9 and 16 m water depth, the seafloor is marked with craters 5 to 50 m in diameter and up to 7 m-deep. These features have proved to be stable for several years, at least (Figge *et al.*, 2002). In detail, spatial extension of the edge of the pits is observed over the years, due to collapsing of the walls (Kubicki, Manso, Diesing, 2007). It is estimated that among the 460,000 m^3 of sediment extracted between 1988 and 2000, half of this volume was dumped back into the sea (Brauckhoff, cited in Diesing *et al.*, 2006). Thus, patches of fine sediment (<2 mm in diameter, mostly sand) are commonly found in the vicinity of the pits (Diesing, 2003). These deposits constitute a possible source of pit refilling. In agreement, core analyses demonstrate the episodic occurrence of sand advection inside the craters (Diesing, 2003; Manso *et al.,* this volume), and repeated side-scan sonar surveys show the presence of bedforms together with rapid changes in the pattern of the sand patches (Diesing, 2003; Diesing *et al.,* 2006). Based upon acoustic seafloor imaging, Kubicki, Manso, and Diesing (2007) observed a decrease in the availability of sand around a pit and a deceleration of the mean (pit) refilling rate, over a 6 years period. The key mechanisms for sediment remobilization are the near-bed orbital motions induced by surface waves entering the bay (Klein, 2003).

METHODS

Data acquisition

Hydrodynamic data were acquired using three self-recording Autonomous Benthic Landers (ABLs), from the 19th to the 23rd of October 2004. Each ABL consists of a device (VALEPORT 808) mounted on a frame weighted with chains. The devices are fitted with a pressure gauge, an Electro-Magnetic Current-Meter (EMCM) and an Optical Backscatter Sensor (OBS). The EMCM and OBS measure the northward and eastward components of the flow (in a horizontal plan), and the scattering of infrared radiation by suspended particles, respectively. One ABL (referred as V3, hereafter) was deployed at ~14.5 m water depth, inside a circular dredged pit (at 54.6291° N; 13.4208° E). The selected pit has been investigated previously by Klein (2003) and Kubicki, Manso, and Diesing (2007). From multibeam bathymetry, the excavation was, in December 2003, 3.5 m-deep and ~30 m in diameter (Kubicki, Manso,and Diesing, 2007). The two other ABLs (referred as V1 and V2, hereafter) were moored at about 20 m from the edge of the pit, at ~11 m water depth (Figure 1). Scuba-divers checked the location of the moorings, within sandy patches displaying symmetrical ripples.

The ABLs were set up to record the pressure, horizontal currents and turbidity at 4 Hz, during bursts of 8 min 32 sec, every 30 min. The pressure sensor, OBS and EMCM were at 0.5, 0.45 and 0.25 m above the sea bed, respectively. In addition, a 20 cm-high cylinder, opened at top, was attached vertically to the frames, in order to trap sediments at the height of the OBS. These traps were collected by scuba-divers at the end of the experiments, together with bed sediment sampled nearby the instruments.

The ABLs were triggered at the same time, allowing direct comparison of the burst records. Because stations V1 and V2 were located relatively close to each others, their outputs are very similar; only the results of station V1 are presented here and compared to the data collected inside the pit (V3).

One hour-averaged wind and air pressure data from Kap Arkona meteorological station (see Figure 1 for location) were provided by the German Weather Forecast Agency. In addition, historical wave parameters were obtained from the BSH (Federal Maritime and Hydrographic Agency); the dataset consists of the readings (significant wave heights, direction, period and wavelength) from a buoy located in the entrance to the bay (Figure 1), between 2003 and 2006, at a 30 min time interval.

Data processing

The pressure is converted to sea surface elevation with standard calculations methods assuming linear wave theory, as described by TUCKER and PITT (2001). A frequency-dependent pressure correction factor that compensates for depth attenuation is applied to wave frequencies from 0.05 to 0.33 Hz. The significant wave height (Hs) and peak period (Tp) are derived from spectral analysis applied to each burst.

Three techniques were combined for grain size analysis: Coulter counter for the mud fraction; settling tower for the sand fraction; and, sieving for coarser grained sediments. The statistics of the particle size distribution are described according to MCMANUS (1988). The distribution of the bottom sediment should be considered with caution. The divers reported the loss of some fines during the sampling, and it is suspected that the d_{50} of the bed sediment is slightly finer than proposed. In addition, sediment distributions are highly variable, even at nearby locations, in relation with the heterogeneous nature of the seafloor (DIESING, 2003).

The observed turbidity was converted to suspended sediment concentration (SSC) in laboratory. Various known concentrations of sediment were stirred in a bucket, during OBS measurements, and a regression was applied to the resulting concentration-turbidity graph. The calibration was performed with the sediments from the traps, i.e. which were in suspension at the height of the sensor during the experiment. The following polynomial equation yields the best correlation coefficient (0.82), and was therefore used to convert the turbidity (T, in Volts) into suspended sediment concentration (SSC, in mg/l) (Figure 2):

$$SSC = 110.36T^2+16.275T \quad (1)$$

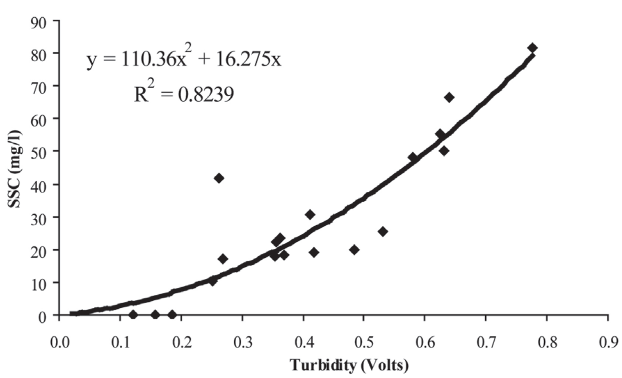


Figure 2. Calibration curve of the OBS.

Bed shear stress

Due to the weakness of the flow during the experiment, the bed shear stress results essentially from the activity of the waves. The wave induced bed shear stress is computed from the near-bed significant orbital velocity (U_{ws}), using SWART (1974) friction factor (F_w) for rough turbulent flow:

$$\tau_w = 0.5\rho\, F_w U_{ws}^{\ 2} \quad (2)$$

with

$$F_w = 0.00251\exp(5.21r^{-0.19}) \quad (3)$$

where r is the relative roughness:

$$r = A/K_s \quad (4)$$

with K_s, the Nikuradse roughness. The grain related bed shear stress is computed using:

$$K_s = 2.5d_{50} \quad (5)$$

where d_{50} is the median grain diameter of the bed material. To compute the total bed shear stress, the Nikuradse roughness (K_s) is derived from the total bed roughness (Z_o) through the relationship:

$$K_s = 30Z_o \quad (6)$$

Z_o is the sum of the skin friction component ($d_{50}/12$) and form drag component of the bed roughness (Z_{of}). Following NIELSEN (1992), Z_{of} is obtained from the wave ripples height (H_r) and wavelength (L_r):

$$Z_{of} = 0.267H_r^{\ 2}/L_r \quad (7)$$

where the size of the ripples is estimated for mobile sand, based upon the wave mobility number (Ψ) and the skin friction Shields parameter (θ_s):

$$H_r = A(0.275\text{-}0.022\Psi^{0.5}) \quad (8)$$

$$L_r = H_r/(0.182\text{-}0.24\ \theta_s^{\ 1.5}) \quad (9)$$

Ψ and θ_s are defined by:

$$\Psi = U_{ws}^{\ 2}/[gd_{50}(s\text{-}1)] \quad (10)$$

$$\theta_s = \tau_{ws}/[gd_{50}(\rho_s - \rho)] \quad (11)$$

with g, the acceleration due to gravity (9.81 m/s^2), τ_{ws}, the skin friction bed shear stress, ρ_s, the sediment density (2650 kg/m^3), ρ, the water density (1027 kg/m^3), and s, the ratio of grain and water densities (ρ_s/ρ). It has been verified that the wash-out conditions (Ψ=156 and θ_s=0.831) were not met during the period of measurements.

In equations (4) and (8), A is the wave semi-orbital excursion:

$$A = U_{ws}T_p/(2\pi) \quad (12)$$

The significant orbital velocity is considered as more representative of the waves' activity than the maximum orbital velocity, during a burst. The orbital velocities are computed for each burst from the EMCM records. The latter are filtered to eliminate the velocity components not related to waves (high pass, 0.1 Hz cut off frequency). The filtered velocity components are rotated in the direction of the waves, and analyzed in the spectral domain, to yield the significant (crest and trough) near-bed wave orbital velocities (i.e. above the wave boundary layer). The difference between the crest and the trough values is generally less than 0.2 cm/s, with a maximum of about 1 cm/s, observed at V1 during the storm, for corresponding significant orbital velocities about 25 cm/s. Thus, the waves can be reasonably considered as symmetrical. Only the crest orbital velocities were used for calculations.

The bed is mobile when the maximum grain related bed shear stress is higher than the critical bed shear stress (τ_{cr}), derived from equation (11), where θ_{cr}, the threshold Shields parameter is obtained using SOULSBY´S (1997) formula:

$$\theta_{cr} = 0.30/(1+1.2D) + 0.055[1\text{-}\exp(\text{-}0.02D)] \quad (13)$$

where D is the dimensionless grain-size:

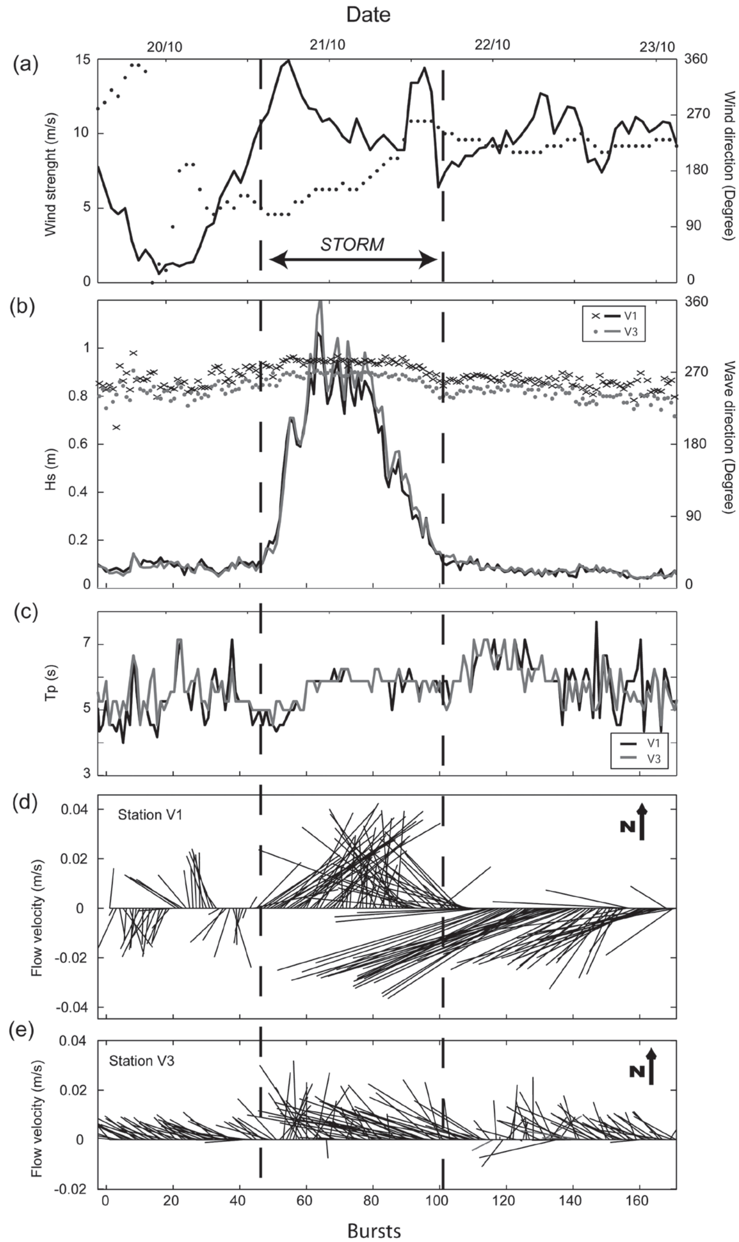


Figure 3. Wind and hydrodynamic conditions during the experiment; (a) wind strength (line) and direction (reported from which it originates, with dots); (b) significant wave height (line) and direction of advance (marks) at both stations (V1: black line and crosses; V3: grey line and dots); (c) Wave peak period at both stations (V1: black; V3: grey); (d) stick plot of the averaged currents at station V1; e) stick plot of the averaged currents at station V3.

Table 1. *Statistical grain-size parameters and descriptive terms after McMANUS (1988).*

Sample	**d_{50}**	**Classification**	**Sorting**	**Skewness**	**Kurtosis**
V1 bed	0.5mm	coarse/medium sand	moderately sorted (0.84)	positively skewed (0.08)	leptokurtic (1.2)
V3 bed	0.34mm	medium sand	well-sorted (0.46)	Symmetrical (-0.03)	mesokurtic (0.98)
V1 trap	0.1mm	very fine sand	poorly sorted (1.21)	symmetrical (-0.07)	leptokurtic (1.19)
V3 trap	0.07mm	very fine sand	poorly sorted (1.43)	symmetrical (-0.09)	leptokurtic (1.24)

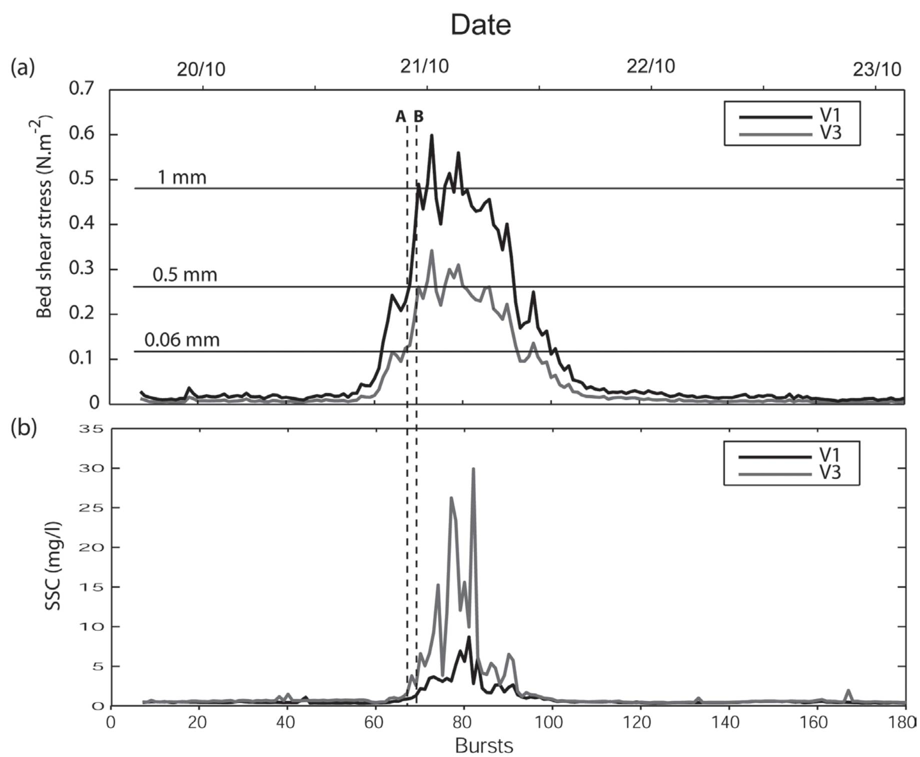


Figure 4. (a) bed shear stress at V1 (black) and V3 (grey), and threshold of motion for grain-sizes of 0.06, 0.5 and 0.1 mm; (b) observed SSC (mg/l). Lines A and B indicate the beginning of the SSC peak at V3 and V1, respectively.

$$D = d_{50}\ [g(s\text{-}1)/\upsilon^2]^{1/3} \tag{14}$$

with υ, the kinematic viscosity ($1.36.10^{-6}$ m^2/s).

RESULTS

From the morning of October 20th, an easterly to south-easterly wind was recorded at Kap Arkona, with an increasing strength peaking at 15 m/s in the afternoon (Figure 3a). Stormy waves, with a saw-toothed significant height signal, up to 1.2 m, were generated inside the bay (Figure 3b). About midday of October 21st, a still strong (about 10 ms/) southwesterly to westerly wind sets in, until the end of the deployment period. The change in wind direction induced a rapid decrease in wave activity, due to the sheltering effect of the coast. During the 26 hours-long storm, the peak period remained fairly constant, about 6 sec, typical of locally generated waves (Figure 3c). The waves were directed towards the west during the whole experiment (Figure 3b). In agreement, coincident side-scan sonar records displayed symmetrical ripples, with ~N-S crest orientation, over the sandy patches and inside the pits (Manso *et al.*, this volume). A systematic slight angle between the wave direction at stations V1 and V3 can be observed. This is attributed to refraction due to changes in bathymetry nearby the pit.

The currents present significant differences inside and outside the pit. At the outer station V1, the flow is about 2, 5 and up to 8 cm/s before, during and after the storm, respectively (Figure 3d). The direction of the flow shows no relation to the waves and wind, suggesting a complicated pattern of water circulation in the bay (this circulation is probably induced mainly by the wind, which pushes the water in or out of the bay). The flow is towards the NE at the beginning of the storm, and then rotates anticlockwise, to the SW, after the storm (Figure 3d). In contrast, the flow recorded at station V3, inside the pit, is weaker, with peak velocities up to 3 cm/s, during the storm (Figure 3e). Apart from short periods of time, its direction is almost constantly towards the NW. This indicates a decoupling of the flow inside and outside the pit, as previously observed by Klein (2003). Nevertheless, the flow orientations inside and outside the pit are better correlated during the storm. Thus, the pit hydrodynamics appears to relate as well to the wind-driven water circulation in the bay during extended periods of strong easterly winds.

The statistical grain-size parameters of the sediment sampled near the ABLs and collected in the traps are displayed in Table 1. Bed sediments are finer (d_{50}=0.34 mm) and better sorted inside the pit (V3), compared to station V1 (d_{50}= 0.5mm). The sediments in the traps consist of poorly-sorted fine sand, with d_{50}=0.1 and 0.07 mm at stations V1 and V3, respectively. In addition, much more sediments were found in the trap attached to V3 (80% of the relative percentage, in weight).

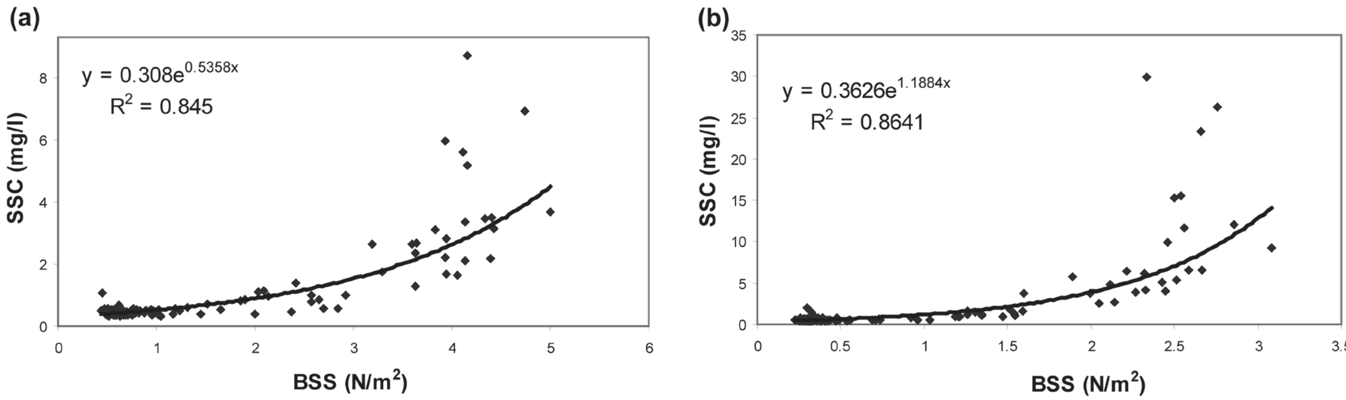


Figure 5. Predicted bed shear stress versus observed SSC, at stations V1 (a) and V3 (b).

During the storm, the predicted (grain related) bed shear stress exceeds the threshold of motion for grain-size up to 1 mm at station V1, and up to 0.5 mm at station V3 (Figure 4a). These grain-sizes correspond to 85% and 90% in weight of the entire grain-size distribution, at V1 and V3, respectively. Thus, most of the sand fraction was mobile at the studied sites during the storm. Peaks in the SSC signal are observed at V1 and V3, from a similar background value, simultaneously with the increase in bed shear stress (Figure 4b). Higher maximum concentrations were noticed inside the pit (~30 mg/l) than outside (~8 mg/l), despite a higher predicted bed shear stress at the outer station. In addition, the SSC inside the pit started to raise for a bed shear stress of ~0.12 N.m^{-2}, i.e. just after the threshold of motion for very fine sand (0.06 mm) was reached (Figure 4). By contrast, at V1, the SSC peak started half an hour later, for bed shear stress values about 4 times larger (~0.4 N.m^{-2}), when a much larger fraction of sediments was already remobilized. Relatively good correlations are observed between bed shear stress and SSC (Figure 5), with best fit lines which follow exponential law equations. However, large discrepancies are observed for high values (of the bed shear stress and SSC), i.e. during the storm.

DISCUSSION

OBS measurements are highly influenced by both the number of particles and the particle size (Xu, 1997). Thus, the differences in SSC values, observed at V1 and V3 during the storm (Figure 4b), can be explained by the presence of finer bed sediment inside than outside the pit, rather than advection from the surroundings. The presence of finer median grain diameter of the bed and trapped material at V3, compared with V1, supports this view (Table 1.); likewise, the relative volume of sediment collected inside the traps was greater inside the pit. In agreement, the SSC at V3 started to increase while the threshold of motion for very fine sand is exceeded (Figure 4). Although at a greater depth, the fines at the bottom of the pit require a relatively lower bed shear stress in order to be uplifted. In turn, they are more easily maintained in suspension, due to slower settling velocities. As an example, the settling velocity (W_s) of the sediment found in the traps (referred hereafter with the subscript 's') are determined using Soulsby's (1997) equation for natural sand:

$$W_s = (\upsilon / d_{50s})[(10.36^2 + 1.049D_s^{\ 3})^{0.5} - 10.36] \qquad (15)$$

The resulting settling velocity is twice as fast at V1 (5.6 mm/s) than at V3 (2.8 mm/s). Approximately, sediment is suspended when the settling velocity is slower than the skin friction velocity (U_{*s}), the latter being function of the square root of the bed shear stress:

$$U_{*s} = (\tau_{ws} / \rho)^{0.5} \qquad (16)$$

Thus, in our example, the trapped sediments at V3 require a much smaller (~4 times) bed shear stress than at V1 to remain in suspension. However, previous investigations in the area indicate that the fines inside the pit originate from the surrounding sandy patches, which material is remobilized during storms (Kubicki, Manso and Diesing, 2007; Diesing, 2003). Sediment advection might contribute partly to the SSC signal observed inside the pit during the storm.

Table 2. *Waves parameters used to predict suspended sediment concentration profiles.*

Storm	Date	Hs (m)	Tz (seconds)	Uws (m/s)	As (m)	Hrs (cm)	Lrs (cm)	Origin of the data
Mild	20/10/2004	1.3	5.4	0.19* (measured=0.2)	0.17*	3.3*	18*	This study
Severe	20/03/2001	3.1	6	0.59*	0.57*	7*(1)	40*(1)	Klein (2003)
Extreme	13/02/2005	4.3	6.7	1*	1.07*	12*	85(2)	BSH+

(*) predicted values (measured otherwise); (1) for d=0.34mm; (2) from side-scan sonar imagery; (+) period 2003-2006, 0-90° quadrant.

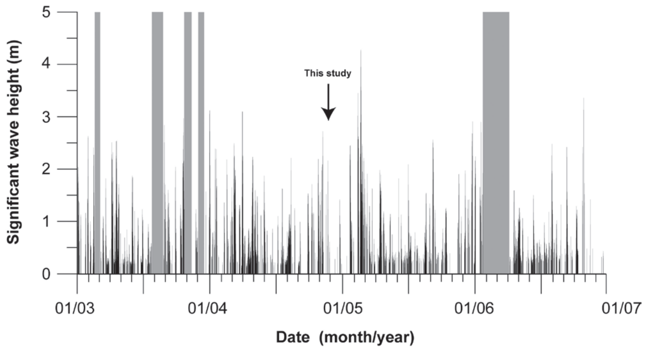


Figure 6. Significant wave heights from the 0-90o quadrant in Tromper Wiek; the periods without records are indicated in grey.

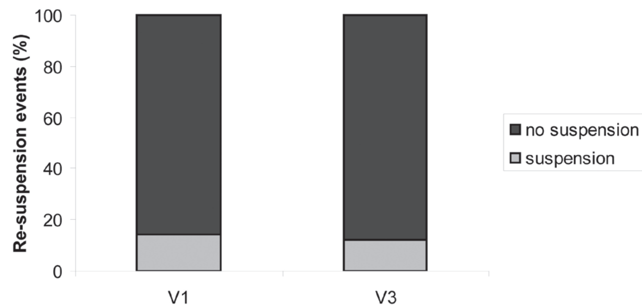


Figure 7. Percentage of sediment re-suspension events at stations V1 and V3, between 2003 and 2006; explanations in the text.

Based upon the relation between predicted bed shear stress and SSC (Figure 5), the historical waves were used to quantify the relative number of sediment re-suspension events, during the years 2003 to 2006. Due to some periods without data, the entire original dataset represents ~37 months-long (30min-averaged) continuous records. Only the waves from the 0-90° quadrant were considered, to account for the sheltering effect of the coast. The significant wave heights are presented in Figure 6.

As mentioned previously, storm events predominate between February and May (note the extreme storm which occurred in February 2005 (Hs>4 m) and the data gap during winter 2006). The bed shear stress has been predicted, based upon the model described previously, and compared to the threshold for sediment re-suspension observed inside and outside the pit (0.12 $N.m^{-2}$ and 0.4 $N.m^{-2}$, respectively) (see Figure 4). This approach documents the percentage of (wave induced) sediment re-suspension events, at 0.45 m above the bed (i.e. height of the sensor), during the 37 months-long period. Results show negligible differences inside and outside the pit (Figure 7).

Sediment re-suspension is predicted to take place during 14.3% and 12.4% of the time, at V1 and V3, respectively. These values represent less than 5.3 months of the (37 months-long) period, confirming the low intensity of the hydrodynamic activity inside the bay. Bed sediment are relatively rarely re-suspended by waves. A slow refilling of the dredged gravel pits is predicted. Towards the assessment of pits' recovery rate, it would be of interest to quantify the concentration of re-suspended sediments. This has not been done here, due to the poor relation obtained between high values of bed shear stress and SSC (Figure 5).

From the echo intensity of ADCP records, KLEIN (2003) proposed that waves may re-suspend bed sediment above the rim of the pits, allowing some material to be episodically removed and redistributed over the shallower surroundings. To test this scenario, vertical concentration profiles were computed, inside the crater (i.e. at 14.5 m water depth) for various wave

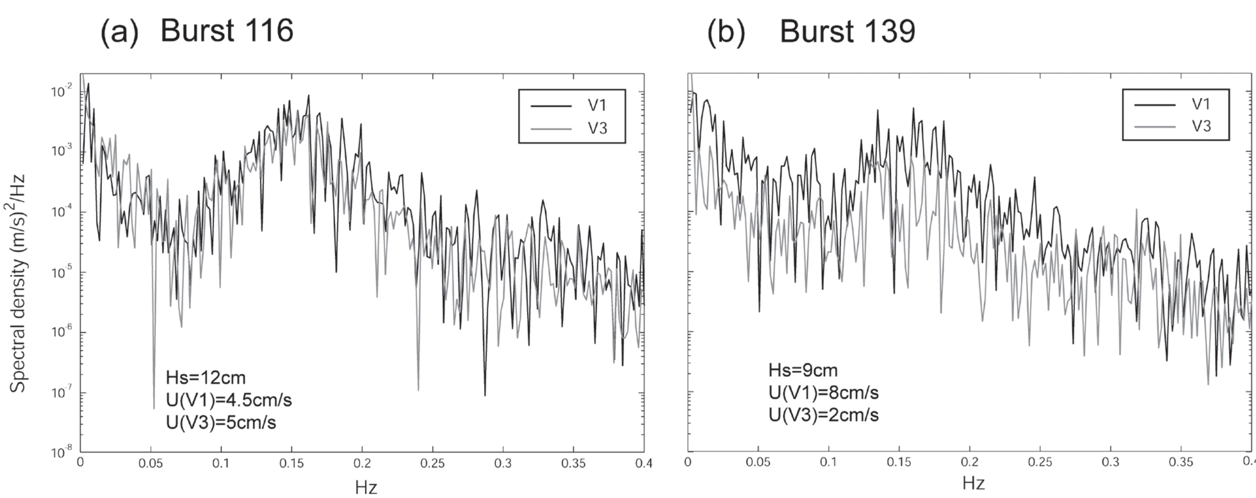


Figure 9. Semi-log plot of the flow magnitude spectrum for bursts 116 (a) and 139 (b).

conditions, referred to mild, severe and extreme storm, hereafter (see Table 2.).

For weak currents (<0.1 m/s), the SSC profile induced by waves only is similar to the one induced by combined waves and currents (VAN RIJN, 1993). Thus, only the time-average wave-induced SSC over rippled beds was modeled, using NIELSEN'S (1992) equation:

$$C(z) = C_o e^{-Z/l} \quad (17)$$

Since $U_{ws}/W_s > 18$, the vertical scale (l) corresponds to:

$$l = 1.4H_r \quad (18)$$

The reference concentration ($C_o=0.005\theta_r^3$) is obtained from the modified effective Shields parameter (θ_r):

$$\theta_r = (F_w U_{ws}^2)/[2(s-1)gd_{50}(1-\pi H_r/L_r)^2] \quad (19)$$

The significant wave orbital velocity, U_{ws}, is estimated from:

$$U_{ws} = \pi H_s/[T_p \sinh(kh)] \quad (20)$$

where sinh is the hyperbolic sine, h, the water depth, k, the wave number (2π/L), and L, the wavelength. Comparisons show very little differences between the wave orbital velocities measured in the present study, and the ones derived from equation (19) (see mild storm, in Table 2.). Equation (17) applies to uniform bed material. For graded bottom sediment, such in the present study, the median grain diameter of the sediment in suspension will be appreciably finer than the one at the bed. In this case, as noted by SOULSBY (1997), reliable methods of predicting sediment concentration profiles under waves are not available yet. In the present model, the situation was simplified by considering a uniform bed, where the median grain diameter relates to the sediment trapped at V3 (i.e. 0.07 mm), rather than to the bed material. The objective is to test a favored case for sediment re-suspension, rather than to aim at accurate predictions. Since the suspended sediment concentration profile is very sensitive to the grain settling velocity, the model predictions are enhanced in comparison with those based upon the bed material. Likewise, ripples have been imposed to the model, to enhance the upwards sediment diffusion: for mild and severe storms, the ripple dimension has been predicted using equations (8) and (9); for extreme storms, it corresponds to large bedforms, as observed with side-scan sonar (MANSO *et al.*, this volume) (although sheet flow conditions are easily met during severe storms, for such fine sediment). The Nielsen's calibration constant (0.005) seems appropriate to compute the reference concentration (C_o), since it is derived from measurements over rippled beds and sheet flow conditions, with sand diameters between 0.08 and 0.55 mm, and wave periods between 1.0 and 9.1 sec (NIELSEN, 1986). The model fails to re-suspended material above the rim of the crater, under these optimized conditions (Figure 8). Then, it is unlikely that the bed sediment inside the pit is extracted due to the action of the waves alone, even during extreme storm events. If some sand is naturally extracted out of this pit, another process has to be considered.

Flow separation and reversal in the near-bed layer, due to adverse pressure gradients, is observed for pits with slopes of 1:5, or steeper (ALFRINK and VAN RIJN, 1983). This effect generates additional turbulence energy which may considerably reduce the settling process, and therefore, enhance the concentration of suspended material. With computed slopes of about 1:3, flow separation may take place in the studied pit. The spectral density of the flow magnitude was computed for bursts corresponding to the fastest flow and lower wave activity during the experiment, at V1 and V3 (i.e. for bursts when flow separation is expected to be the most pronounced). In the case of significant flow separation inside the pit, the flow magnitude spectra at V3 should comprise additional (high frequency) energy in comparison with V1. The results show energy peaks which correspond to the sea wave frequencies, but no significant difference is observed between V1 and V3 (Figure 9). Obviously, the current recorded during our survey were too weak to be significantly affected by the morphology (~3 cm/s, at maximum, inside the pit). The fastest currents measured by KLEIN (2003) at the bottom of the pit, in March and April 2001, were less than 8 cm/s (and only ~4 cm/s during the severe storm of March 2001). Based upon these observations, storms are not associated with stronger bottom currents. Thus, flow separation has probably a reduced effect, if any, on the suspended sediment concentration profile in the dredged pits.

Dredged pits have minimal impacts upon (regional) sediment transport patterns if their bottom (fine) sediments are frequently extracted by waves' action. At a yearly scale, extreme stormy waves are too rare in the bay for frequent redistribution of these fines over the area. During the more common severe storms, significant amount of (very fine) sand are uplifted at ~1 m above a bottom lying at 14.5 m water depth (Figure 8). In other words, the model predicts frequent material removal out of ~1 m-deep pits, or less, at ~13.5 m water depth. As pointed out before, the predicted SSC profiles correspond to optimal conditions, and are therefore over-estimated. Thus, bed sediments are probably long-termed (years) trapped in pits more than 1 m-deep, with bottom at 14.5 m water depth. At this water depth, the maximum depth of excavation, for frequent wave-induced sediment extraction, is very shallow, estimated less than 1 m.

CONCLUSION

Hydrodynamic measurements were carried out at Tromper Wiek, close to the bottom of a 3.5 m-deep dredged gravel pit (14.5 m water depth), and at a shallower nearby patch of sand (11 m water depth). Our investigations confirm the generally weak sediment dynamics, governed by the waves' activity. It is estimated that sediment re-suspension events are observed, at 0.45 m above the bed, during ~5 months over a 37 months-long period (i.e. less than 15% of the time), without significant difference inside and outside the pit. During a moderate storm (Hs up to 1.2 m), most of the sand fraction was remobilized, including inside the pit. There, bed sediments are finer than at the surroundings sandy patches. They are therefore easier to uplift, resulting in relatively stronger SSC. However, it is unlikely that these fines are re-suspended high enough to be removed out of the pit, even during historical extreme storm events (Hs=5.1 m). We suggest that pits at 13-14 m water depth should be very shallow (<1 m-deep) for the fines to be frequently redistributed over the area. Dredged pits are generally much deeper (e.g. MANSO *et al.*, this volume). Thus, fine sediments located in dredged pits at 14.5 m water depth, or deeper, are probably trapped over the long-term (years).

The estimation of reliable (dredged pits) recovery rate is fundamental to carry out comprehensive environmental impact assessments. Towards this objective, numerical models must be calibrated by field observations, in order to quantify accurately sediment re-suspension events under various wave conditions. For further studies, detailed investigations of the suspended sediment composition and concentration, inside dredged pits, are recommended.

ACKNOWLEDGMENTS

This work was undertaken as part of the EUMARSAND Research Training Network (European Sand and Gravel Resources: Evaluation and Environmental Impact of Extraction, HPRN-CT-2002-00222). The help of the officers and crew of the research vessel R/V *Alkor* in collecting the data is gratefully acknowledged. Thanks are extended to the German Weather Forecast Agency and BSH (Federal Maritime and Hydrographic Agency) for providing meteorological and wave data. The helpful comments of the reviewers are gratefully acknowledged.

LITERATURE CITED

Alfrink, B.J. and Van Rijn, L.C., 1983. Two-equation turbulence model for flow in trenches. *Journal of Hydraulics Division*, ASCE, 109(3), 941-957.

Boers, M., 2005. Effects of a deep sand extraction pit. *Final report of the PUTMOR measurements at the Lowered Dump Site*, Ministerie van Verkeer en Waterstaat, 87p.

Boyd, S.E.; Limpenny, D.S.; Rees, H.L., and Cooper, K.M., 2005. The effects of marine sand and gravel extraction on the macrobenthos at a commercial dredging site (results 6 years post-dredging). *ICES Journal of Marine Science*, 62, 145-162.

Diesing, M., 2003. Die Regeneration von Materialentnahmestellen in der südwestlichen Ostsee unter besonderer Berücksichtigung der rezenten Sedimentdynamik. Christian-Albrechts-Universität zu Kiel, Ph.D. thesis, 158 p. (http://e-diss.uni-kiel.de/diss_755/)

Diesing, M.; Schwarzer, K.; Zeiler, M., and Klein, H., 2006. Comparison of marine sediment extraction sites by means of shoreface zonation. *Journal of Coastal Research*, Special Issue, 39, 783-788.

Figge, K.; Zeiler, M.; Griewatsch, K.; Mittelstaedt, E.; Klein, H.; Schwarzer, K., and Diesing, M., 2002. KFKI-Projekt Regenerierung von Materialentnahmestellen in Nord-und Ostee. *Final Report, Bundesamt für Seeschiffahrt und Hydrographie*, 94p.

ICES, 2001. *Effects of extraction of marine sediments on the marine ecosystem*. WG-EXT. Copenhagen, International Council for the Exploration of the Sea (ICES), 247, 80p.

Kenny, A.J. and Rees, H.L., 1996. The effects of marine gravel extraction on the macrobenthos: results 2 years post-dredging. *Marine Pollution Bulletin,* 32(8/9), 615-622.

Klein, H., 2003. Investigating sediment re-mobilisation due to wave action by means of ADCP echo intensity data. Field data from the Tromper Wiek, western Baltic Sea. *Estuarine, Coastal and Shelf Science*, 58, 467-474.

Kortekaas, S.; Bagdanaviciute, I.; Gyssels, P.; Alonso Huerta, J.M., and Héquette, A., this volume. Assessment of the effects of marine aggregate extraction on the coastline: an example from the German Baltic Sea coast. *Journal of Coastal Research*.

Kubicki, A.; Manso, F., and Diesing, M., 2007. Morphological evolution of gravel and sand extraction pits, Tromper Wiek, Baltic Sea. *Estuarine, Coastal and Shelf Science*, 71, 647-656.

Manso, F.; Radzevičius, R.; Blažauskas, N.; Balay, A., and Schwarzer, K., this volume. Nearshore dredging on the Baltic Sea: sate after cessation of activities and regeneration assessment. *Journal of Coastal Research*.

McManus, J., 1988. Grain size determination and interpretation. *In*: Tucker, M. (ed.), *Techniques in Sedimentology*. Oxford, England: Blackwell Scientific Publications, pp. 63-85.

Mohrholz, V., 1998. Transport and mixing processes in the Pomeranian Bight. *Marine Science Reports*, 33, 106 p. (in German).

Nielsen, P., 1986. Suspended sediment concentrations under waves. *Coastal Engineering*, 10, 23-31.

Nielsen, P., 1992. Coastal bottom boundary layers and sediment transport. *Advanced Series on Ocean Engineering,* Vol. 4, Ed. World Scientific, 324 p.

Radzevičius, R.; Velegrakis, A.F.; Bonne, W.; Kortekaas, S.; Garel, E.; Blažauskas, N., and Asariotis, R., this volume. Marine aggregate extraction: regulation and management in EU member states. *Journal of Coastal Research*.

Soulsby, R L., 1997. *Dynamics of Marine Sands*. London: Thomas Telford Publications, 249 p.

Swart, D.H., 1974. Offshore sediment transport and equilibrium beach profiles. Delft Hydraulics Lab., Publ. 131p.

Tucker, M.J. and Pitt, E.G., 2001. *Waves in ocean engineering*. Elsevier, Amsterdam: Elsevier ocean engineering book series vol. 5, 521 p.

Van Rijn, L. C., 1993. Principles of sediment transport in rivers, estuaries and coastal seas. Amsterdam: Aqua Publications, 614 p.

Van Rijn, L. C.; Soulsby, R.L.; Hoekstra, P., and Davies, A.G. (eds.), 2005. *SANDPIT, Sand Transport and Morphology of Offshore Mining Pits*. The Netherlands: Aqua Publications, 716 p.

Xu, J.P., 1997. Converting near-bottom OBS measurements into suspended sediment concentrations. *Geo-Marine Letters*, 17, 154-161.

Zeiler, M.; Figge, K.; Griewatsch, K.; Diesing, M., and Schwarzer, K., 2004. Regenerierung von materialentnahmestellen in Nord- und Ostsee. *Die Kueste*, 68, 67-98.

Journal of Coastal Research	SI	51	205-214	West Palm Beach, Florida	Summer 2010

Assessment of the Effects of Marine Aggregate Extraction on the Coastline: an Example from the German Baltic Sea Coast

Stella Kortekaas[1*], Ingrida Bagdanaviciute[2], Paolo Gyssels[3], Jose M. Alonso Huerta[4] and Arnaud Héquette[1].

[1] Laboratoire d'Océanologie et de Géosciences
UMR CNRS 8187
Université du Littoral Côte d'Opale
32 Ave Foch
62930 Wimereux, France

[*] Present address: Fugro Engineers B.V.
Veurse Achterweg 10
2264 SG Leidschendam, The Netherlands
s.kortekaas@fugro.nl

[2] Coastal Research and Planning Institute
Klaipeda University
H. Manto 84, LT 92294
Klaipeda, Lithuania

[3] Tecnoconsult Engineering Construction S.r.l.
Strada Nazionale Adriatica Sud, 149
61032 Metaurilia di Fano (PU), Italy

[4] ALATEC Ingenieros
Consultores y Arquitectos
C/ José Echegaray 14
Parque Empresarial Las Rozas
28230 Las Rozas - Madrid, Spain

ABSTRACT

The German Baltic Sea coast between Warnemünde and Darss is rapidly eroding. In this area, extensive sand extraction takes place at water depths of 8-13 m, for both local beach nourishment and industrial use. Sand resources in the area are restricted to a layer of <2 m of Holocene sand, whilst contemporary input of sand is limited to erosion of the cliff sections. To investigate if sand extraction in this area has any effect on the coastline, bathymetric data from two particular time periods were compared, as well as the location of the coastline over 5 different years, ranging from 1953-2002. Waves and wave-induced sediment transport were simulated using the integrated coastal zone model, Sistema de Modelado Costero (SMC). Results indicate some primary areas of concern: small changes in bathymetry of approximately 10% are sufficient to cause significant modifications in sediment transport potential at the coast; and, thus, alternations in the patterns of erosion and accretion. Sediment transport by both wave action and currents, induced by the inflow of North Sea water, is in a NE direction towards Darss. Here, deposition takes place in a National Park, where dredging is prohibited. There is very little input of sediment in the system. Any sand that is removed by marine aggregate extraction, for industrial use, will have a negative effect on the total sediment budget at the shoreline.

ADDITIONAL INDEX WORDS: *dredging, sediment transport, integrated coastal zone model, Sistema de Modelado Costero (SMC), differential bathymetry, beach erosion.*

INTRODUCTION

Sand is extracted from the seabed for many uses, including the construction industry and beach nourishment. In response to increasing demand, more marine sand is extracted from the inner continental shelf (<60 m water depth) in Europe, every year. As such, concerns have been raised about the adverse effects on the coastal system, including ecology, the seabed and the adjacent shoreline. For example, the results of a questionnaire sent to local residents in South Wales, have shown that a vast majority believes that marine aggregate (MA) extraction is responsible for the increased rates of beach erosion at local beaches (Simons and Hollingham, 2001).

There are different ways in which offshore MA extraction may cause changes to the coastline. For example, Brampton and Evans (1998) identify 5 effects: (a) beach draw-down; (b) modifications to tidal currents; (c) changes in sediment transport; (d) variations in nearshore wave conditions; and (e) a reduction in shelter provided to the coastline. Many of these effects are interrelated (as discussed below). Nairn *et al.* (2004) suggest that shoreline changes occur in two ways: (i) an extraction site interrupts or modifies the sediment supply pathways to the coast, reducing the sediment budget at the shoreline; or (ii) modifications in wave transformation patterns change the character of the waves reaching the coast, altering sediment transport and, eventually, changing erosional and accretional patterns. The study of coastal impact of dredging is not straightforward and, as such, many different approaches have been adopted.

Extensive MA extraction takes place in the Baltic Sea, in the area between Warnemünde and Darss (Figure 1), for both beach nourishment purposes and industrial use (Krause, 1998). Two of the offshore extraction sites are located close to the coast, i.e. Graal Müritz and Wustrow; they are located in water depths of 8-12 and 11-13 m, respectively (Figures 1 and 2). Wave conditions and wave-induced sediment transport within the area of these extraction sites are investigated here, to assess if the dredging may impact upon the coast. Offshore bathymetry and the location of coastlines, over a number of years, were compared to study patterns of erosion and accretion. Waves (in the absence of tides) and sediment transport were modelled using Sistema de Modelado Costero (SMC), an integrated coastal zone model.

DOI: 10.2112 / SI51-019.1 received 13 January 2007; accepted in revision 2 April 2008.

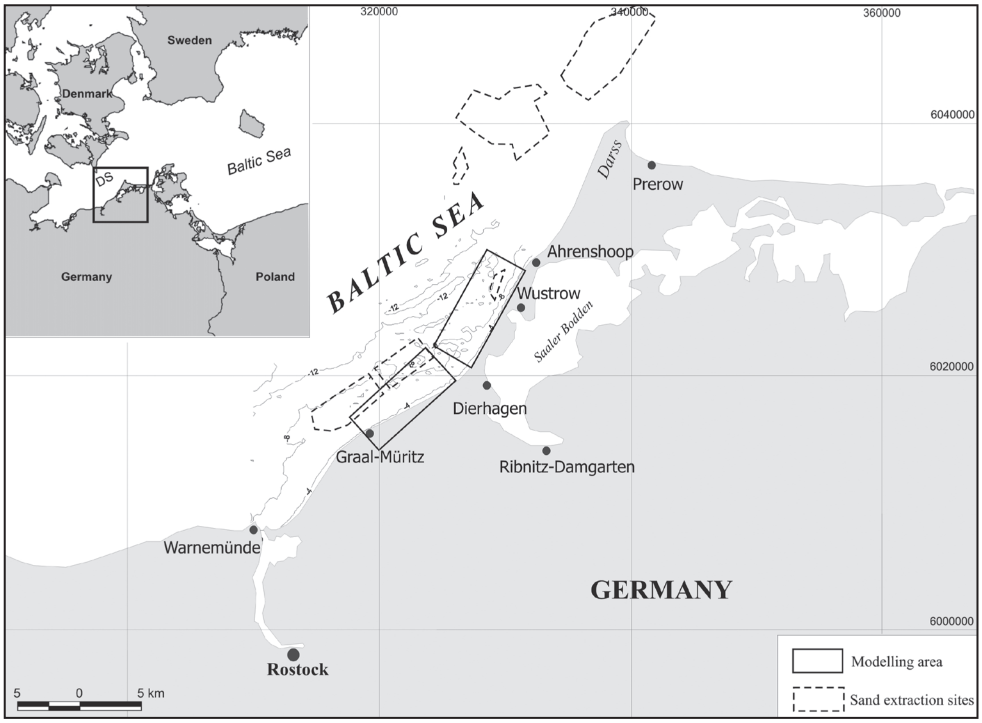


Figure 1. Location map, showing the major towns, extraction sites Graal Müritz and Wustrow, and the fine grids used for modelling. DS = Darss Sill.

EFFECTS OF MA EXTRACTION ON THE COASTLINE

Effects on Coastal Sediment Budget

The most direct effect of MA extraction on the coastline is beach draw-down; this may occur when material is extracted from within the active beach profile. Beach sand or gravel, transported seawards during storm events, remains trapped in the depression. It will not return to the upper beach during calm conditions, thus resulting in a net loss of beach material (Brampton and Evans, 1998). Beach draw-down was the cause of the destruction of the coastal village of Hallsands, Devon (UK), in 1917, where between 1897 and 1902 some 382,000 m^3 of gravel was extracted from the foreshore (Pearce, 1996; Simons and Hollingham, 2001).

Reduction in the sediment budget at the shoreline may occur also due to modification or interruption of the sediment supply pathways, towards the coast. Such a reduction may occur in two ways: dredging may remove sediment that would normally supply the beach; or an extraction site may trap sediment, which would otherwise have been transported towards the coast. The latter process is suggested to be the reason for the weak recovery of the Pakiri-Mangawhai coast in New Zealand, following storms in 1978. Although extraction in this area takes place within the surf zone, it has been impossible to prove a cause-effect relationship between sand extraction and backshore stability (Hilton and Hesp, 1996). Anctil and Ouellet (1990) have calculated littoral drift changes for three dredging scenarios in Quebec (Canada) and found that only excavation at the sea bed of 2 m or more in depth had a significant impact on sediment transport. These investigations have concluded that the coastal impact can be limited, by gradually changing the bathymetry, leaving the system sufficient time to adjust. This outcome is achievable by preventing multiple dredging over the same area.

Effects on Waves and Currents

Modification of the bathymetry may alter nearshore wave conditions, by changing the wave refraction patterns; hence, the wave direction, or the total wave energy, reaching the coast. Since breaking waves are generally considered to be the dominant factor affecting the coast, Maa, Hobbs, and Hardaway (2001); Maa *et al.* (2004) have used the change in breaking wave height to assess the coastal impact of changing wave transformation, caused by extraction. Even though the local wave height between the extraction site and the coast can increase by as much as two-fold, the change in the breaking wave height is less significant, as most of the wave energy is dissipated before the waves reach the shore (Byrnes *et al.,* 2004a; Maa *et al.,* 2004). However, in areas with a steep shoreface, the wave energy does not dissipate significantly and, instead, increases considerably upon reaching the coast (Byrnes *et al.,* 2004b). For example, at Grand Isle, Louisiana (USA), two large salients and areas of increased erosion developed shoreward of an offshore extraction site that was situated some 800 m offshore, in a water depth of 4.6 m (Bender and Dean, 2003). The extraction pit affected the wave propagation pattern, which, in turn, caused changes in erosion and accretion at the coast.

Maa and Hobbs (1998) have examined longshore sediment transport, using breaking wave conditions, calculated from modelled wave transformation processes. The model results

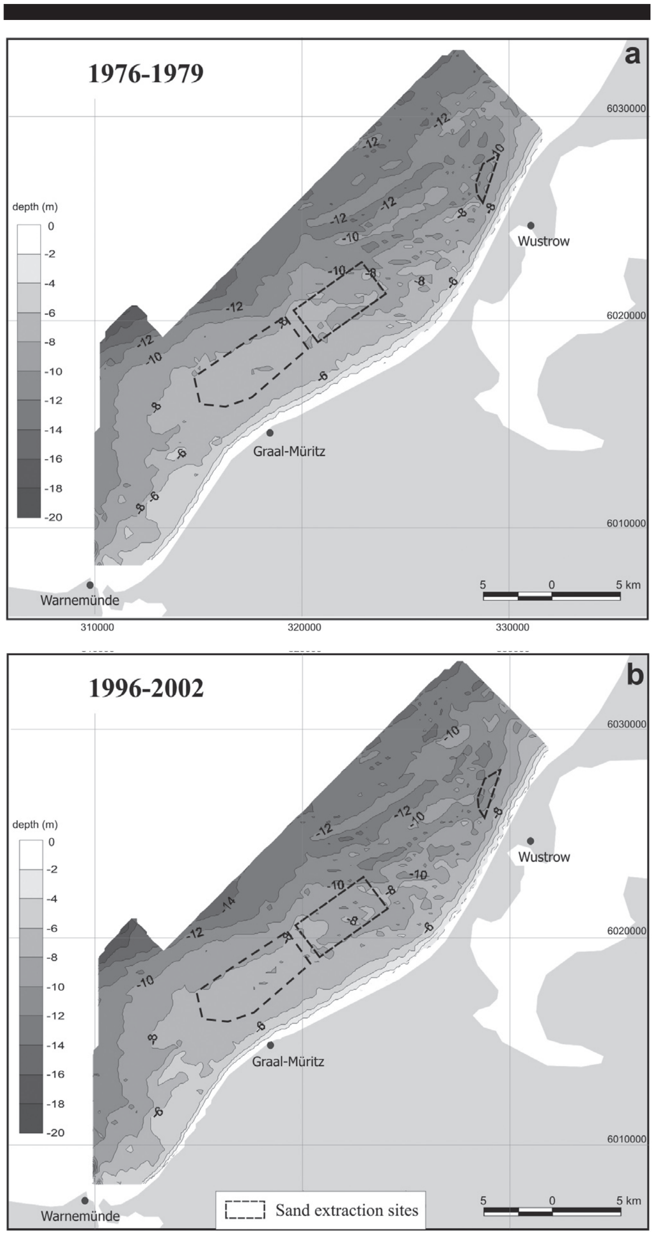


Figure 2. Bathymetry of (a) 1976-1979 and (b) 1998-2002, with the extraction sites indicated.

showed considerable natural wave energy convergence, which could be responsible for severe beach erosion over the same area. However, the dredging effects on wave transformation and longshore sediment transport were found to be insignificant. Kelley, Ramsey, and Byrnes (2004) developed a new approach for evaluating the coastal impact of an extraction site, incorporating natural spatial and temporal variability in the wave climate, as the basis for determining the level of significance. A coast with a natural high variety of wave conditions and, consequently, sediment transport will be less sensitive to wave modifications caused by dredging, than a coast with a limited range of wave conditions.

Wave conditions at the shoreline may change also as a result of dredging of nearshore sandbanks, reducing the shelter provided to the coastline. The disappearance, or lowering, of the bank will change the wave patterns between the bank and the coast; this, in turn, will cause changes in sediment transport and, hence, erosion and accretion patterns at the shoreline (Hayes and Nairn, 2004). An example is the 1996 beach nourishment project undertaken in Martin County, Florida (USA), where sand was extracted from a shoal located some 910 m offshore, in a water depth of 12.8 m. By lowering the shoal height, the coast was exposed to increased wave action, resulting in localised erosion (Bender and Dean, 2003). Similarly, sand extraction from a large shore-parallel shoal, located 10 km offshore of the coast of Louisiana, USA, would increase erosion and overwash on the adjacent shoreline (Suter, Mossa, and Penland, 1989).

The effects on tidal currents are, typically, limited and very localised. For example, Maa *et al.* (2004) modelled the influence of dredging of two shoals offshore of Maryland and Delaware (USA), on the tidal currents. The results showed only small changes in the maximum near-bed tidal current velocity at the shoals, indicating only a negligible impact. Elsewhere, Byrnes *et al.* (2004a) found that, whilst the extraction at sites offshore from Alabama (USA) could produce a localised effect on the currents, there was no impact upon the prevailing or ambient flow characteristics.

SITE DESCRIPTION

The German Baltic Sea coast is a micro-tidal area, with a negligible tidal range. The study area is situated between Warnemünde and Ahrenshoop (Figure 1). The shoreline in this area consists of narrow beaches, with dunes and cliffs of Pleistocene deposits (Lampe, 2002). The main source of sediment in the coastal zone is retreating cliff sections. Sediment input from rivers is negligible. The slow-flowing Warnow River drains into the Baltic Sea at Warnemünde, but its sediment discharge consists mainly of suspended fines. The coastal zone here is experiencing long-term erosion, with an average coastal retreat varying from 30-70 m/100 years, over the last 160 years (Janke and Lampe, 1998). In order to maintain the beaches, sand has been extracted offshore for beach nourishment projects, since 1968. Besides beach and dune nourishment, a wide range of shore protection structures have been installed, e.g. groynes, breakwaters and dykes, to reduce coastal erosion. In this study, two sediment extraction sites are considered, which are located close to the coast: Graal-Müritz and Wustrow (Figure 1).

The offshore area is characterised by the Darss Sill (Figure 1). Approximately 73 % of the water exchange between the Baltic Sea and the North Sea is through this relatively shallow, narrow strait. The seafloor consists of glacial till, overlain by a thin layer (<30 cm) of lag deposits which, in turn, is covered, over a small part of the area, by Holocene marine sand (Lemke *et al.,* 1994). In the area of Graal-Müritz, the overlying marine sand has a maximum thickness of 1.1 m (Diesing, 2003). NNW-SSE oriented sandwaves, with heights of up to 2.7 m and a wavelength of approximately 180 m, are present in this area. Within their troughs, coarse lag sediments are exposed (Diesing, 2003). The extraction site of Graal-Müritz is located some 2.5-5.5 km offshore, within a water depth of

8-12 m. Extraction at this site has taken place since 1988 (Diesing, 2003). The Wustrow extraction site is located about 1 km off the coast, near Wustrow, in a water depth of 11-13 m. Sand has been extracted here, for beach nourishment projects, since 1997. The mean thickness of the overlying marine sand, in this area, is 1.9 m (Krause, 2002). For extraction at both sites, a trailer suction hopper dredger is used; this creates shallow (ca. 0.5 m deep) furrows on the seafloor, which have widths of 3-10 m and lengths of up to 1 km (Diesing, 2003; Manso *et al.,* this volume).

The bathymetry of the extended offshore area (Warnemünde to Ahrenshoop) shows that the nearshore zone (<10 m water depth) becomes narrower towards the north (Figure 2). Whilst the 10 m depth contour is located approximately 10 km offshore of Graal-Müritz, it is only 2.5 km away from the coast at Wustrow. Large offshore sandbanks are present within this area, oriented obliquely to the coast (Figure 2).

METHODOLOGY AND DATA

Bathymetric Data

Bathymetry relating to two different time periods was compared: 1976-1979 (before dredging) and 1996-2002 (after dredging). The data were obtained from the BSH (Bundesamt für Seeschifffahrt und Hydrographie = Federal Maritime and Hydrographic Agency), Germany. It was necessary to use data sets derived from multiple surveys, undertaken over several years, because no survey covered the complete area, within any particular year. The horizontal error of the older data set is about 20 m + 5% of the depth; for the recent data set, it is about 5 m + 5% of the depth. The vertical error is highly dependent upon water depth; it ranges from 0.50-0.56 m and 1.00-1.10 m for the new and old bathymetry data sets, respectively (IHO, 1998; MONK, 2005 pers. comm.).

Aerial Photographs

In order to compare the location of the coastline, over time, aerial photos were used. Sets of photos from 4 different years (1953, 1980, 1994 and 1998), together with a set of orthophotos (2002), were obtained from the Landesvermessungsamt, Mecklenburg-Vorpommern, Germany (Table 1). The aerial photos were scanned and rectified, using the orthophotos (with a resolution of 8 dm) and the software ER-Mapper 6.4. The rectification error was maintained at less than 1 m, for most of the photos. However, for some of the photos, especially the older ones, this was not possible; as such, the error could extend up to 2 m. When taking into account the resolution of the orthophotos of 8 dm, together with the size of the pixels of the scanned aerial photos of about 1.5 m, the maximum total error may have been about 4 m. Following rectification, mosaics were created and the coastlines from different years were digitised and compiled in a GIS database (ArcView).

Wave and Sediment Transport Modelling

In this study, the software Sistema de Modelado Costero (SMC), translated as Coastal Modelling System, has been used to simulate wave propagation, as well as the currents induced and sediment transport in the coastal area of Graal-Müritz and Wustrow. SMC was developed by the Coastal Engineering and Oceanography Group (G.I.O.C., 2002), of the University of Cantabria, in collaboration with the Coastal and Environmental Department of the Spanish Government. SMC includes different modules and numerical implementation, to assist in coastal dynamics studies; it utilises the parabolic solution of the mild-slope equations (Kirby and Dalrymple, 1983), for wave propagation. The software allows the simulation of monochromatic or spectral waves from deep waters, to the coast. In each case, wave-induced currents and potential sediment transport can be obtained. Sediment transport is computed from the previously obtained wave and current fields, using the formulae of Bailard (1981) and Soulsby (1997). Both methods compute the total sediment transport, taking into account bed load and suspended load transport.

Table 1. *Year, number and scale of the aerial photographs used to study coastline changes.*

Date	Number of aerial photographs	Scale
1953	9	1:22000
1988	16	1:18000
1994	20	1:12500
1998	23	1:12500
2002	47 (ortho-photos)	pixel size: 8 dm

Two areas were selected for modelling: Graal-Müritz and Wustrow. For both areas, two coarse offshore grids (300 x 300 m) were established for the different wave directions, each with a fine grid (15 x 30 m) attached, for the nearshore area. Monochromatic waves were used in the model.

Wave Climate

The NNW-WNW-facing coast, between Warnemünde and Ahrenshoop, is a fetch-limited coastline and is sheltered from waves coming from the Baltic Sea, to the east (Figure 1). A continuous five-year record (1998-2002) of directional wave data, measured every hour, was available from a measuring station located close to Ahrenshoop. Over this period, the dominant wave direction was from W-WNW, with more than 65 % of all waves originating from this direction (Figure 3 and Table 2). Large storm waves originate, typically, from a WNW direction.

Table 2. *Proportion of all waves with Hs >0.2 m in different directions.*

Direction	N	NNW	NW	WNW	W	WSW
Percentage	9.95	8.42	4.99	23.70	41.60	8.97

For the wave modelling, five "wave cases" were selected, corresponding to two different directions. The most common wave condition is represented by a significant wave height (Hs) of 0.68 m, a period (Tm) of 4.64 s and a direction (Dir) of 276°. Within this context, long period swell waves in this area have a direction of 347°, a wave height of 0.31 m and a period of 6.09 s. For completeness, locally-generated wind waves from this direction were also simulated; these have a wave height of 0.56 m and a period of 4.44 s. Furthermore, an average yearly storm wave (Hs 1.29 m, Tm 5.77 s, Dir 276°) and the average 5-yearly storm wave (Hs 1.40 m, Tm 6.00 s, Dir 276°) were modelled (Table 3). Because most sediment transport takes place during storm conditions, the results of the latter will be discussed in detail.

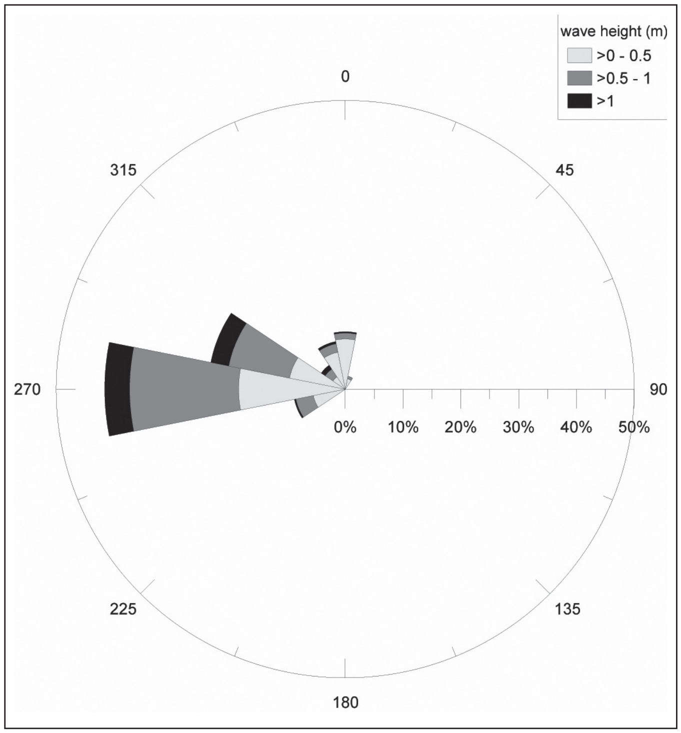


Figure 3. Distribution of wave directions and wave height, from measurements obtained at the StAUN Messnetz station at Ahrenshoop, for the period 1998-2002.

Table 3. *Parameters of the modelled wave conditions (significant wave height, mean period and wave direction).*

Wave cases	Hs (m)	Tm (s)	Dir (°)
Local waves 1	0.68	4.64	276
Local waves 2	0.56	4.44	347
Swell	0.31	6.09	347
Storm (1y)	1.29	5.77	276
Storm (5y)	1.40	6.00	276

RESULTS

Bathymetry

Bathymetric changes between 1976-1979 and 1996-2002 are subtle (Figure 4) and, in general, lie within the range of the maximum vertical error of the bathymetry (around ± 1 m). The highest rate of seabed erosion (4.5 m, in ca. 20 years) can be found in a small area close to the extraction site of Wustrow. The broad shallow zone (<10 m), offshore of Graal-Müritz is stable, typically showing no change. In general, accretion takes place in the coastal zone close to the Wustrow coast; erosion occurs in the offshore area to the NE of Graal-Müritz (Figure 4).

Coastline

The location of the coastline has fluctuated considerably between 1953 and 2002. Comparing the 1953 and 2002 coastlines, two areas of maximum erosion (of up to 3 m per year) can be identified: the coast to the south of Graal Müritz, and the Darss area (Figure 5). However, a maximum accretion of 3-5 m per year takes place at the northerly tip of the Darss Peninsula, immediately to the north of the rapidly-eroding Darss coast (Figure 6). In general, the coastline from the south of Graal-Müritz to Dierhagen is mainly erosional, except for a small section of prograding coastline, lying close to the town of Graal-Müritz. This accretional zone is located in an area where repeated beach nourishment has been undertaken (MBLU, 1995). The coast from Dierhagen to Wustrow has experienced, overall, a small amount of accretion; whilst, from the north of Wustrow up to Darss, an overall erosional trend was observed.

The extensive coastal protection works, including groynes, breakwaters and beach nourishment projects, make it difficult to distinguish (from the aerial photographs) the natural trend in shoreline evolution. For example, the two large accretional peaks near Wustrow and Ahrenshoop (Figure 5) are associated with the breakwater construction in 1985 and 1986, respectively. Subsequently, considerable accretion has taken place on the lee side of these breakwaters.

Wave and sediment transport modelling

The results of the simulation of WNW storm waves show that they focus upon particular areas of the coastline, as a result of the offshore bathymetry. The subtle differences between the old and new bathymetry cause also small changes in the nearshore wave conditions (Figure 7). Within the Graal-Müritz area, the offshore wave height has increased; however, most of the energy dissipates before the waves reach the shore (Figure 7). The changes in the Wustrow area are most

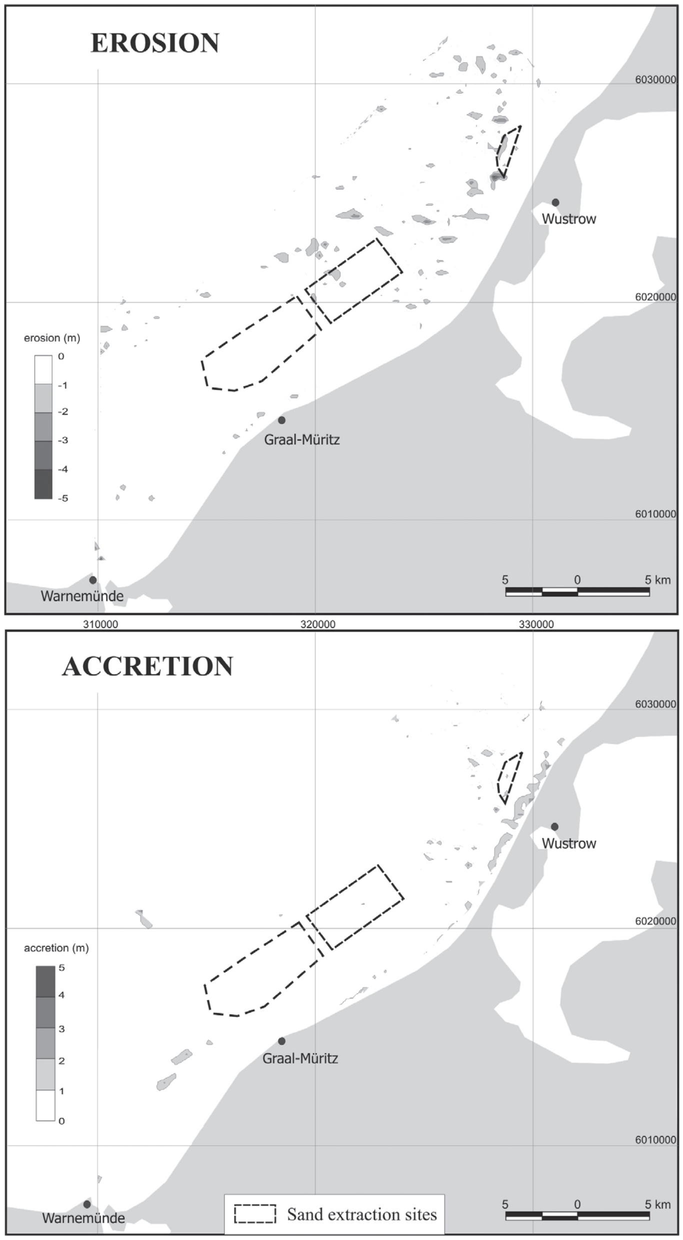


Figure 4. Comparison of the bathymetry of 1976-1979 and 1998-2002, showing areas of erosion and accretion. Corresponding to a maximum vertical error of ca. 1 m, the changes from 1 m and more are indicated. The largest erosion of almost 5 m is found directly to the SW of the Wustrow extraction site.

pronounced at the extraction site, where wave heights have increased.

Most sediment transport takes place during storm conditions. The simulation of WNW storm waves shows sediment transport mainly at bathymetric depths down to 2-3 m and not beyond the 4 m depth contour. The direction of wave-induced sediment transport, for waves coming from a 276° direction, is towards the NE. However, the modelled waves, with a direction of 347°, generate sediment transport in a SW direction. Since the prevailing wave direction is from the W and WNW (Figure 3 and Table 2), the dominant sediment transport direction is towards the NE.

The calculations of sediment transport potential for the modelled storm waves show distinct peaks along the coast, in the Wustrow area. These peaks are located generally within the same area for the pre- and post-dredging bathymetries. However, there is an increase in transport potential in the area located landward of the extraction site, in the post-dredging scenario. Comparison of the transport potential, for the old and new bathymetry in the Graal-Müritz area, shows a very distinct peak of 58 m^3/h/m during the period of 1976-

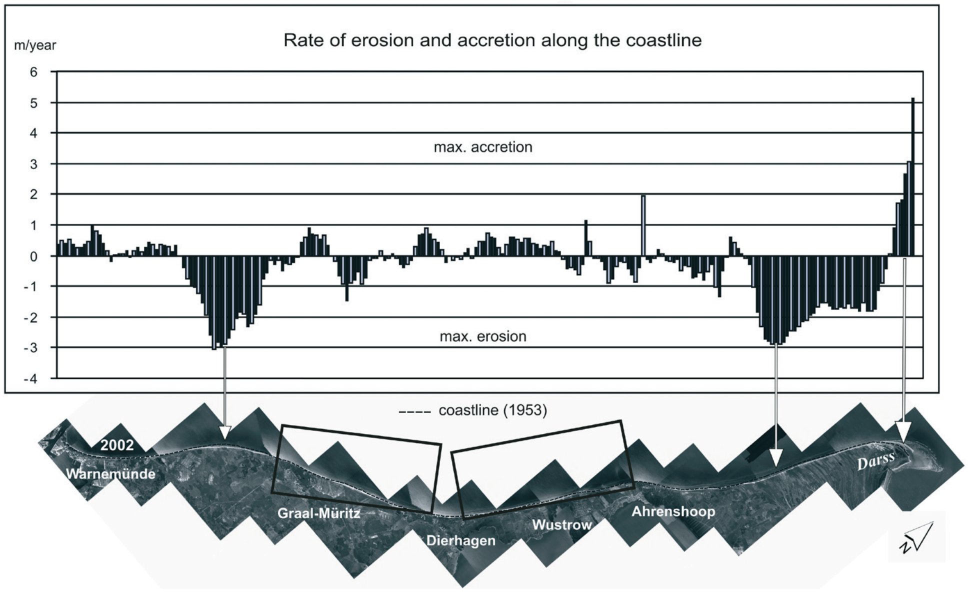


Figure 5. A rotated mosaic of aerial photographs of the 2002 coastline, from Warnemünde in the South to the Darss Peninsula in the North. The mouth of the Warnow River can be seen in the South, close to Warnemünde.The two rectangles indicate the modelling grids. The graph shows the average rate of erosion and accretion (m/year) along the coastline, between 1953 and 2002.

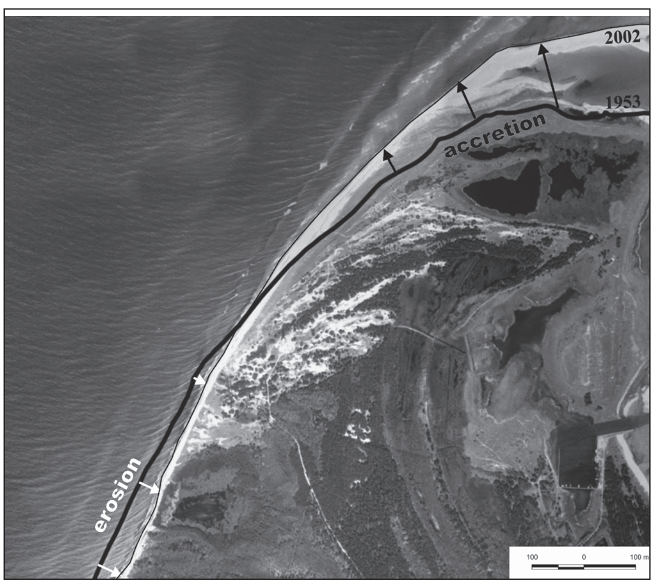


Figure 6. Aerial photograph of 2002, focusing in upon the northern part of the Darss Peninsula. The coastlines from 2002 and 1953 are shown, indicating clearly a change from erosion in the south to accretion in the north.

1979, which has disappeared almost entirely in 1996-2002 (Figure 8). The analysis of the coastline locations indicates that, between 1953 and 1988, this area was eroding rapidly, even though beach nourishment was undertaken here (MBLU, 1995). Erosion rates have decreased over the period extending from 1988 to 2002 (Figure 8).

DISCUSSION

Offshore sediment extraction may affect the coastline in different ways. It may interrupt or modify coastal sediment supply, or alter sediment transport rates and pathways, as a result of changing waves or currents. In the micro-tidal German Baltic Sea, the effect of MA extraction on tidal currents can be neglected. Furthermore, dredging takes place well beyond the active beach profile. Sand extraction in this area does not remove nearshore sandbanks and, hence, will not cause any reduction in the shelter provided to the coastline. As such, extraction in this area may affect nearshore wave conditions and associated sediment transport and the total sediment budget at the shoreline; these factors need to be assessed.

Wave modelling has shown that, even though the changes in bathymetry observed over a period of 20 years are subtle, they have resulted in modifications to the waves. Consequently, alterations have taken place in the sediment transport at the coast (Figure 8). The largest change in transport potential is identified as lying between Graal-Müritz and Dierhagen, where a decrease from 58 m^3/h in 1976-1979, to approximately 20 m^3/h in 1996-2002, was found. Overall, the sediment transport potential is higher for the Wustrow area, than for the Graal-Müritz area; this corresponds to the findings of WEILBEER and ZIELKE (1999). Their investigations conclude that the steeper bathymetry, to the north, causes more wave energy to reach the coast; this, in turn, results in a higher transport potential.

The results of the modelling show that the extraction sites lie outside the area of wave-induced sediment transport; this is consistent with the results of DIESING *et al.* (2006), who calculated that the closure depth for this area is 4 m. Detectable morphological changes over longer timescales (decades to centuries), occur down to a limiting depth

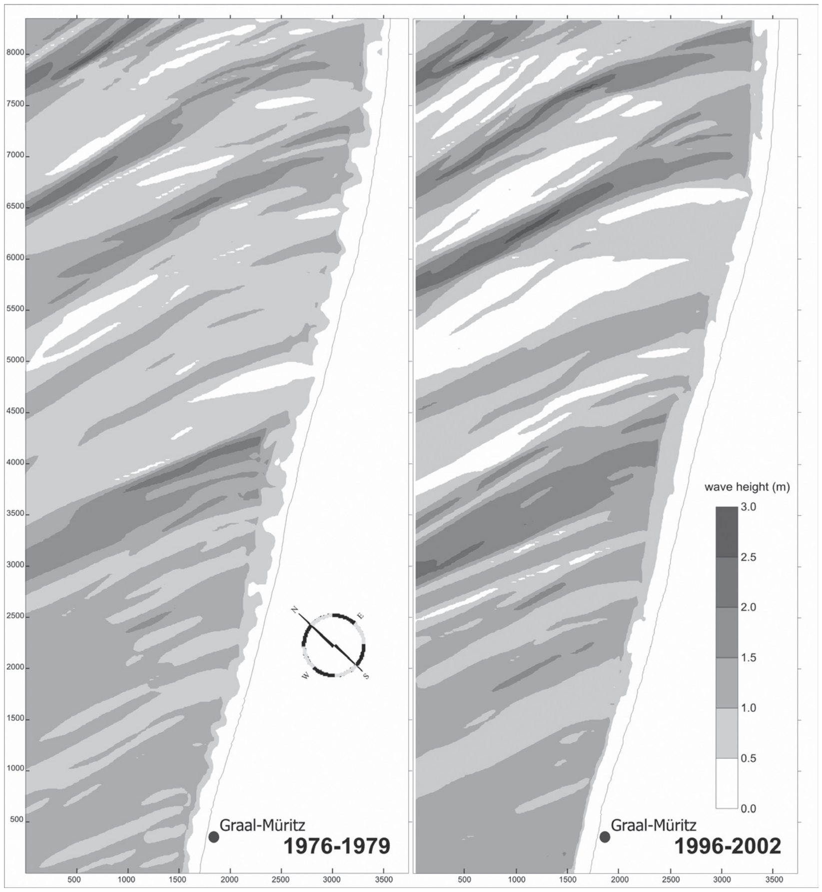


Figure 7. Wave heights for the modelled 5-yearly storm (Hs 1.40 m, Tm 6.00 s, Dir 276°) in the Graal-Müritz area: (a) modelled wave heights for the 1976-1979 bathymetry; and (b) modelled wave heights for the 1998-2002 bathymetry. Note the areas of wave focussing in the north and centre of the coastline. For the location of the modelling area, see Figures 1.and 5.

of h_i = 10 m (Diesing *et al.,* 2006). However, short-term changes and, therefore, sediment transport, were shown to occur down to depths of 8-13 m, as observed from repeated side-scan sonar surveys, following dredging. The dredged furrows at Graal Müritz were almost completely refilled after 6 months (Diesing, 2003); those at Wustrow showed considerable infilling, after 10 months (Krause, 2002). Interestingly, the bedforms offshore from Wustrow are located also in water depths lying beyond those associated with wave-induced sediment transport. According to Lemke *et al.* (1994), these bedforms are the result of currents generated by the inflow of saline bottom water from the North Sea. Bedform changes that have been observed indicate flow velocities of 70-100 cm/s; these only seldomly occur, typically on time-scales of months-years (Lemke *et al.,* 1994). These NE-flowing currents cause the transport of sediments in offshore areas beyond the zone of wave-induced transport. Thus, both the dominant directions of wave-induced sediment transport and the current-induced sediment transport are in a NE direction. Such transport moves sediment out of the area, to Darss, where it is deposited, accumulating along the Darss Peninsula. Long-term accretion in this area is indicated also by a sequence of Holocene beach ridges (Lampe, 2002), running parallel to the present-day coastline (Figure 6). The Darss area is a National Park, where extraction activities are prohibited.

Overall, the coast from Warnemünde to Darss has only a limited amount of marine sand resources: the cover of Holocene sand is thin (Diesing, 2003; Krause, 2002), whilst there is little contemporary input from the rivers. The main sediment source is erosion of retreating cliff sections (Hoffmann and Lampe, 2007). An increase in storminess in the Baltic Sea area, as reported by Kont *et al.* (2005), together with a rise in sea level will result in an increase in cliff erosion; hence, increase the supply of sediment to the coastal zone (Hoffmann and Lampe, 2007). At the same time, it will lead also to an increase in beach erosion and sediment transport, by wave action. Extraction of sediment for local beach nourishment may bring offshore sand into the zone of wave-dominated sediment transport, where it will be transported towards the northeast. Extraction of sediment for industrial use will leave the system completely.

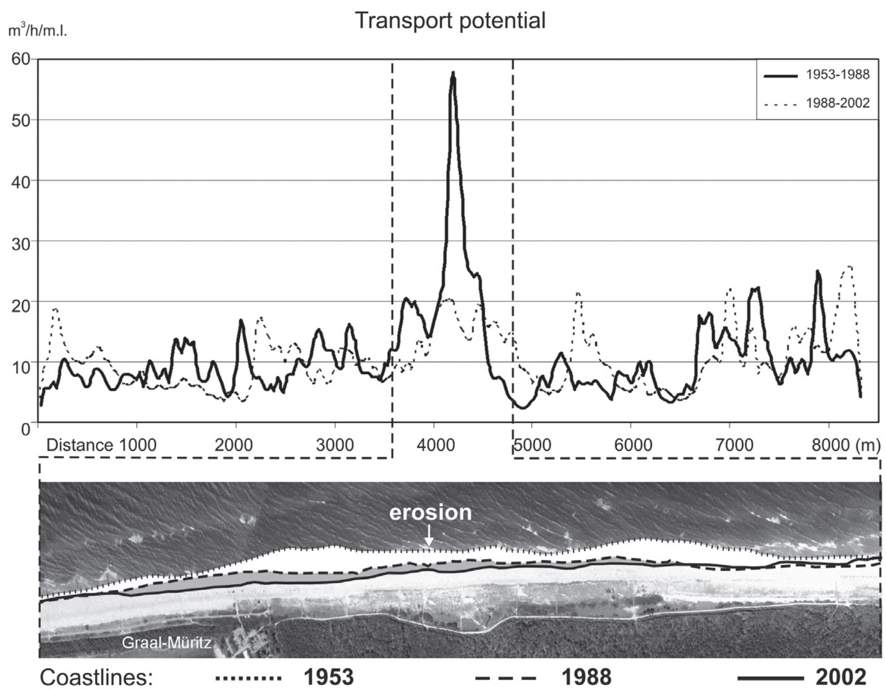


Figure 8. Sediment transport potential calculated by SMT for the coast from Warnemünde to the Darss Peninsula. Note the large peak in transport potential for the old bathymetry, which has now completely disappeared. The aerial photograph shows the location of the peak in sediment transport potential along the coastline between Graal Müritz to Dierhagen (the area between the dotted lines in the graph). Also indicated are the coastlines of 2002, 1988 and 1953.

CONCLUSIONS

Few examples exist of direct coastal erosion caused by marine sand extraction; these relate to the removal of sand from the upper shoreface. In the Baltic Sea, dredging takes place well beyond the depth of wave action, i.e. in water depths of 8-13 m. No direct relationship was found between changes in bathymetry and those at the coastline. It is suggested that the coastal changes result mainly from extensive coastal protection works carried out in the area. Therefore, it is difficult to assess the effects of dredging on the coastline in the area of Warnemünde to Darss. However the present study has indicated a few points of concern, as outlined below.

- Only very small changes in bathymetry (1-2 m) are sufficient to cause significant modifications in sediment transport potential at the coast and, thus, alternations in the patterns of erosion and accretion. Therefore, care should be taken that extraction does not cause lasting changes in the bathymetry.
- Overall, the coast from Warnemünde to Darss is an eroding coast. Sediment is transported in a NE direction by both wave action and currents, induced by the inflow of North Sea water. Such material is deposited in the Darss area, in a National Park, where dredging is prohibited.
- There is very little input of sediment into the system. The main source of sediment is material eroded from cliff sections. Any sand that is removed by MA extraction, for industrial use, will have a negative effect on the total sediment budget at the shoreline.

ACKNOWLEDGEMENTS

This research is funded by the European Union, within the framework of the EUMARSAND Project (HPRN-CT-2002-00222). We would like to thank Jürgen Monk from the BSH (Bundesamt für Seeschifffahrt und Hydrographie) for his help in obtaining the bathymetric data; likewise, Knut Sommermeier from StAUN-Rostock (Staatliche Ämter für Umwelt und Natur Rostock), for making available wave and current data from das Messnetz. We are grateful to Michael Collins and Klaus Schwarzer for their valuable comments on previous versions of this paper and to Markus Diesing for his help to find information. Also, we would like to thank three anonymous reviewers, for their constructive comments on the manuscript.

LITERATURE CITED

Anctil, F. and Ouellet, Y., 1990. Preliminary evaluation of impact of sand extraction near Iles-de-la-Madeleine Archipelago, Québec, Canada. *Journal of Coastal Research,* 6(1), 37-51.

Bailard, J.A., 1981. An energetic total load sediment transport model for a plane sloping beach. *Journal Geophysical Research*, 86(C11), 10938-10954.

Bender, C.J. and Dean, R.G., 2003. Wave field modifications by bathymetric anomalies and resulting shoreline changes: a review with recent results. *Coastal Engineering*, 49, 125-153.

Brampton, A.H. and Evans, C.D.R., 1998. Regional seabed sediment studies and assessment of marine aggregate dredging. London, UK: Construction Industry Research and Information Association, *Report CIRIA C505*, 82p.

Byrnes, M.R.; Hammer, R.M.; Thibaut, T.D., and Snyder, D.B., 2004a. Physical and biological effects of sand mining offshore Alabama, USA. *Journal of Coastal Research,* 20(1), 6-24.

Byrnes, M.R.; Hammer, R.M.; Thibaut, T.D., and Snyder, D.B., 2004b. Effects of sand mining on physical processes and biological communities offshore New Jersey, USA. *Journal of Coastal Research*, 20(1), 25-43.

Diesing, M., 2003. Die Regeneration von Materialnahmestellen in der südwestlichen Ostsee unter besonderer Berücksichtigung der rezenten sedimentdynamik. Kiel, Gemany: Christian-Albrechts Universität, Ph.D. thesis, 158p.

Diesing, M.; Schwarzer, K.; Zeiler, M., and Klein, H., 2006. Comparison of marine extraction sites by means of shoreface zonation. *Journal of Coastal Research*, Special Issue 39, 783-788.

G.I.O.C., 2002. Grupo De Ingeniería Oceanográfica y de Costas, University of Cantabria. Santander, Spain, *Manual de Usuario del SMC.*

Hayes, M.O. and Nairn, R.B., 2004. Natural maintenance of sand ridges and linear shoals on the U.S. Gulf and Atlantic continental shelves and the potential impact of dredging. *Journal of Coastal Research*, 20(1), 138-148.

Hilton, M.J. and Hesp, P., 1996. Determining the limits of beach-nearshore sand systems and the impact of offshore coastal sand mining. *Journal of Coastal Research*, 12(2), 496-519.

Hoffmann, G. and Lampe, R., 2007. Sediment budget calculation to estimate Holocene coastal changes on the southwest Baltic Sea (Germany). *Marine Geology*, 243, 143-156.

IHO –International Hydrographic Organization., 1998. *IHO Standards for Hydrographic surveys*, 4th edition. Monaco: International Hydrographic Bureau, Special Publication 44, 23p.

Janke, W. and Lampe, R., 1998. Die Entwicklung der Nehrung Fischland – Darss – Zingst und ihres Umlandes seit der Litorina-Transgression und die Rekonstruktion ihrer subrezenten Dynamik mittels historischer Karten. *Zeitschrift für Geomorphologie N.F*, 112, 177-194.

Kelley, S.W.; Ramsey, J.S., and Byrnes, M.R., 2004. Evaluating shoreline response to offshore sand mining for beach nourishment. *Journal of Coastal Research*, 20(1), 89-100.

Kirby, J.T. and Dalrymple, R.A., 1983. A parabolic equation for the combined refraction-diffraction of Stokes waves by mildly-varying topography. *Journal of Fluid Mechanics*, 136, 543-566.

Kont, A.; Orviku, K.; Jaagus, J.; Rivis, R., and Tonisson, H., 2005. Evolution of sandy beches in Estonia as indicator of increased storminess in the Baltic Sea region. *In*: Herrier, J.-L.; Mees, J.; Salman, A.; Seys, J.; Van Nieuwenhuyse, H., and Dubbelaere, I. (eds.), *Proceedings Dunes and Estuaries 2005 – International Conference on Nature Restauration Practices in European Coastal Habitats*. Koksijde, Belgium: VLIZ Special Publication 19, xiv, pp. 607-609.

Krause, J.C., 1998. Auswirkungen des Sand- und Kiesabbaus auf das Makrozoobenthos an des Küste vor Mecklenburg-Vorpommern –Ein Überblick der vorläufige Ergebnisse aktueller Untersuchungen. *In*: Von Nordheim, H. and Boedeker, D. (eds.), *Umweltvorsorge bei der marinen Sand- und Kiesgewinnung*. BLANO-Workshop, INA Insel Vilm, Germany, BFN-skripten 23, pp. 58-71.

Krause, J.C., 2002. The effects of marine sand extraction on sensitive macrozoobenthic species in the southern Baltic Sea. Rostock. Germany: University of Rostock, Ph.D. thesis, 127p.

Lampe, R., 2002. Holocene evolution and coastal dynamics of the Fischland-Darss-Zingst peninsula. *Greifswalder Geographische Arbeiten*, 27, D1, 155-163.

Lemke, W.; Kuijpers, A.; Hoffamn, G.; Milkert, D., and Atzler, R., 1994. The Darss Sill, hydrographic threshold in the southwestern Baltic: Late Quaternary geology and recent sediment dynamics. *Continental Shelf Research*, 14, 847-870.

Maa, J. P.-Y. and Hobbs III, C.H., 1998. Physical impact of waves on adjacent coasts resulting from dredging at Sandbridge Shoal, Virginia. *Journal of Coastal Research*, 14(2), 525-536.

Maa, J.P.-Y.; Hobbs III, C.H., and Hardaway JR., C.S., 2001. A criterion for determining the impact on shorelines caused by altering wave transformation. *Journal of Coastal Research*, 17(1), 107-113.

Maa, J.P.-Y.; Hobbs III, C.H.; Kim, S.C., and Wei, E., 2004. Potential impacts of sand mining offshore of Maryland and Delaware: Part 1 –Impacts on physical oceanographic processes. *Journal of Coastal Research*, 20(1), 44-60.

Manso, F.; Radzevicius, R.; Blažauskas, N.; Balay, A., and Schwarzer, K., this volume. Nearshore dredging on the Baltic Sea. State after cessation of activities and regeneration assessment.

Mblu Mblu, Ministerium für Bau, Landesentwicklung und Umwelt des Landes Mecklenburg-Vorpommern., 1995. *Generalplan Küsten- und Hochwasserschutz Mecklenburg-Vorpommern. Schwerin*, 108p

Nairn, R.; Johnson, J.A.; Hardin, D., and Michel, J., 2004. A biological and physical monitoring program to evaluate long-term impacts from sand dredging operations in the United States outer continental shelf. *Journal of Coastal Research*, 20(1), 126-137.

Pearce, F., 1996. Crumbling away. Is dredging the villain in the drama of Britain's eroding coasts? *New Scientist*, 152, 14-15.

Simons , R. and Hollingham, S., 2001. *Marine aggregate dredging: a review of current procedures for assessing coastal processes and impact at the coastline*. London, UK: Civil and Engineering Department, UCL, *Technical Report HYD10401*, 81p.

Soulsby, R. (1997). *Dynamics of marine sands: A Manuel for Practical Applications.* London, UK: Thomas Telford Publications, 249p.

Suter, J.R.; Mossa, J., and Penland, S., 1989. Preliminary assessments of the occurrence and effects of utilization of sand and aggregate resources of the Louisiana inner shelf. *Marine Geology*, 90, 31-37.

Weilbeer, H. and Zielke, W., 1999. Modellierung großräumiger hydrodynamischer und morphologischer Prozesse an den Außenküsten von Fischland, Darß und Zingst. *Die Küste*, 61, 177-194.

Journal of Coastal Research	SI	51	205-214	West Palm Beach, Florida	Summer 2010

Assessment of the Effects of Marine Aggregate Extraction on the Coastline: an Example from the German Baltic Sea Coast

Stella Kortekaas[1*], Ingrida Bagdanaviciute[2], Paolo Gyssels[3], Jose M. Alonso Huerta[4] and Arnaud Héquette[1].

[1] Laboratoire d'Océanologie et de Géosciences
UMR CNRS 8187
Université du Littoral Côte d'Opale
32 Ave Foch
62930 Wimereux, France

[*] Present address: Fugro Engineers B.V.
Veurse Achterweg 10
2264 SG Leidschendam, The Netherlands
s.kortekaas@fugro.nl

[2] Coastal Research and Planning Institute
Klaipeda University
H. Manto 84, LT 92294
Klaipeda, Lithuania

[3] Tecnoconsult Engineering Construction S.r.l.
Strada Nazionale Adriatica Sud, 149
61032 Metaurilia di Fano (PU), Italy

[4] ALATEC Ingenieros
Consultores y Arquitectos
C/ José Echegaray 14
Parque Empresarial Las Rozas
28230 Las Rozas - Madrid, Spain

ABSTRACT

The German Baltic Sea coast between Warnemünde and Darss is rapidly eroding. In this area, extensive sand extraction takes place at water depths of 8-13 m, for both local beach nourishment and industrial use. Sand resources in the area are restricted to a layer of <2 m of Holocene sand, whilst contemporary input of sand is limited to erosion of the cliff sections. To investigate if sand extraction in this area has any effect on the coastline, bathymetric data from two particular time periods were compared, as well as the location of the coastline over 5 different years, ranging from 1953-2002. Waves and wave-induced sediment transport were simulated using the integrated coastal zone model, Sistema de Modelado Costero (SMC). Results indicate some primary areas of concern: small changes in bathymetry of approximately 10% are sufficient to cause significant modifications in sediment transport potential at the coast; and, thus, alternations in the patterns of erosion and accretion. Sediment transport by both wave action and currents, induced by the inflow of North Sea water, is in a NE direction towards Darss. Here, deposition takes place in a National Park, where dredging is prohibited. There is very little input of sediment in the system. Any sand that is removed by marine aggregate extraction, for industrial use, will have a negative effect on the total sediment budget at the shoreline.

ADDITIONAL INDEX WORDS: *dredging, sediment transport, integrated coastal zone model, Sistema de Modelado Costero (SMC), differential bathymetry, beach erosion.*

INTRODUCTION

Sand is extracted from the seabed for many uses, including the construction industry and beach nourishment. In response to increasing demand, more marine sand is extracted from the inner continental shelf (<60 m water depth) in Europe, every year. As such, concerns have been raised about the adverse effects on the coastal system, including ecology, the seabed and the adjacent shoreline. For example, the results of a questionnaire sent to local residents in South Wales, have shown that a vast majority believes that marine aggregate (MA) extraction is responsible for the increased rates of beach erosion at local beaches (Simons and Hollingham, 2001).

There are different ways in which offshore MA extraction may cause changes to the coastline. For example, Brampton and Evans (1998) identify 5 effects: (a) beach draw-down; (b) modifications to tidal currents; (c) changes in sediment transport; (d) variations in nearshore wave conditions; and (e) a reduction in shelter provided to the coastline. Many of these effects are interrelated (as discussed below). Nairn *et al.* (2004) suggest that shoreline changes occur in two ways: (i) an extraction site interrupts or modifies the sediment supply pathways to the coast, reducing the sediment budget at the shoreline; or (ii) modifications in wave transformation patterns change the character of the waves reaching the coast, altering sediment transport and, eventually, changing erosional and accretional patterns. The study of coastal impact of dredging is not straightforward and, as such, many different approaches have been adopted.

Extensive MA extraction takes place in the Baltic Sea, in the area between Warnemünde and Darss (Figure 1), for both beach nourishment purposes and industrial use (Krause, 1998). Two of the offshore extraction sites are located close to the coast, i.e. Graal Müritz and Wustrow; they are located in water depths of 8-12 and 11-13 m, respectively (Figures 1 and 2). Wave conditions and wave-induced sediment transport within the area of these extraction sites are investigated here, to assess if the dredging may impact upon the coast. Offshore bathymetry and the location of coastlines, over a number of years, were compared to study patterns of erosion and accretion. Waves (in the absence of tides) and sediment transport were modelled using Sistema de Modelado Costero (SMC), an integrated coastal zone model.

DOI: 10.2112 / SI51-019.1 received 13 January 2007; accepted in revision 2 April 2008.

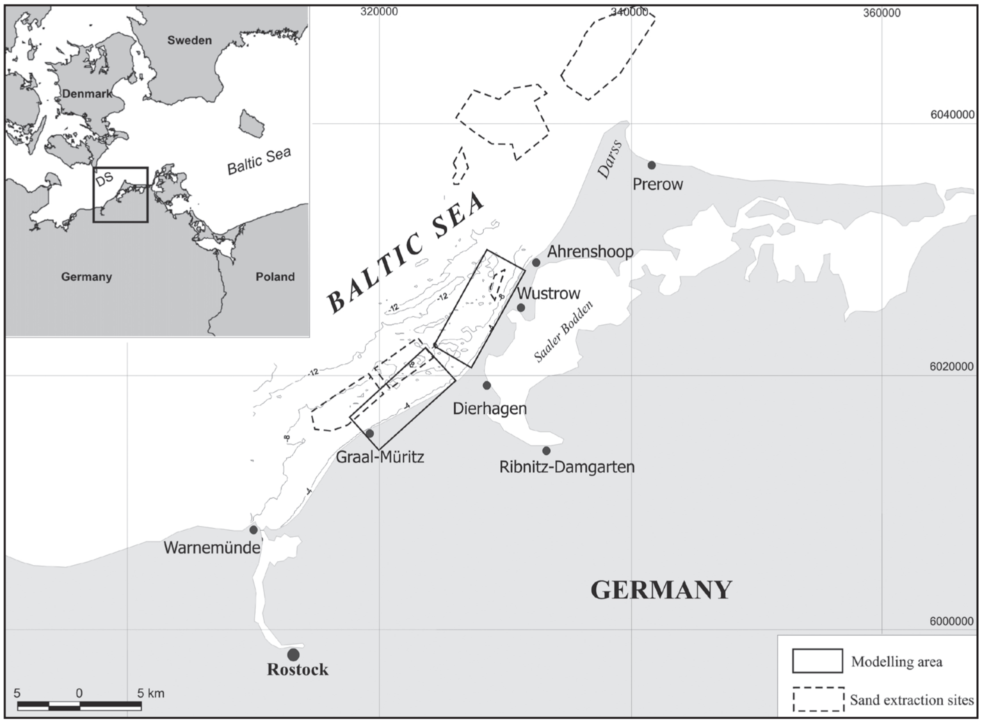


Figure 1. Location map, showing the major towns, extraction sites Graal Müritz and Wustrow, and the fine grids used for modelling. DS = Darss Sill.

EFFECTS OF MA EXTRACTION ON THE COASTLINE

Effects on Coastal Sediment Budget

The most direct effect of MA extraction on the coastline is beach draw-down; this may occur when material is extracted from within the active beach profile. Beach sand or gravel, transported seawards during storm events, remains trapped in the depression. It will not return to the upper beach during calm conditions, thus resulting in a net loss of beach material (Brampton and Evans, 1998). Beach draw-down was the cause of the destruction of the coastal village of Hallsands, Devon (UK), in 1917, where between 1897 and 1902 some 382,000 m^3 of gravel was extracted from the foreshore (Pearce, 1996; Simons and Hollingham, 2001).

Reduction in the sediment budget at the shoreline may occur also due to modification or interruption of the sediment supply pathways, towards the coast. Such a reduction may occur in two ways: dredging may remove sediment that would normally supply the beach; or an extraction site may trap sediment, which would otherwise have been transported towards the coast. The latter process is suggested to be the reason for the weak recovery of the Pakiri-Mangawhai coast in New Zealand, following storms in 1978. Although extraction in this area takes place within the surf zone, it has been impossible to prove a cause-effect relationship between sand extraction and backshore stability (Hilton and Hesp, 1996). Anctil and Ouellet (1990) have calculated littoral drift changes for three dredging scenarios in Quebec (Canada) and found that only excavation at the sea bed of 2 m or more in depth had a significant impact on sediment transport. These investigations have concluded that the coastal impact can be limited, by gradually changing the bathymetry, leaving the system sufficient time to adjust. This outcome is achievable by preventing multiple dredging over the same area.

Effects on Waves and Currents

Modification of the bathymetry may alter nearshore wave conditions, by changing the wave refraction patterns; hence, the wave direction, or the total wave energy, reaching the coast. Since breaking waves are generally considered to be the dominant factor affecting the coast, Maa, Hobbs, and Hardaway (2001); Maa *et al.* (2004) have used the change in breaking wave height to assess the coastal impact of changing wave transformation, caused by extraction. Even though the local wave height between the extraction site and the coast can increase by as much as two-fold, the change in the breaking wave height is less significant, as most of the wave energy is dissipated before the waves reach the shore (Byrnes *et al.,* 2004a; Maa *et al.,* 2004). However, in areas with a steep shoreface, the wave energy does not dissipate significantly and, instead, increases considerably upon reaching the coast (Byrnes *et al.,* 2004b). For example, at Grand Isle, Louisiana (USA), two large salients and areas of increased erosion developed shoreward of an offshore extraction site that was situated some 800 m offshore, in a water depth of 4.6 m (Bender and Dean, 2003). The extraction pit affected the wave propagation pattern, which, in turn, caused changes in erosion and accretion at the coast.

Maa and Hobbs (1998) have examined longshore sediment transport, using breaking wave conditions, calculated from modelled wave transformation processes. The model results

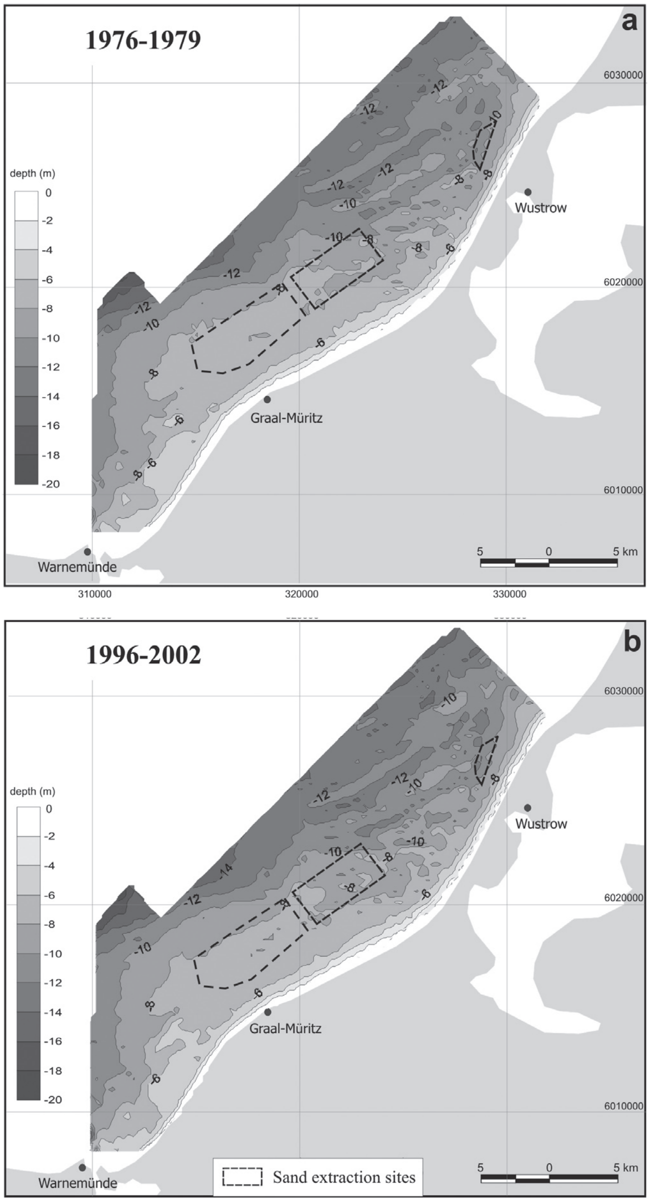


Figure 2. Bathymetry of (a) 1976-1979 and (b) 1998-2002, with the extraction sites indicated.

showed considerable natural wave energy convergence, which could be responsible for severe beach erosion over the same area. However, the dredging effects on wave transformation and longshore sediment transport were found to be insignificant. Kelley, Ramsey, and Byrnes (2004) developed a new approach for evaluating the coastal impact of an extraction site, incorporating natural spatial and temporal variability in the wave climate, as the basis for determining the level of significance. A coast with a natural high variety of wave conditions and, consequently, sediment transport will be less sensitive to wave modifications caused by dredging, than a coast with a limited range of wave conditions.

Wave conditions at the shoreline may change also as a result of dredging of nearshore sandbanks, reducing the shelter provided to the coastline. The disappearance, or lowering, of the bank will change the wave patterns between the bank and the coast; this, in turn, will cause changes in sediment transport and, hence, erosion and accretion patterns at the shoreline (Hayes and Nairn, 2004). An example is the 1996 beach nourishment project undertaken in Martin County, Florida (USA), where sand was extracted from a shoal located some 910 m offshore, in a water depth of 12.8 m. By lowering the shoal height, the coast was exposed to increased wave action, resulting in localised erosion (Bender and Dean, 2003). Similarly, sand extraction from a large shore-parallel shoal, located 10 km offshore of the coast of Louisiana, USA, would increase erosion and overwash on the adjacent shoreline (Suter, Mossa, and Penland, 1989).

The effects on tidal currents are, typically, limited and very localised. For example, Maa *et al.* (2004) modelled the influence of dredging of two shoals offshore of Maryland and Delaware (USA), on the tidal currents. The results showed only small changes in the maximum near-bed tidal current velocity at the shoals, indicating only a negligible impact. Elsewhere, Byrnes *et al.* (2004a) found that, whilst the extraction at sites offshore from Alabama (USA) could produce a localised effect on the currents, there was no impact upon the prevailing or ambient flow characteristics.

SITE DESCRIPTION

The German Baltic Sea coast is a micro-tidal area, with a negligible tidal range. The study area is situated between Warnemünde and Ahrenshoop (Figure 1). The shoreline in this area consists of narrow beaches, with dunes and cliffs of Pleistocene deposits (Lampe, 2002). The main source of sediment in the coastal zone is retreating cliff sections. Sediment input from rivers is negligible. The slow-flowing Warnow River drains into the Baltic Sea at Warnemünde, but its sediment discharge consists mainly of suspended fines. The coastal zone here is experiencing long-term erosion, with an average coastal retreat varying from 30-70 m/100 years, over the last 160 years (Janke and Lampe, 1998). In order to maintain the beaches, sand has been extracted offshore for beach nourishment projects, since 1968. Besides beach and dune nourishment, a wide range of shore protection structures have been installed, e.g. groynes, breakwaters and dykes, to reduce coastal erosion. In this study, two sediment extraction sites are considered, which are located close to the coast: Graal-Müritz and Wustrow (Figure 1).

The offshore area is characterised by the Darss Sill (Figure 1). Approximately 73 % of the water exchange between the Baltic Sea and the North Sea is through this relatively shallow, narrow strait. The seafloor consists of glacial till, overlain by a thin layer (<30 cm) of lag deposits which, in turn, is covered, over a small part of the area, by Holocene marine sand (Lemke *et al.,* 1994). In the area of Graal-Müritz, the overlying marine sand has a maximum thickness of 1.1 m (Diesing, 2003). NNW-SSE oriented sandwaves, with heights of up to 2.7 m and a wavelength of approximately 180 m, are present in this area. Within their troughs, coarse lag sediments are exposed (Diesing, 2003). The extraction site of Graal-Müritz is located some 2.5-5.5 km offshore, within a water depth of

8-12 m. Extraction at this site has taken place since 1988 (Diesing, 2003). The Wustrow extraction site is located about 1 km off the coast, near Wustrow, in a water depth of 11-13 m. Sand has been extracted here, for beach nourishment projects, since 1997. The mean thickness of the overlying marine sand, in this area, is 1.9 m (Krause, 2002). For extraction at both sites, a trailer suction hopper dredger is used; this creates shallow (ca. 0.5 m deep) furrows on the seafloor, which have widths of 3-10 m and lengths of up to 1 km (Diesing, 2003; Manso *et al.,* this volume).

The bathymetry of the extended offshore area (Warnemünde to Ahrenshoop) shows that the nearshore zone (<10 m water depth) becomes narrower towards the north (Figure 2). Whilst the 10 m depth contour is located approximately 10 km offshore of Graal-Müritz, it is only 2.5 km away from the coast at Wustrow. Large offshore sandbanks are present within this area, oriented obliquely to the coast (Figure 2).

METHODOLOGY AND DATA

Bathymetric Data

Bathymetry relating to two different time periods was compared: 1976-1979 (before dredging) and 1996-2002 (after dredging). The data were obtained from the BSH (Bundesamt für Seeschifffahrt und Hydrographie = Federal Maritime and Hydrographic Agency), Germany. It was necessary to use data sets derived from multiple surveys, undertaken over several years, because no survey covered the complete area, within any particular year. The horizontal error of the older data set is about 20 m + 5% of the depth; for the recent data set, it is about 5 m + 5% of the depth. The vertical error is highly dependent upon water depth; it ranges from 0.50-0.56 m and 1.00-1.10 m for the new and old bathymetry data sets, respectively (IHO, 1998; MONK, 2005 pers. comm.).

Aerial Photographs

In order to compare the location of the coastline, over time, aerial photos were used. Sets of photos from 4 different years (1953, 1980, 1994 and 1998), together with a set of orthophotos (2002), were obtained from the Landesvermessungsamt, Mecklenburg-Vorpommern, Germany (Table 1). The aerial photos were scanned and rectified, using the orthophotos (with a resolution of 8 dm) and the software ER-Mapper 6.4. The rectification error was maintained at less than 1 m, for most of the photos. However, for some of the photos, especially the older ones, this was not possible; as such, the error could extend up to 2 m. When taking into account the resolution of the orthophotos of 8 dm, together with the size of the pixels of the scanned aerial photos of about 1.5 m, the maximum total error may have been about 4 m. Following rectification, mosaics were created and the coastlines from different years were digitised and compiled in a GIS database (ArcView).

Wave and Sediment Transport Modelling

In this study, the software Sistema de Modelado Costero (SMC), translated as Coastal Modelling System, has been used to simulate wave propagation, as well as the currents induced and sediment transport in the coastal area of Graal-Müritz and Wustrow. SMC was developed by the Coastal Engineering and Oceanography Group (G.I.O.C., 2002), of the University of Cantabria, in collaboration with the Coastal and Environmental Department of the Spanish Government. SMC includes different modules and numerical implementation, to assist in coastal dynamics studies; it utilises the parabolic solution of the mild-slope equations (Kirby and Dalrymple, 1983), for wave propagation. The software allows the simulation of monochromatic or spectral waves from deep waters, to the coast. In each case, wave-induced currents and potential sediment transport can be obtained. Sediment transport is computed from the previously obtained wave and current fields, using the formulae of Bailard (1981) and Soulsby (1997). Both methods compute the total sediment transport, taking into account bed load and suspended load transport.

Two areas were selected for modelling: Graal-Müritz and Wustrow. For both areas, two coarse offshore grids (300 x 300 m) were established for the different wave directions, each with a fine grid (15 x 30 m) attached, for the nearshore area. Monochromatic waves were used in the model.

Table 1. *Year, number and scale of the aerial photographs used to study coastline changes.*

Date	Number of aerial photographs	Scale
1953	9	1:22000
1988	16	1:18000
1994	20	1:12500
1998	23	1:12500
2002	47 (ortho-photos)	pixel size: 8 dm

Wave Climate

The NNW-WNW-facing coast, between Warnemünde and Ahrenshoop, is a fetch-limited coastline and is sheltered from waves coming from the Baltic Sea, to the east (Figure 1). A continuous five-year record (1998-2002) of directional wave data, measured every hour, was available from a measuring station located close to Ahrenshoop. Over this period, the dominant wave direction was from W-WNW, with more than 65 % of all waves originating from this direction (Figure 3 and Table 2). Large storm waves originate, typically, from a WNW direction.

Table 2. *Proportion of all waves with Hs >0.2 m in different directions.*

Direction	N	NNW	NW	WNW	W	WSW
Percentage	9.95	8.42	4.99	23.70	41.60	8.97

For the wave modelling, five “wave cases” were selected, corresponding to two different directions. The most common wave condition is represented by a significant wave height (Hs) of 0.68 m, a period (Tm) of 4.64 s and a direction (Dir) of 276°. Within this context, long period swell waves in this area have a direction of 347°, a wave height of 0.31 m and a period of 6.09 s. For completeness, locally-generated wind waves from this direction were also simulated; these have a wave height of 0.56 m and a period of 4.44 s. Furthermore, an average yearly storm wave (Hs 1.29 m, Tm 5.77 s, Dir 276°) and the average 5-yearly storm wave (Hs 1.40 m, Tm 6.00 s, Dir 276°) were modelled (Table 3). Because most sediment transport takes place during storm conditions, the results of the latter will be discussed in detail.

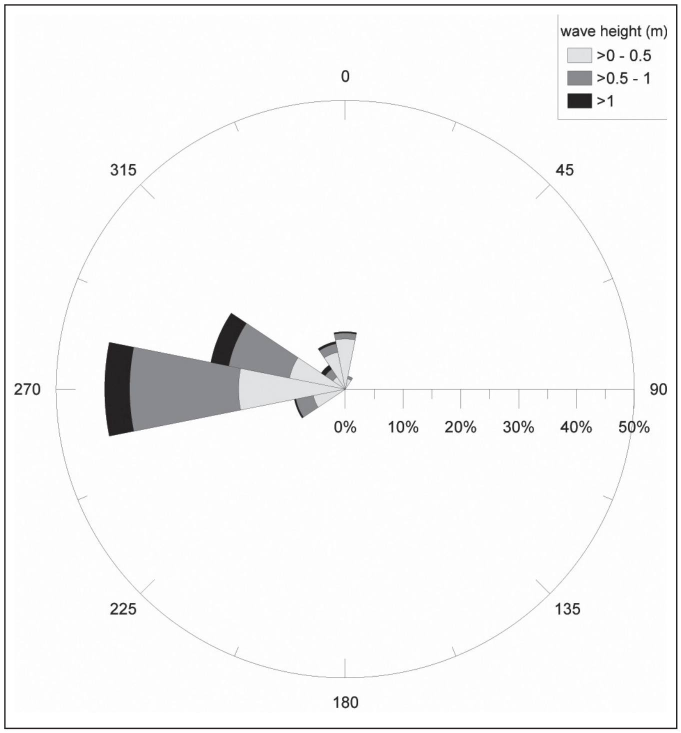


Figure 3. Distribution of wave directions and wave height, from measurements obtained at the StAUN Messnetz station at Ahrenshoop, for the period 1998-2002.

Table 3. *Parameters of the modelled wave conditions (significant wave height, mean period and wave direction).*

Wave cases	Hs (m)	Tm (s)	Dir (°)
Local waves 1	0.68	4.64	276
Local waves 2	0.56	4.44	347
Swell	0.31	6.09	347
Storm (1y)	1.29	5.77	276
Storm (5y)	1.40	6.00	276

RESULTS

Bathymetry

Bathymetric changes between 1976-1979 and 1996-2002 are subtle (Figure 4) and, in general, lie within the range of the maximum vertical error of the bathymetry (around ± 1 m). The highest rate of seabed erosion (4.5 m, in ca. 20 years) can be found in a small area close to the extraction site of Wustrow. The broad shallow zone (<10 m), offshore of Graal-Müritz is stable, typically showing no change. In general, accretion takes place in the coastal zone close to the Wustrow coast; erosion occurs in the offshore area to the NE of Graal-Müritz (Figure 4).

Coastline

The location of the coastline has fluctuated considerably between 1953 and 2002. Comparing the 1953 and 2002 coastlines, two areas of maximum erosion (of up to 3 m per year) can be identified: the coast to the south of Graal Müritz, and the Darss area (Figure 5). However, a maximum accretion of 3-5 m per year takes place at the northerly tip of the Darss Peninsula, immediately to the north of the rapidly-eroding Darss coast (Figure 6). In general, the coastline from the south of Graal-Müritz to Dierhagen is mainly erosional, except for a small section of prograding coastline, lying close to the town of Graal-Müritz. This accretional zone is located in an area where repeated beach nourishment has been undertaken (MBLU, 1995). The coast from Dierhagen to Wustrow has experienced, overall, a small amount of accretion; whilst, from the north of Wustrow up to Darss, an overall erosional trend was observed.

The extensive coastal protection works, including groynes, breakwaters and beach nourishment projects, make it difficult to distinguish (from the aerial photographs) the natural trend in shoreline evolution. For example, the two large accretional peaks near Wustrow and Ahrenshoop (Figure 5) are associated with the breakwater construction in 1985 and 1986, respectively. Subsequently, considerable accretion has taken place on the lee side of these breakwaters.

Wave and sediment transport modelling

The results of the simulation of WNW storm waves show that they focus upon particular areas of the coastline, as a result of the offshore bathymetry. The subtle differences between the old and new bathymetry cause also small changes in the nearshore wave conditions (Figure 7). Within the Graal-Müritz area, the offshore wave height has increased; however, most of the energy dissipates before the waves reach the shore (Figure 7). The changes in the Wustrow area are most

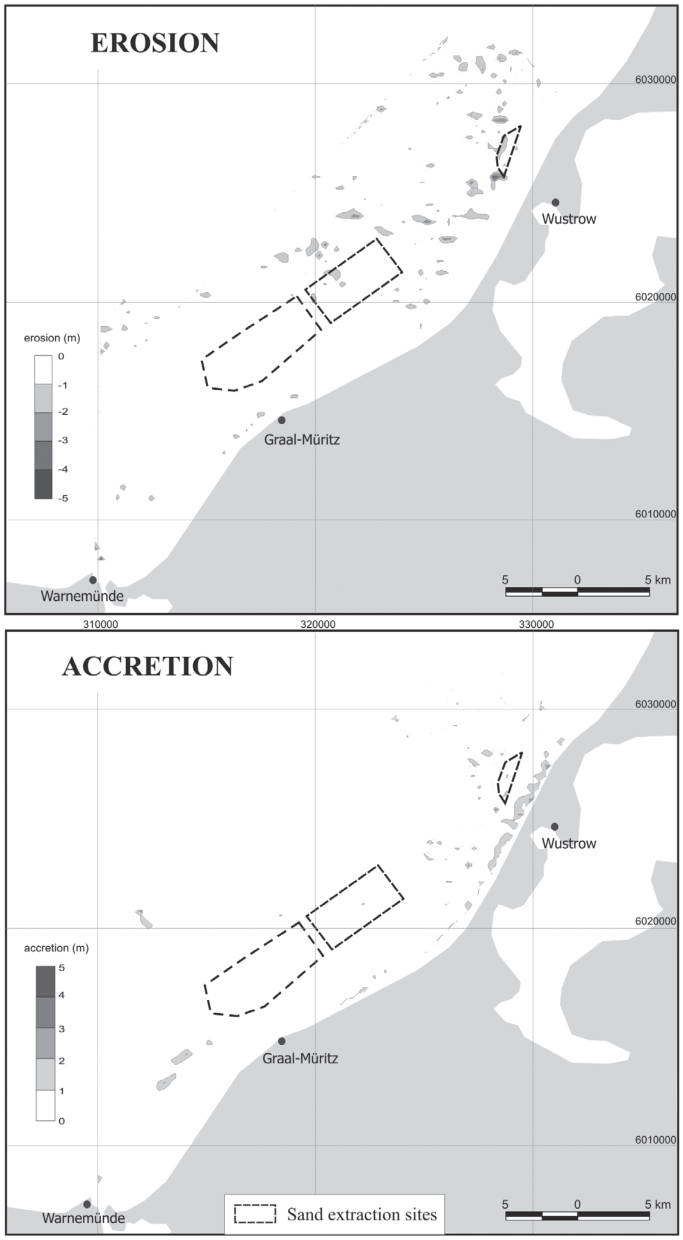


Figure 4. Comparison of the bathymetry of 1976-1979 and 1998-2002, showing areas of erosion and accretion. Corresponding to a maximum vertical error of ca. 1 m, the changes from 1 m and more are indicated. The largest erosion of almost 5 m is found directly to the SW of the Wustrow extraction site.

pronounced at the extraction site, where wave heights have increased.

Most sediment transport takes place during storm conditions. The simulation of WNW storm waves shows sediment transport mainly at bathymetric depths down to 2-3 m and not beyond the 4 m depth contour. The direction of wave-induced sediment transport, for waves coming from a 276° direction, is towards the NE. However, the modelled waves, with a direction of 347°, generate sediment transport in a SW direction. Since the prevailing wave direction is from the W and WNW (Figure 3 and Table 2), the dominant sediment transport direction is towards the NE.

The calculations of sediment transport potential for the modelled storm waves show distinct peaks along the coast, in the Wustrow area. These peaks are located generally within the same area for the pre- and post-dredging bathymetries. However, there is an increase in transport potential in the area located landward of the extraction site, in the post-dredging scenario. Comparison of the transport potential, for the old and new bathymetry in the Graal-Müritz area, shows a very distinct peak of 58 $m^3/h/m$ during the period of 1976-

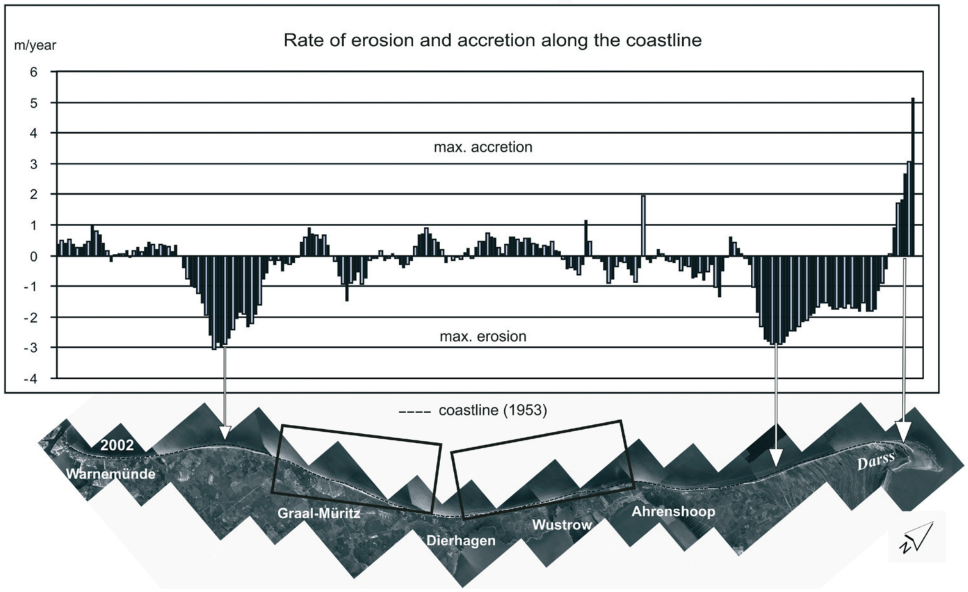


Figure 5. A rotated mosaic of aerial photographs of the 2002 coastline, from Warnemünde in the South to the Darss Peninsula in the North. The mouth of the Warnow River can be seen in the South, close to Warnemünde.The two rectangles indicate the modelling grids. The graph shows the average rate of erosion and accretion (m/year) along the coastline, between 1953 and 2002.

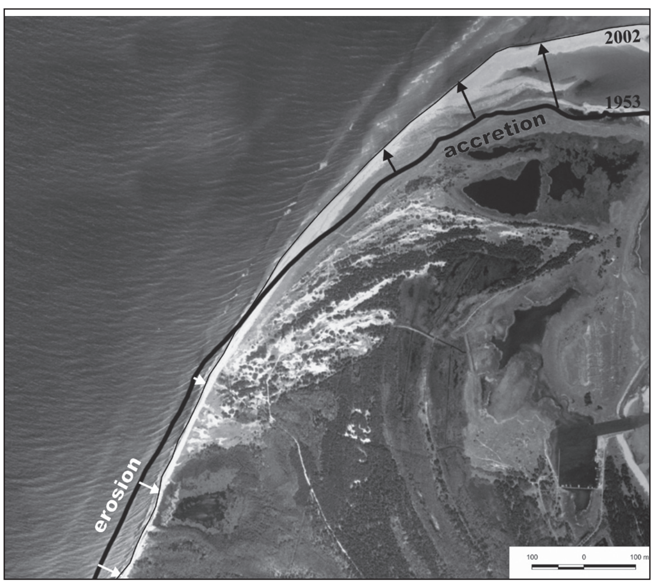


Figure 6. Aerial photograph of 2002, focusing in upon the northern part of the Darss Peninsula. The coastlines from 2002 and 1953 are shown, indicating clearly a change from erosion in the south to accretion in the north.

1979, which has disappeared almost entirely in 1996-2002 (Figure 8). The analysis of the coastline locations indicates that, between 1953 and 1988, this area was eroding rapidly, even though beach nourishment was undertaken here (MBLU, 1995). Erosion rates have decreased over the period extending from 1988 to 2002 (Figure 8).

DISCUSSION

Offshore sediment extraction may affect the coastline in different ways. It may interrupt or modify coastal sediment supply, or alter sediment transport rates and pathways, as a result of changing waves or currents. In the micro-tidal German Baltic Sea, the effect of MA extraction on tidal currents can be neglected. Furthermore, dredging takes place well beyond the active beach profile. Sand extraction in this area does not remove nearshore sandbanks and, hence, will not cause any reduction in the shelter provided to the coastline. As such, extraction in this area may affect nearshore wave conditions and associated sediment transport and the total sediment budget at the shoreline; these factors need to be assessed.

Wave modelling has shown that, even though the changes in bathymetry observed over a period of 20 years are subtle, they have resulted in modifications to the waves. Consequently, alterations have taken place in the sediment transport at the coast (Figure 8). The largest change in transport potential is identified as lying between Graal-Müritz and Dierhagen, where a decrease from 58 m^3/h in 1976-1979, to approximately 20 m^3/h in 1996-2002, was found. Overall, the sediment transport potential is higher for the Wustrow area, than for the Graal-Müritz area; this corresponds to the findings of WEILBEER and ZIELKE (1999). Their investigations conclude that the steeper bathymetry, to the north, causes more wave energy to reach the coast; this, in turn, results in a higher transport potential.

The results of the modelling show that the extraction sites lie outside the area of wave-induced sediment transport; this is consistent with the results of DIESING *et al.* (2006), who calculated that the closure depth for this area is 4 m. Detectable morphological changes over longer timescales (decades to centuries), occur down to a limiting depth

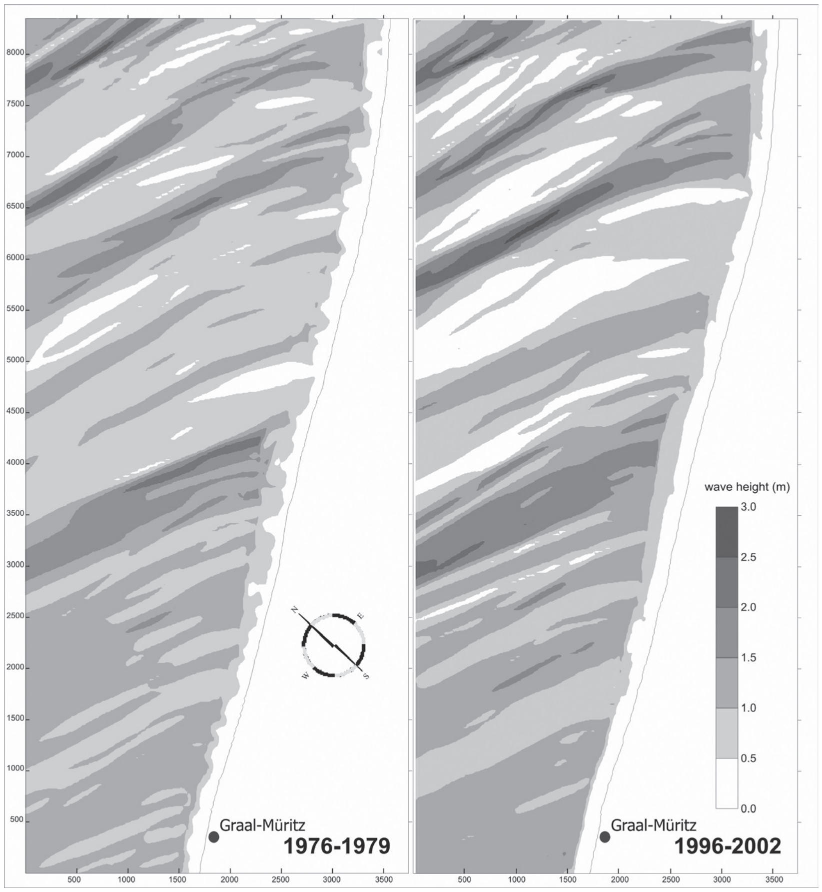


Figure 7. Wave heights for the modelled 5-yearly storm (Hs 1.40 m, Tm 6.00 s, Dir 276°) in the Graal-Müritz area: (a) modelled wave heights for the 1976-1979 bathymetry; and (b) modelled wave heights for the 1998-2002 bathymetry. Note the areas of wave focussing in the north and centre of the coastline. For the location of the modelling area, see Figures 1.and 5.

of h_i = 10 m (Diesing *et al.,* 2006). However, short-term changes and, therefore, sediment transport, were shown to occur down to depths of 8-13 m, as observed from repeated side-scan sonar surveys, following dredging. The dredged furrows at Graal Müritz were almost completely refilled after 6 months (Diesing, 2003); those at Wustrow showed considerable infilling, after 10 months (Krause, 2002). Interestingly, the bedforms offshore from Wustrow are located also in water depths lying beyond those associated with wave-induced sediment transport. According to Lemke *et al.* (1994), these bedforms are the result of currents generated by the inflow of saline bottom water from the North Sea. Bedform changes that have been observed indicate flow velocities of 70-100 cm/s; these only seldomly occur, typically on time-scales of months-years (Lemke *et al.,* 1994). These NE-flowing currents cause the transport of sediments in offshore areas beyond the zone of wave-induced transport. Thus, both the dominant directions of wave-induced sediment transport and the current-induced sediment transport are in a NE direction. Such transport moves sediment out of the area, to Darss, where it is deposited, accumulating along the Darss Peninsula. Long-term accretion in this area is indicated also by a sequence of Holocene beach ridges (Lampe, 2002), running parallel to the present-day coastline (Figure 6). The Darss area is a National Park, where extraction activities are prohibited.

Overall, the coast from Warnemünde to Darss has only a limited amount of marine sand resources: the cover of Holocene sand is thin (Diesing, 2003; Krause, 2002), whilst there is little contemporary input from the rivers. The main sediment source is erosion of retreating cliff sections (Hoffmann and Lampe, 2007). An increase in storminess in the Baltic Sea area, as reported by Kont *et al.* (2005), together with a rise in sea level will result in an increase in cliff erosion; hence, increase the supply of sediment to the coastal zone (Hoffmann and Lampe, 2007). At the same time, it will lead also to an increase in beach erosion and sediment transport, by wave action. Extraction of sediment for local beach nourishment may bring offshore sand into the zone of wave-dominated sediment transport, where it will be transported towards the northeast. Extraction of sediment for industrial use will leave the system completely.

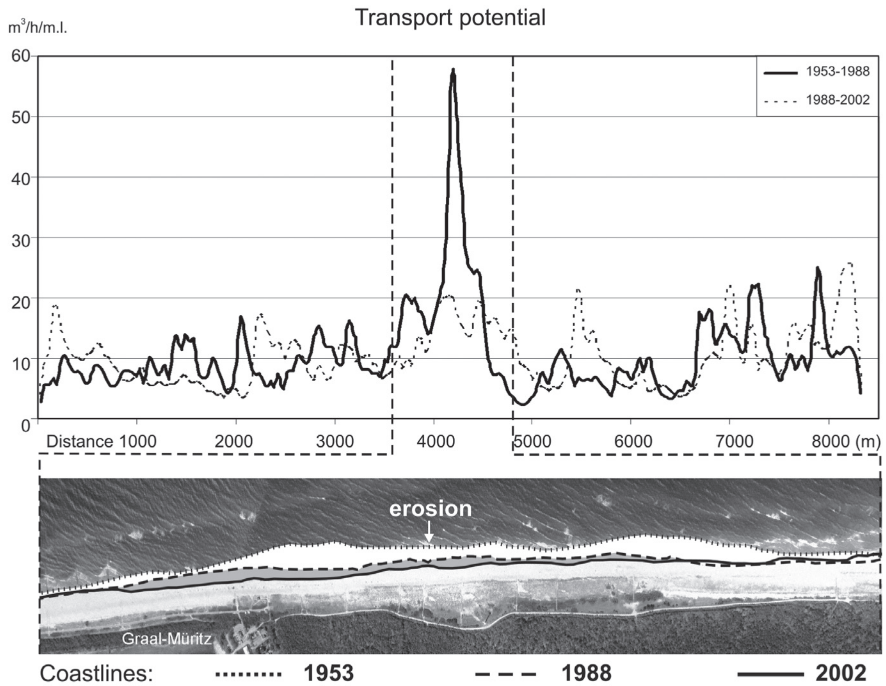


Figure 8. Sediment transport potential calculated by SMT for the coast from Warnemünde to the Darss Peninsula. Note the large peak in transport potential for the old bathymetry, which has now completely disappeared. The aerial photograph shows the location of the peak in sediment transport potential along the coastline between Graal Müritz to Dierhagen (the area between the dotted lines in the graph). Also indicated are the coastlines of 2002, 1988 and 1953.

CONCLUSIONS

Few examples exist of direct coastal erosion caused by marine sand extraction; these relate to the removal of sand from the upper shoreface. In the Baltic Sea, dredging takes place well beyond the depth of wave action, i.e. in water depths of 8-13 m. No direct relationship was found between changes in bathymetry and those at the coastline. It is suggested that the coastal changes result mainly from extensive coastal protection works carried out in the area. Therefore, it is difficult to assess the effects of dredging on the coastline in the area of Warnemünde to Darss. However the present study has indicated a few points of concern, as outlined below.

– Only very small changes in bathymetry (1-2 m) are sufficient to cause significant modifications in sediment transport potential at the coast and, thus, alternations in the patterns of erosion and accretion. Therefore, care should be taken that extraction does not cause lasting changes in the bathymetry.
– Overall, the coast from Warnemünde to Darss is an eroding coast. Sediment is transported in a NE direction by both wave action and currents, induced by the inflow of North Sea water. Such material is deposited in the Darss area, in a National Park, where dredging is prohibited.
– There is very little input of sediment into the system. The main source of sediment is material eroded from cliff sections. Any sand that is removed by MA extraction, for industrial use, will have a negative effect on the total sediment budget at the shoreline.

ACKNOWLEDGEMENTS

This research is funded by the European Union, within the framework of the EUMARSAND Project (HPRN-CT-2002-00222). We would like to thank Jürgen Monk from the BSH (Bundesamt für Seeschifffahrt und Hydrographie) for his help in obtaining the bathymetric data; likewise, Knut Sommermeier from StAUN-Rostock (Staatliche Ämter für Umwelt und Natur Rostock), for making available wave and current data from das Messnetz. We are grateful to Michael Collins and Klaus Schwarzer for their valuable comments on previous versions of this paper and to Markus Diesing for his help to find information. Also, we would like to thank three anonymous reviewers, for their constructive comments on the manuscript.

LITERATURE CITED

Anctil, F. and Ouellet, Y., 1990. Preliminary evaluation of impact of sand extraction near Iles-de-la-Madeleine Archipelago, Québec, Canada. *Journal of Coastal Research,* 6(1), 37-51.

Bailard, J.A., 1981. An energetic total load sediment transport model for a plane sloping beach. *Journal Geophysical Research*, 86(C11), 10938-10954.

Bender, C.J. and Dean, R.G., 2003. Wave field modifications by bathymetric anomalies and resulting shoreline changes: a review with recent results. *Coastal Engineering*, 49, 125-153.

Brampton, A.H. and Evans, C.D.R., 1998. Regional seabed sediment studies and assessment of marine aggregate dredging. London, UK: Construction Industry Research and Information Association, *Report CIRIA C505*, 82p.

Byrnes, M.R.; Hammer, R.M.; Thibaut, T.D., and Snyder, D.B., 2004a. Physical and biological effects of sand mining offshore Alabama, USA. *Journal of Coastal Research,* 20(1), 6-24.

Byrnes, M.R.; Hammer, R.M.; Thibaut, T.D., and Snyder, D.B., 2004b. Effects of sand mining on physical processes and biological communities offshore New Jersey, USA. *Journal of Coastal Research*, 20(1), 25-43.

Diesing, M., 2003. Die Regeneration von Materialnahmestellen in der südwestlichen Ostsee unter besonderer Berücksichtigung der rezenten sedimentdynamik. Kiel, Gemany: Christian-Albrechts Universität, Ph.D. thesis, 158p.

Diesing, M.; Schwarzer, K.; Zeiler, M., and Klein, H., 2006. Comparison of marine extraction sites by means of shoreface zonation. *Journal of Coastal Research*, Special Issue 39, 783-788.

G.I.O.C., 2002. Grupo De Ingeniería Oceanográfica y de Costas, University of Cantabria. Santander, Spain, *Manual de Usuario del SMC.*

Hayes, M.O. and Nairn, R.B., 2004. Natural maintenance of sand ridges and linear shoals on the U.S. Gulf and Atlantic continental shelves and the potential impact of dredging. *Journal of Coastal Research*, 20(1), 138-148.

Hilton, M.J. and Hesp, P., 1996. Determining the limits of beach-nearshore sand systems and the impact of offshore coastal sand mining. *Journal of Coastal Research*, 12(2), 496-519.

Hoffmann, G. and Lampe, R., 2007. Sediment budget calculation to estimate Holocene coastal changes on the southwest Baltic Sea (Germany). *Marine Geology*, 243, 143-156.

IHO –International Hydrographic Organization., 1998. *IHO Standards for Hydrographic surveys*, 4th edition. Monaco: International Hydrographic Bureau, Special Publication 44, 23p.

Janke, W. and Lampe, R., 1998. Die Entwicklung der Nehrung Fischland – Darss – Zingst und ihres Umlandes seit der Litorina-Transgression und die Rekonstruktion ihrer subrezenten Dynamik mittels historischer Karten. *Zeitschrift für Geomorphologie N.F*, 112, 177-194.

Kelley, S.W.; Ramsey, J.S., and Byrnes, M.R., 2004. Evaluating shoreline response to offshore sand mining for beach nourishment. *Journal of Coastal Research*, 20(1), 89-100.

Kirby, J.T. and Dalrymple, R.A., 1983. A parabolic equation for the combined refraction-diffraction of Stokes waves by mildly-varying topography. *Journal of Fluid Mechanics*, 136, 543-566.

Kont, A.; Orviku, K.; Jaagus, J.; Rivis, R., and Tonisson, H., 2005. Evolution of sandy beches in Estonia as indicator of increased storminess in the Baltic Sea region. *In*: Herrier, J.-L.; Mees, J.; Salman, A.; Seys, J.; Van Nieuwenhuyse, H., and Dubbelaere, I. (eds.), *Proceedings Dunes and Estuaries 2005 – International Conference on Nature Restauration Practices in European Coastal Habitats*. Koksijde, Belgium: VLIZ Special Publication 19, xiv, pp. 607-609.

Krause, J.C., 1998. Auswirkungen des Sand- und Kiesabbaus auf das Makrozoobenthos an des Küste vor Mecklenburg-Vorpommern –Ein Überblick der vorläufige Ergebnisse aktueller Untersuchungen. *In*: Von Nordheim, H. and Boedeker, D. (eds.), *Umweltvorsorge bei der marinen Sand- und Kiesgewinnung*. BLANO-Workshop, INA Insel Vilm, Germany, BFN-skripten 23, pp. 58-71.

Krause, J.C., 2002. The effects of marine sand extraction on sensitive macrozoobenthic species in the southern Baltic Sea. Rostock. Germany: University of Rostock, Ph.D. thesis, 127p.

Lampe, R., 2002. Holocene evolution and coastal dynamics of the Fischland-Darss-Zingst peninsula. *Greifswalder Geographische Arbeiten*, 27, D1, 155-163.

Lemke, W.; Kuijpers, A.; Hoffamn, G.; Milkert, D., and Atzler, R., 1994. The Darss Sill, hydrographic threshold in the southwestern Baltic: Late Quaternary geology and recent sediment dynamics. *Continental Shelf Research*, 14, 847-870.

Maa, J. P.-Y. and Hobbs III, C.H., 1998. Physical impact of waves on adjacent coasts resulting from dredging at Sandbridge Shoal, Virginia. *Journal of Coastal Research*, 14(2), 525-536.

Maa, J.P.-Y.; Hobbs III, C.H., and Hardaway JR., C.S., 2001. A criterion for determining the impact on shorelines caused by altering wave transformation. *Journal of Coastal Research*, 17(1), 107-113.

Maa, J.P.-Y.; Hobbs III, C.H.; Kim, S.C., and Wei, E., 2004. Potential impacts of sand mining offshore of Maryland and Delaware: Part 1 –Impacts on physical oceanographic processes. *Journal of Coastal Research*, 20(1), 44-60.

Manso, F.; Radzevicius, R.; Blažauskas, N.; Balay, A., and Schwarzer, K., this volume. Nearshore dredging on the Baltic Sea. State after cessation of activities and regeneration assessment.

Mblu Mblu, Ministerium für Bau, Landesentwicklung und Umwelt des Landes Mecklenburg-Vorpommern., 1995. *Generalplan Küsten- und Hochwasserschutz Mecklenburg-Vorpommern. Schwerin*, 108p

Nairn, R.; Johnson, J.A.; Hardin, D., and Michel, J., 2004. A biological and physical monitoring program to evaluate long-term impacts from sand dredging operations in the United States outer continental shelf. *Journal of Coastal Research*, 20(1), 126-137.

Pearce, F., 1996. Crumbling away. Is dredging the villain in the drama of Britain's eroding coasts? *New Scientist*, 152, 14-15.

Simons , R. and Hollingham, S., 2001. *Marine aggregate dredging: a review of current procedures for assessing coastal processes and impact at the coastline*. London, UK: Civil and Engineering Department, UCL, *Technical Report HYD10401*, 81p.

Soulsby, R. (1997). *Dynamics of marine sands: A Manuel for Practical Applications.* London, UK: Thomas Telford Publications, 249p.

Suter, J.R.; Mossa, J., and Penland, S., 1989. Preliminary assessments of the occurrence and effects of utilization of sand and aggregate resources of the Louisiana inner shelf. *Marine Geology*, 90, 31-37.

Weilbeer, H. and Zielke, W., 1999. Modellierung großräumiger hydrodynamischer und morphologischer Prozesse an den Außenküsten von Fischland, Darß und Zingst. *Die Küste*, 61, 177-194.

Journal of Coastal Research	SI	51	215-226	West Palm Beach, Florida	Summer 2010

The Physical and Biological Impact of Sand Extraction: a Case Study of the Western Baltic Sea

Jochen Christian Krause[1], Markus Diesing[2*] and Günther Arlt[3]

[1] Federal Agency for Nature Conservation of Germany
Isle of Vilm
D-18581 Putbus, Germany
jochen.krause@bfn-vilm.de

[2] Institute of Geosciences
Christian-Albrechts-University
Olshausenstr. 40-60
D-24098 Kiel, Germany

* Present address:
Centre for Environment, Fisheries and Aquaculture Science
Pakefield Road
Lowestoft, Suffolk
NR33 0HT, United Kingdom

[3] University of Rostock
Institute of Bioscience
Marine Biology
D-18059 Rostock, Germany

ABSTRACT

In autumn 1997, approximately 320,000 m^3 of sand were extracted from a site located ca. 2.5 km off Wustrow, Germany, Western Baltic Sea. The physical impacts of dredging on the sea floor are assessed on the basis of side-scan sonar, sediment texture, and oxygen profile approaches. Benthic macrofaunal effects are analysed, in terms of species, abundance, and biomass (SAB), addressing the responses of sensitive and non-sensitive species.

Seabed modification was patchy within the dredging site. Morphology, texture, and oxygen characteristics returned to pre-dredging conditions over most of the site, during the first year of post-dredging. A smaller part of the area deepened by ca. 5 m and caused by multiple dredge furrows, was altered more drastically. During the year following the extraction, a shift to finer sediments with a higher organic carbon content and reduced oxygen levels was observed, at this location. Sensitive benthic species abundance did not recover to pre-impact levels, within a year after dredging. Slow recovery of the sensitive species can be overlooked easily by common environmental assessment measures, such as the SAB approach. Related to benthic habitats, environmentally-sound dredging practices should consider the various impacts that the creation of deep pits can have on the seabed, and compared those of shallow and isolated furrows.

ADDITIONAL INDEX WORDS: *aggregates, mining, side-scan sonar, sediment micro- profiles, macrozoobenthos, SAB approach, sensitive benthic species, dredging furrows, recolonisation, recovery.*

INTRODUCTION

Whilst several studies have investigated the effects of marine sand dredging on benthic associations (e.g. Essink, 1998; Øresundkonsortiet, 1998; van der Veer, Bergman, and Beukema, 1985), a substantially lower number of studies have dealt with gravel extraction (Boyd *et al.*, 2005; Cooper et al., 2007; Kenny and Rees, 1994, 1996); fewer still have investigated Baltic Sea conditions (Bonsdorff, 1980; Øresundkonsortiet, 1998). In order to develop an improved understanding of the physical recovery and macrofaunal recolonisation processes of dredged habitats in the western Baltic Sea, a dredging operation has been examined, at different spatial scales. At a broad scale, results were obtained from: (a) acoustic devices which covered an area > 1,000,000 m^2; (b) grab samples, permitting examination of processes occurring over a few m^2; and (c) sediment cores and oxygen profiles, providing information at a millimetre-scale. The overall objective of this study was to develop a better understanding of the physical and biological impact of dredging operations, within the Baltic Sea.

The western Baltic Sea (Schwarzer , this volume) can be regarded as a brackish water transition zone of decreasing salinity (5 - 20 psu). Faunistic diversity reaches its minimum within this salinity range (*horohaloclinicum*; Kinne, 1971, Remane, 1940). Macrofaunal species in this zone have often been described as \`transgressive´ or \`opportunistic´ (Gray, 1979; Pearson and Rosenberg, 1978); relatively \`immune´ to many anthropogenic stress factors (Wilson, 1994). However, Wilson and Elkaim (1991) have shown that not all estuarine species act as opportunists. The present study focuses upon the sensitive species, assuming that they are an important part of the local biodiversity: these mostly rare species, in accordance with the \`flush and crash´ speciation model (Piraino, Fanelli, and Boero, 2002), ensure the continuation of biological diversity.

For this study, species sensitive to physical disturbance of the seabed are defined following a concept of the \`Benthos Ecology Working Group´ of the International Council for the Exploration of the Sea (ICES), published in 1994 (ICES, 1994) and reviewed in 1995 (ICES, 1995). The ICES list of general criteria was published to develop "biogeographically-specific" lists for macrobenthic communities, to permit the prediction of disturbance related to any physical modification of the seabed. The list was based upon the assumption that, initially, any impact has a negative effect on individuals within a specific area. Sediment extraction can harm macrobenthic individuals, by damaging their bodies, burrows or shells, or by removing animals (potentially, with their tubes) from the substratum. However, disturbance can harm significantly the affected pop-

DOI: 10.2112 / SI51-020.1 received 23 February 2007; accepted in revision 1 April 2008.

ulations, only if the autecological characteristics of the population are characterised predominately by `sensitive´ features. The main criteria in the definition of `sensitive´ species are: a low growth rate; reduced regeneration capacities; low fecundity; infrequent recruitment; low propagule mobility; specialised habitat requirements; or narrow substratum tolerances. In contrast, macrobenthic populations with `non-vulnerable´ features are regarded as being resistant to the impact, e.g. r-strategic and highly mobile species. This ICES guideline does not draw up a list of species, but, rather, identifies standard criteria to establish regional lists. Table 2 from KRAUSE, VON NORDHEIM, and GOSSELCK (1996) provide an overview of the sensitive macrobenthic species, for the planned extraction sites of region under investigation.

SETTING

The study site was located 2.5 km northwest of Wustrow, Germany, off the coast of the Fischland Peninsula (Figure 1), in water depths of between 10 and 12 m, below Mean Sea Level. The site is situated to the south of the Darss Sill,a shoal that inhibits the inflow of bottom water of higher salinity, into the central Baltic Sea. As a consequence, salinities are usually higher (> 10 psu), to the southwest of the Darss Sill, than to the northeast of it (≈ 7 psu).

The dredging site "Wustrow II" encloses a surface area of approximately 1,100,000 m^2. The seafloor consists of moderately-sorted fine sands (Udden-Wentworth scale, TAUBER and LEMKE (1995)). The mean grain-size of surface sediments ranges from 210 to 250 µm, whilst the average thickness of the deposit amounts to 1.9 m, overlying till (StAUN Rostock, pers. comm.).In November 1997, approximately 320,000 m^3 of sand were extracted from the site, by trailer suction hopper dredging. This method leads to the production of shallow linear or curved furrows on the seafloor (BOYD *et al.*, 2004). Extracted sediments were utilised for beach replenishment, on the Fischland Peninsula.

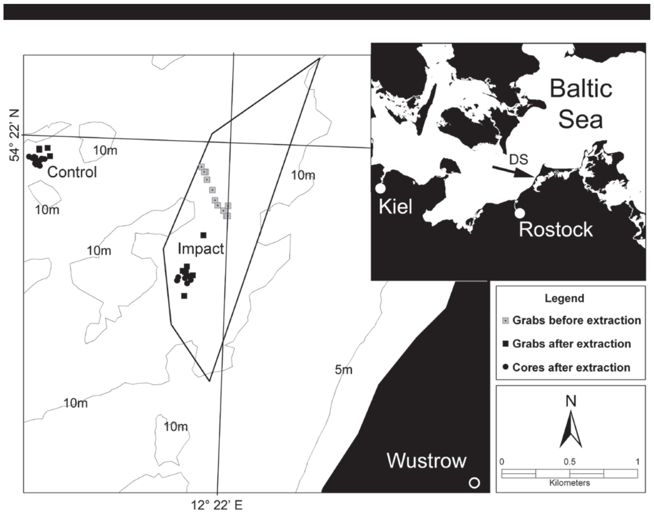


Figure 1. Map showing the location of the dredging site Wustrow II (black polygon in Figure), in the western Baltic Sea. Symbols of pre-extraction control samples are overlain by post-extraction symbols. Video imagery and observations of SCUBA divers suggested that impact sample sites be relocated after extraction to the more heavily impacted area. According to video imagery, control sites and impact sites were homogeneous sandy plains, before extraction. DS – Darss Sill.

METHODS

Side-Scan Sonar

Side-scan sonar surveys were carried out on 30 March, 1998 and 17 September, 1998, aboard *RV Littorina*. A Klein 595 dual-frequency (100 and 384 kHz) side-scan sonar was operated, in high-frequency mode, in order to permit the highest-resolution imaging, with a range of 75 m and a typical altitude of 8 - 10 m. Sonar returns were recorded on paper print-outs. Differential GPS was used for vessel positioning. The sonar tow fish had a layback of 15 - 20 m, whilst a sound velocity of 1500 ms^{-1} was assumed.

The analogue paper records were scanned and georeferenced, according to the method of KUBICKI and DIESING (2006). For every logged ship position (1 min^{-1}), four additional points were computed for the two side-scan sonar channels, describing both swath and water column extent. The latter points were assigned lying on the side-scan centre line . A geo-referencing method of 'rubber sheeting' was then applied (see KUBICKI and DIESING, 2006 for details); in this, the sonographs were stretched, or compressed, between two neighbouring geo-referenced points. In this way, the entire water column was removed . This method introduces positioning errors of the order of a few metres. In the absence of a more sophisticated method, to convert analogue print-outs into geo-referenced data, it was the "method-of-choice", bearing in mind its limitations.

The georeferenced side-scan sonar data were projected in Universal Transverse Mercator (UTM) projection, then displayed in a geographical information system (Esri ArcView 3.2). Blocks of 100 m by 100 m, in size, were defined according to the UTM grid. The number of identifiable tracks, per block, was counted visually for each of the surveys. As a result, maps displaying the number of dredge tracks per 100 m by 100 m block, were created.

Ground-truthing was undertaken using an underwater video camera, with an on-board control and positioning system; it was towed at an altitude of < 1 m over the sea bottom. Two transects, running from east to west and north to south, were surveyed: 4 months before extraction (August 1997); and 1 month (December 1997), , 6 months (May 1998), and 10 months (September 1998) after.

Sampling

The effects of the extraction on the sediment and macrobenthic communities were examined, using a classical BACI (before-after-control-impact) approach (HEWITT, THRUSH and CUMMINGS, 2001). The various sample locations are plotted in Figure 1. Pre-extraction samples were collected from the centre of the intended dredging site, but sites were relocated after the extraction took place (as UW-video observations located the actual centre of the dredging activity). In contrast, the control sites were not relocated. Grab and core samples were collected from both the control and impact sites. Grab samples were collected using a `heavy´ van-Veen-grab (0.1 m²), according to the international recommendations and calibration guidelines for monitoring macrozoobenthos in the Baltic Sea (HELCOM, 1988; ICES, 1990). A minimum of three replicates were collected at each sampling site. The minimum penetration depth was 10 cm. Grab samples were collected 4 and 2 months before and 1, 4, and 10 months after extraction. 6 and 10 months after extraction, 6 to 12 core samples were collected by SCUBA divers, at the control and impact sites, respectively. These cores were taken by means of large plastic tubes (10 cm diameter, 30 cm in lenght), which could be closed underwater, at both ends. The minimum penetration depth here was 15 cm. The cores were sampled directly, at the extraction site, from the furrows. Typically, the distance between the cores was 2 m. The sample positions were assumed to be the ship's position, as measured by differential GPS (SCUBA divers were attached to the boat by a rope).

Sediment Analyses

Grain Size and Carbon Content

From each site, a grab sample was transported to the laboratory, for analysis of grain-size distribution and organic carbon content. Mean grain-size was calculated from one sub-set, using the wet sieving method of Dyer (1986). Another portion was dried for 24 h at 60 °C and was powdered. These samples were subdivided; one half was treated with excess 1M HCl (hydrochloric acid), then dried for 12 h; the other remained untreated. The carbon content of both sub-samples was determined using a "CN-Analyser" (Fision Instruments). Finally, organic carbon content was calculated by subtracting the C-values of the treated sub-samples (inorganic C), from the C-values of the untreated subsamples (total C); this was noted as a proportion of the total sediment mass.

Oxygen Profiles

SCUBA divers collected all of the cores within a single day. The collecting time was approximately two hours, for 12 cores. Measurements on the core material were made within 12 h, in a field laboratory. During measurements, untreated cores were stored open in the dark and at a temperature of approximately 10 °C.

Oxygen concentration profiles were recorded in the sediment cores, with a robust stainless steel needle electrode (Microscale Measurements), containing a sensing tip (120µm in length) for oxygen (Au-plated Pt cathode) of 120 µm (Van Gemerden *et al.*, 1989). Electrodes were polarised at least one hour before commencement of the measurement. A cellulose-nitrate membrane was installed, prior to the measurements. These were replaced each time. Calibration was carried out in an extra tube with black sediment and saturated seawater (0 % and 100 % air saturation), in which the oxygen content was measured by a calibrated electrode (WTW EOT 196). A micromanipulator was used to insert the electrode, step-wise into the sediment. Signals from the sensor were digitised by an analogue-to-digital converter, then transmitted to a notebook using the software WINDAQ (Dataq Instruments). Each measurement was repeated at least once, for each core. Samples were processed in a method similar to those of Visscher, Beukema and van Gemerden (1991) and Vopel *et al.* (1998). For further data analyses, the mean oxygen concentration for each core was calculated, in 1 to 5 mm steps.

Macrofauna

Each grab sample replicate was sieved at sea, using a 1 mm screen, before preserving the sample with 4 % buffered formosaline solution. At the laboratory, organisms were extracted and identified to species level, except for Nematoda, Turbellaria, Bryozoa, Hydrozoa, Nemertini, Oligochaeta, and Diptera, as identification was impractical. Organisms were blotted (duration varied from a few seconds for small polychaete, to several minutes for large bivalves); afterwards, the wet mass was determined with a precision of 0.1 mg. Molluscs were weighed always with shell. Identified species were classified as endangered, according to existing local and biogeographic red lists (Helcom, 1998; Merck and von Nordheim, 1996) and as \`sensitive´ or \`non-vulnerable´, according to guidelines of the \`Benthic Ecology Working Group of ICES´ (ICES, 1994; 1995), adapted for sediment extraction by Krause, von Nordheim and Gosselck (1996).

Average species abundance and biomass were calculated per square metre, for all the sampled taxa. Number of species, abundance, and biomass were compared between control and impact sites. To avoid double usage of the same data set, neither control site data nor these of impact sites were tested statistically, between times i.e. before/after dredging. The results showed non-normal distributions; thus, transformations were avoided, with differences tested by non-parametric Mann-Whitney U and Wilcoxon tests (Bortz, Lienert and Boehnke, 1990). Contents of grab and core samples were analysed separately. Analyses were performed using a spreadsheet calculation (MS Excel) and NCSS (Hintze, 2001).

Out of 50 taxa, only 28 species were used for the multivariate statistical analysis. All other taxa were excluded from the analyses, for various reasons, i.e. not systematically sampled species like epifauna, and hyperbenthic species (e.g. *Neomysis integer*); low taxonomic resolution (e.g. Diptera); patchily distributed (e.g. *Mytilus edulis*) and species which occurred within less than 1 % of all of the samples (e.g. *Calliopius laeviusculus*). The data were used for cluster analysis and non-metric multi-dimensional scaling (nMDS) ordination, according to Clarke and Warwick (1994). The analyses were based upon Bray Curtis (Steinhaus) similarity of the fourth-root transformed abundance data. In this study, the (hierarchical) \`unweighted arithmetic average clustering´, also called \`UPGMA´ (Legendre and Legendre, 1998) was used; it is a standard method used in benthic ecology (Clarke and Warwick, 1994).

All statistical calculations and procedures were performed with the software packages PCOrd (McCune and Mefford, 1999), Primer 5 (Clarke and Warwick, 1994) and NCSS

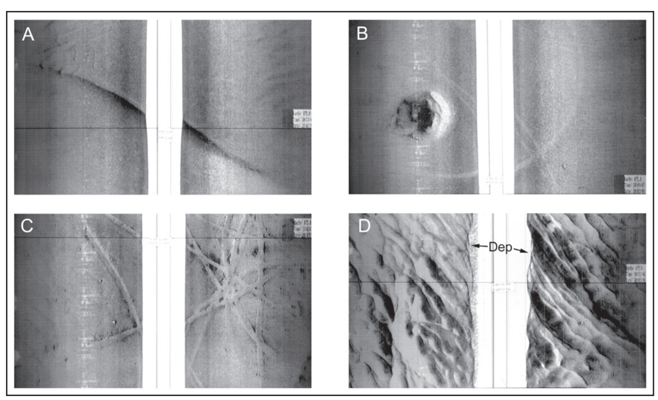


Figure 2. Representative examples of sea floor morphology revealed from 384 kHz side-scan sonar data, 4 months post-dredging: (a) sandy dunes in the control site; (b) pit of 15 m diameter and 3 m depth; (c) dredge furrows of approximately 2 m in width; and (d) multiple dredge tracks, building a depression of up to 5 m deep at the extraction site. Note: uncorrected sonographs, with a slant range of 75 m.

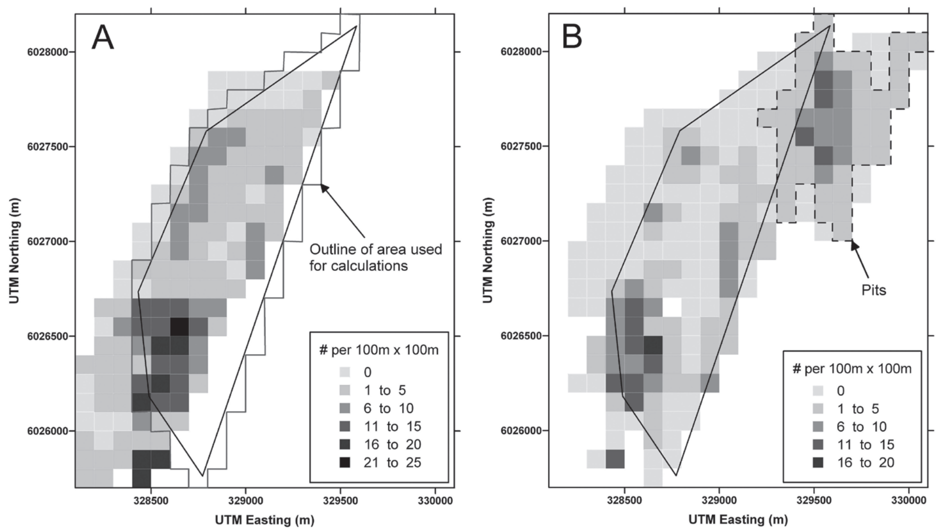


Figure 3. Number of dredge tracks per 100 m x 100 m block: (a) March 1998, 4 months post-dredging; (b) September 1998, 10 months post-dredging. Hatched line indicates area affected by static dredging causing pits (see Figure 2b.).

(Hintze, 2001). Original data were stored and reassigned for calculations, using Access and Excel (Microsoft). The results were visualised using Grapher (Golden Software) and SigmaPlot (SPSS Inc.).

RESULTS

Seabed Morphology

From the UW video observations and side-scan sonar data, it is evident that the subaqueous dunes were present seafloor off Wustrow was predominantly sandy, with small patches of coarse-grained lag deposits to the west of the surveyed area, with wavelengths of 40 to 70 m (Figure 2a). In an area outside of the designated boundary, to the northeast of the dredging sites (Figure 2b), side-scan sonar imagery (validated by diver observations) revealed dredge pits of 10 to 40 m in diameter and up to 4 m in depth (Figure 2b). Dredge tracks of approximately 2 m in width, with a mean depth of 0.5 m (Figure 2c), were widely distributed. Where the seafloor was dredged repeatedly, multiple dredge tracks created larger depressions. In such areas, the seafloor was deepened by 3 to 5 m (Figure 2d).

Such multiple dredge tracks were present in the southwest of the designated extraction site (Figure 3a and 3b).

The intensity of the dredging impact was estimated, by evaluating the number of dredge tracks found in 100 m x 100 m blocks of the seabed. Some 142 blocks were assumed to lie within the extraction site, covering an area of 1,420,000 m^2 (Figure 3a). Four months after dredging, at least 59 % (840,000 m^2) of the site, had at least one visible furrow (Figure 3a). Ten months post-dredging, 53 % (750,000 m^2) of the dredging site had at least one furrow. This calculation does not consider the “out-of-area” dredge zone, to the SE and N (approx. 520,000 m^2, Figure 3b). Most disturbances occurred in the southwestern part of the extraction site (Figure 2d). This area contained fewer dredge tracks in September, than in March 1998.

Alteration of Sediment Characteristics

SCUBA diver observations, 6 and 10 months after extraction, indicated differences between the sediment characteristics between the control and impact sites. The flat sea bed at the control sites consisted of yellow sand whereas, following extraction at the impact site, the seafloor was composed of black and muddy sediments; occasionally, *Beggiatoa* mats were observed in the depressions and furrows.

Before dredging, the upper 10 cm of the control sites consisted of fine to medium sands (mean d = 2.4 ϕ); they were low in organic carbon (C_{org}) content (< 0.2 %) (Figure 4a). Sediments from the licensed dredging areas consisted of similar medium-sized sands (mean d = 1.8 ϕ), with a similar low organic carbon content (C_{org} < 0.35 %) (Figure 4a). Following extraction, the sediments of the dredged sites were altered fundamentally, whilst the sediments of the control sites were unchanged. Following dredging, the upper sediment layer consisted of fine sands (mean d = 2.7 ϕ) enriched in organic content ($C_{org} \approx 1.9$ %) (Figure 4a).

The core samples showed that sediments at the control sites were relatively homogeneous, not changing markedly over time. Conversely, the upper sediment layer at the impact sites revealed a fining trend, over time (Figure 4b). Thus, it may be concluded, at the impact sites, finer sediments enriched in organic carbon were accumulated on top of the original sediment (Figure 4b).

Six months after dredging the oxygen profiles from the impact sites were almost identical to these representative of pre-dredging conditions. There was a significant (n = 23; p = 0.05; Wilcoxon rank test) difference in the oxygen penetration depths, between the control site cores (mean depth: -10.9 ± 3.9 mm (11 cores; 22 profiles) and those collected from the bottom of the dredged pits (mean depth: -7.4 ± 3.6 mm (12 cores; 24 profiles)) (Figure 5a). Ten months after dredging, oxygen depletion was measured in sediment cores from the dredged furrows (mean depth: -1.6 ± 2.8 mm (3 cores; 6 profiles)), whereas the typical control site cores were more

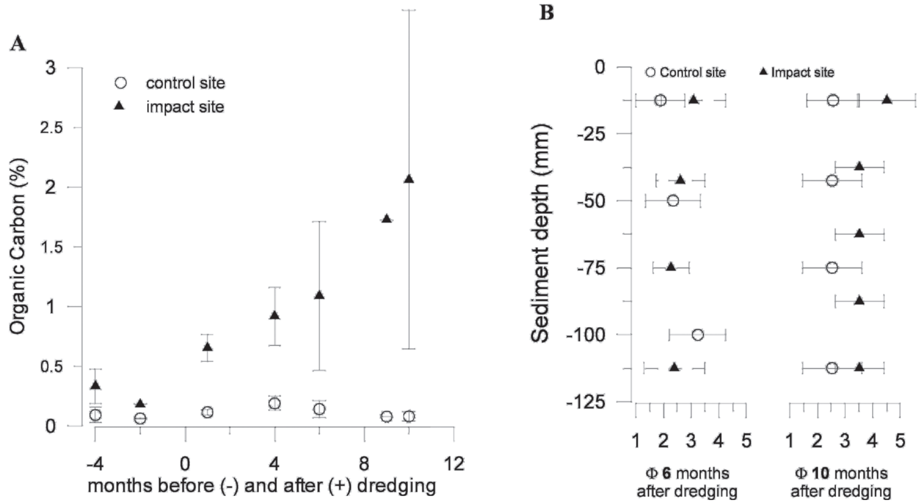


Figure 4. (a) Mean organic carbon content of one dissected representative, core at the control (open circles) and impact site (closed triangles), before and after dredging. Error bars indicate the standard deviation between the vertical sections of the core; and (b) Mean grain-size (ϕ) in 1, of the 6 sediment cores, used for the oxygen profile measurements, at the control site (open circles) and the impact site (closed triangles), 6 and 10 months after dredging. Error bars indicate the standard deviation of the sample.

oxygenated (mean depth: -38.3 ± 7.6 mm (3 cores, 6 profiles)) (Figure 5b).

Alteration of Macrofaunal Assemblages

Fifty macrobenthic taxa were sampled from the control and the impact sites; this is a representative number for this region of the Baltic Sea (Zettler, Bönsch and Gosselck, 2000). The most frequently-occurring taxa were: *Nereis* (*Hediste*) *diversicolor* (100 % occurrence, mean abundance (MA) = 85 individuals m^{-2}); *Hydrobia ulvae* (95 % occurrence, MA = 2475 individuals m^{-2}); *Pygospio elegans* (95 % occurrence, MA = 2703 individuals m^{-2}); *Macoma balthica* (95 % occurrence, MA = 77 individuals m^{-2}); *Scoloplos armiger* (91 % occurrence, MA = 281 individuals m^{-2}); and *Mytilus edulis* (86 % occurrence, MA = 313 individuals m^{-2}). Six species with `sensitive´ population characteristics were sampled before dredging. Four of these species were recorded in, at least, 50 % of control sites samples: *Mya arenaria* (91 % occurrence, MA = 407 individuals m^{-2}); *Bathyporeia pilosa* (82 % occurrence, MA = 121 individuals m^{-2}); *Travisia forbesii* (68 % occurrence, MA = 148 individuals m^{-2}); and *Cerastoderma lamarcki* (50 % occurrence, MA = 188 individuals m^{-2}). Of the other two sensitive species, *Ophelia rathkei* (29 % occurrence) was collected regularly, but only at the control sites; whereas *Bathyporeia pelagica* was generally rare (10 % occurrence).

Table 1. *Impact of dredging – SAB approach. Total number of taxa, abundance in individuals (ind m^{-2}), including standard deviation (sd) and biomass in grams (g m^{-2}), were examined at the control and the impact sites. Key: Time Before/After = month before and after extraction (year/month); (Sample type) Grab = Van Veen grab samples, Core = core samples obtained by SCUBA divers (number of samples from control site / number of samples from impact site); nd = no data; significance tested between samples from control and impact sites (Mann Whitney U-test); (ns) not significant, (*) p< 0.01, (**) p< 0.001.*

Time	Sample type	Total number of species			Abundance ind m-2 (sd)					Biomass g m-2 (sd)				
	(n control / n impact)	Control	Impact		Control		Impact			Control		Impact		
Before														
4 (97/07)	Grab (7/7)	27	31	ns	4031	(253)	6622	(316)	ns	88	(8)	119	(8)	ns
2 (97/09)	Grab (7/6)	24	25	ns	12894	(1308)	8297	(907)	ns	1072	(186)	222	(31)	ns
After														
1 (97/12)	Grab (6/3)	31	18	*	3122	(218)	2679	(366)	ns	56	(3)	87	(18)	*
4 (98/03)	Grab (5/3)	22	6	**	3508	(469)	199	(45)	**	53	(6)	0.6	(0.1)	ns
6 (98/05)	Core (5/5)	17	15	ns	12535	(1540)	4153	(448)	ns	88	(15)	6	(0.5)	ns
10 (98/09)	Grab (3/3)	23	19	**	3517	(329)	6195	(714)	**	62	(5)	21	(2)	**
10 (98/09)	Core (5/5)	11	2	**	5605	(759)	191	(0)	**	438	(120)	0	(0)	**
13 (98/12)	Grab (-/2)	nd	4		nd	1155	(473)		nd	2	(1)			

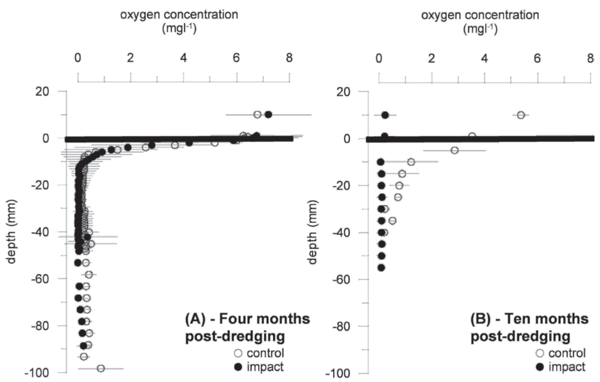


Figure 5. Sediment oxygen profiles at the control and impact site: (a) 4 months (N (cores control) = 11; N (cores impact) = 12); and (b) 10 months ((N (cores control) = 3; N (cores impact) = 3), after extraction, in November 1997. Error bars indicate one standard deviation.

Two cores and a single grab sample collected, respectively, 10 and 13 months after dredging, contained no macrobenthic animals. Comparison of Van Veen grab samples, from both the control and impact sites, 4 (n = 14) and 2 months (n = 13) before dredging, showed no significant differences ($p > 0.05$, Mann Whitney U-test) in number of species, abundance, or biomass (Table 1). One month after extraction, the number of species was lower at the impact sites, than before the dredging. Abundance and biomass in the control and impact sites decreased significantly, compared to the situation before dredging (Table 1). Four months after dredging, the number of species, abundance and biomass were lower at the impact sites, than at the control sites (significant, for richness and abundance) (Table 1). Ten months after dredging, control and impact sites differed significantly for the number of species, abundance, and biomass (Table 1).

The number of non-vulnerable species (Table 2) decreased after dredging at the impact sites (Table 3); they were less abundant 1 month after dredging (Table 3). Sensitive species were not found at the impact sites after dredging (Table 3),

Table 2. *List of `non vulnerable´ and `sensitive´ taxa. From 50 sampled taxa, 28 were used for multivariate statistical analysis. Taxa were determined according to Hayward and Ryland (1990) and Hartmann-Schröder (1996). Abbreviations: RL = red list of endangered species; MV = Mecklenburg-Vorpommern (local list); and BS = Baltic Sea. Class: O = Oligochaeta; P = Polychaeta; A = Amphipoda; C = Cumacea; I = Isopoda; and B = Bivalvia. Feeding Type (categories according to Fauchald and Jumars (1979)): gr = grazer; ff = filter feeder; sdf = selective deposit feeder; n-s df = non-selective deposit feeder; p = predator; gr = grazer; om = omnivore; and sc = scavenger. Category (ICES 1994; 1995): nks = biology not known sufficiently; nv = non-vulnerable; s = sensitive; and b = both. Red list: ** = presumably not endangered at present; P = potentially endangered; 3 = endangered; and 2 = critically endangered.*

Taxon	Class	Feeding type	Cat ICES	RL MV	RL BS
Arenicola marina (LINNAEUS 1758)	P	n-s df	nv		
Aricidea (Allia) suecica ELIASON 1920	P	n-s df	s	P	**
Bylgides sarsi (KINBERG 1865)	P	n-s df	nv		
Eteone longa (FABRICIUS 1780)	P	P	nv		
Marenzelleria viridis (VERRILL 1873)	P	ff & sdf	nv		
Neanthes succinea (FREY & LEUCKART 1847)	P	sc & om	nv		
Nereis (Hediste) diversicolor (O. F. MÜLLER 1776)	P	n-s df & p	nv		
Ophelia rathkei McINTOSH 1908	P	n-s df	s	P	P
Pygospio elegans CLAPARÉDE 1863	P	sdf / gr	nv		
Scoloplos armiger (O.F.MÜLLER 1776)	P	n-s df	nv		
Spio filicornis (O. F. MÜLLER 1776)	P	ff & sdf	nv		
Spio goniocephala THULIN 1957	P	ff & sdf	nks		
Travisia forbesii JOHNSTON 1890	P	n-s df	s	P	P
Heteromastus filiformis (CLAPARÉDE 1864)	P	n-s df	nv		
Capitella capitata (FABRICIUS 1780)	P	n-s df & p	nv		
Oligochaeta	O	sc & om	nv		
Tubificoides benedeni (UDEKEM 1855)	O	sc & om	nv		
Bathyporeia pelagica (BATE 1856)	A	sdf / gr	nks		
Bathyporeia pilosa LINDSTRÖM 1855	A	sdf / gr	s	P	P
Corophium volutator (PALLAS 1766)	A	n-s df	nv		
Gammarus oceanicus SEGERSTRÅLE 1947	A	p & gr	b		
Gammarus salinus SPOONER 1947	A	p & gr	b		
Diastylis rathkei KRØYER 1841	C	(non)-sdf / gr	nv	P	**
Cyathura carinata KRØYER 1848	I	p & om	s	3	3
Idotea baltica (PALLAS 1772)	I	sdf / gr	s		
Cerastoderma lamarcki (REEVE 1844)	B	ff	s	3	2
Macoma balthica (LINNAEUS 1758)	B	sdf / gr & ff	nv		
Mya arenaria LINNAEUS 1758	B	ff	b		

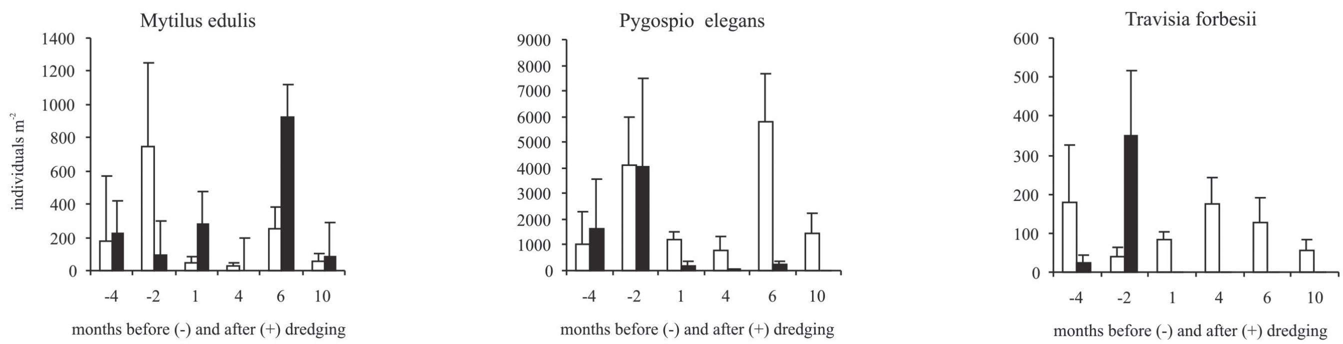


Figure 6. Mean abundance (ind m-2) of three macrobenthic species in samples, at the control and impact sites before (-) and after (+) extraction. Key: Control site - open bars; impact site - black bars. Error bars indicate one standard deviation.

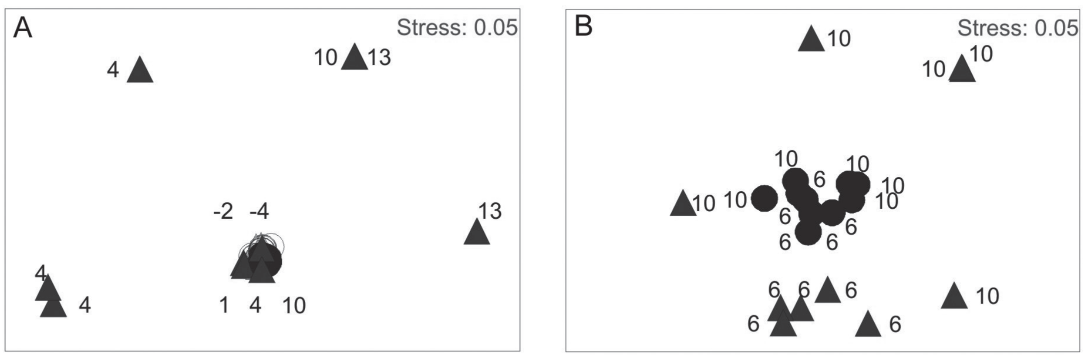


Figure 7. Non-metric MDS ordination of Steinhaus (Bray-Curtis) similarities, computed for fourth root transformed abundances, of 28 macro invertebrate species (Table 2.): (a) for 11 grab sample locations (n = 52); and (b) for 4 core sample locations (n = 20). Note that in (a), most symbols are grouped in the middle of the plot. Therefore, the numbers indicate only the months when samples in the cluster were collected, i.e. and not the specific one shown in (b). Key: open symbols-before extraction; closed symbols-after extraction; circles-control site; triangles- impact site; and numbers indicate months before (-) and after (+) dredging.

Table 3. *Effect of dredging on abundance of non-vulnerable and sensitive species. Total number of taxa and abundance (ind m*$^{-2}$ *and standard deviation) as examined of the `non vulnerable´ and `sensitive´ species (Table 2.), from the total analysis. Time Before/After: Month before and after extraction (Year/Month); sample type: (Grab) Van Veen grab samples and (Core) core samples by SCUBA divers (number of samples from control site / number of samples from impact site); nd = no data; significance of each species type tested between samples from control and impact sites (Mann Whitney U-test): (ns) not significant, (*) p< 0.05, (**) p< 0.01.*

		Non vulnerable species (16 present)					**Sensitive species (7 present)**				
Time	**Sample type**	**Total number of taxa**		**Abundance ind m^{-2} (sd)**			**Total number of taxa**		**Abundance ind m^{-2} (sd)**		
	(n control / n impact)	Control	Impact	Control	Impact		Control	Impact	Control	Control	
Before											
4 (97/07)	Grab (7/7)	16	16	2307 (368)	4292 (403)	ns	5	4	949 (299)	217 (21)	ns
2 (97/09)	Grab (7/6)	16	15	6650 (997)	5029 (994)	ns	3	4	662 (270)	426 (142)	ns
After											
1 (97/12)	Grab (6/3)	15	10	1784 (298)	611 (61)	ns	7	0	158 (27)	0 (0)	**
4 (98/03)	Grab (5/3)	13	3	903 (132)	43 (4)	*	5	0	263 (67)	0 (0)	*
6 (98/05)	Core (5/5)	9	12	6714 (1388)	4108 (433)	ns	3	0	786 (147)	0 (0)	ns
10 (98/09)	Grab (3/3)	13	12	1681 (344)	3825 (751)	ns	5	2	890 (271)	331 (156)	ns
10 (98/09)	Core (3/5)	4	1	2229 (615)	127 (0)	*	3	0	828 (210)	0 (0)	ns
13 (98/12)	Grab (-/2)	nd	2	nd	38 (10)	-	nd	1	nd	28 (0)	-

except for a few small individuals of the bivalve *Cerastoderma lamarcki* and a single individual of the polychaete *Travisia forbesii*, 10 month after dredging (Table 3). At the same time, sensitive species were still sampled regularly at the control sites (Table 3). Differences in abundance before and after dredging of *Mytilus edulis* (non-vulnerable species), *Pygospio elegans* (non-vulnerable species), and *Travisia forbesii (sensitive species)* are illustrated in Figure 6. *Mytilus edulis*, as an indicator for 'non-vulnerable' and robust species, showed some abilities to cope directly with potentially-harmful alterations of the seafloor, after extraction. *Pygospio elegans* showed slow, but immediate recovery, most likely by migration, indicating 'non-vulnerability´ with good recolonising abilities. *Travisia forbesii*, as a 'sensitive' species, dwelled constantly at the control site, but its population did not recover at the impact site within the first year post- extraction (Figure 6).

Differences before and after extraction, at the control and impact sites (all the n values in Table 1) were analysed also by a non-metric multi-dimensional scaling (nMDS) (Figure 7), based upon Bray-Curtis (Steinhaus) similarities of the fourth-root transformed abundances of 28 macrobenthic species (Table 2), from the grab samples (Figure 7a) and core samples (Figure 7b). The results obtained illustrate that macrobenthic communities at the control sites were similar at all times. Additionally, no differences between the grab samples of the impact sites, before extraction, together with control sites before and after dredging, were plotted (Figure 7a). However, some 4,10, and 13 months after extraction, some samples at the impact sites showed a modified macrozoobenthic community;showed similarities (Figure 7a).

This observation illustrates the locally-heterogeneous effect of dredging. In particular, cores sampled by SCUBA divers from within the furrows in the impact sites, showed an overall difference between the macrobenthic community at the control and impact sites (Figure 7b).

DISCUSSION

In general, methods selected for analysis (as outlined above), focus on an improvement of the understanding of the effects of extraction on macrobenthic communities at different spatial scales. The number of samples is in general at the lower limit to describe alterations of benthic assemblages. However, the distribution of macrofauna in the Baltic Sea is due to only a few species occurring, which is less patchy than in other marine ecosystems (Zettler, Bönsch and Gosselck, 2000).

Seasonal effects have been controlled by sampling at the control and impact sites, at the same time. However, it was not possible to compensate for the influence of stochastic effects, such as locally-different salt-water intrusions in the study area (Prena *et al.*, 1997).

Additionally, only a small portion of the dredged area was sampled at high densities. This was possible for this site only, because of intensive observations (by both divers and a towed underwater video camera) showing that, prior to dredging, sediment surface texture and morphology were homogeneous. In the extraction area, the sample sites were relocated after extraction, to a more intensively dredged area. This approach was adopted to describe a `worst case' scenario and to avoid ambiguous results, as the singular extraction of 320,000 m^3 at Wustrow II could be considered to be a small- to medium-sized dredging operation.

Marine aggregates are used in at least 14 countries around the North Sea and the Baltic Sea, for different purposes (ICES, 2001). Such aggregates are extracted using different methods (trailer suction hopper and static suction hopper dredging), in differing environments under various hydrodynamic boundary conditions (e.g. wave-dominated vs. tide-dominated, low-energy vs. high-energy). As a consequence, the impacts of dredging, on benthic organisms and in different seas, are diverse and mostly poorly understood.

Marine aggregate extraction leads clearly to a physical disturbance of the seafloor and benthic communities. Therefore, an increasing number of studies examine physical and biological recovery, but mainly focus upon biological recolonisation. For example, Van Dalfsen and Essink (1997) and Essink (1998) have described the effects of sand extraction on benthic communities in the North Sea, reporting rapid recolonisation by surrounding fauna, within 2 to 4 years. Boers (2005) has measured the recovery of benthic communities, in a 5 - 12 m deep and 1,300 m x 500 m wide pit in the North Sea, on the Dutch Continental Shelf; this showed biomass recovery during a period of 1 to >4 years. Distribution trends in benthic communities of gravel sediments were studied, following a single experimental dredging (Kenny and Rees, 1994, 1996) and cessation of long-term dredging (Boyd *et al.*, 2003, 2004, 2005; Desprez, 2000; and Cooper *et al.*, 2007). Kenny and Rees (1996) have demonstrated rapid infilling of dredge tracks, with sand and gravel , together with rapid recolonisation by dominant species. However, the biomass was still reduced substantially, compared to its pre-dredged state, some 24 months after dredging. The results obtained by Boyd *et al.* (2005) show that the effects of high dredging intensities, on the composition of sediments and fauna, are discernable have some 6 years after the cessation of dredging.

Few studies have analysed the effects of extraction in the Baltic Sea. Bonsdorff (1980) investigated the causes of maintenance dredging in the Gulf of Finland. Øresundkonsortiet (1998), have recording the effects of sand extraction on a sandbank in the western Baltic Sea. Both of these studies have documented only minor impacts, with a rapid recovery of the original macrofauna. Recently, studies have described the physical recovery of extraction sites in the German Baltic Sea (Diesing *et al.*, 2006; Zeiler *et al.*, 2004). Diesing *et al.* (2006) showed a clear influence of water depth on physical recovery, under similar wave energy levels. Dredge tracks in Tromper Wiek were clearly discernable in 20 m of water after 12 years: similar tracks were almost obscured off Graal-Müritz, in 8 - 10 m water depth, within a year.

The modest short-term sediment extraction, examined in this study, resulted in heterogeneous alterations of the bottom morphology (Figures 2 and 3). During the first year post-dredging, physical recovery of areas with single furrows (Figure 2c) was more rapid, than in areas with dense furrows (Figure 2d); this was indicated by the decreasing numbers of detectable tracks by side-scan sonar, particularly in the northern part of the extraction field (Figure 3). Recently published results show that recognisable, but heavily weathered dredge tracks, were limited almost exclusively to the highly impacted southwestern part, some 30 months post-dredging (Diesing, 2007). Boyd *et al.* (2005) had described already such differences, in the long-term recovery of a gravel extraction site.

Quantification of large-scale heterogeneity was made possible by using side-scan sonar data sets. Therefore, its use is recommended as a standard tool for sediment extraction-related environmental impact assessments, albeit combined with adequate ground-truthing.

Major grain-size and organic carbon modifications occurred after the cessation of extraction activities. The new depression (which was previously a flat sea floor), functioned very likely as a sediment trap, collecting fine-grained and organic-rich material. Sediment fining after dredging has been described, elsewhere, by many authors (e.g. JONES & CANDY, 1981; KAPLAN *et al.*, 1975; VAN DER VEER, BERGMAN and BEUKEMA, 1985; and ZEILER *et al.*, 2004),but was ascribed to onboard screening of fine material (e.g. DESPREZ, 2000). According to the licensing procedures, this was not allowed for the extraction site, at Wustrow II.

In many studies, interpretation of the recovery trends is based upon the concept that the impact on the benthic communities ceased immediately following the cessation of dredging, when recolonisation can commence. However, in the present study, 6 to 10 months after dredging, oxygen deficiencies developed in the depression of the impact site: this was related to enrichment of organic material and the presence of stagnant water bodies in the furrows. The accumulation of silt and the development of a black and nearly anaerobic surface layer have been observed by VAN DER VEER, BERGMAN and BEUKEMA (1985), in the Wadden Sea. Similarly, in the Baltic Sea, the accumulation of organic detritus and oxygen deficiency, during periods of water body stratification, has been described for deep extraction, resilting in the creation of pits (NORDEN-ANDERSEN, NIELSEN, and LETH (1992). Conversely, in a 65 m deep natural pit, formed by gas eruption in the North Sea, THATJE, GERDES and RACHOR (1999) observed faunal changes; however, no oxygen deficiencies were detected. It is postulated that these dramatic consequences, on the macrobenthic communities, might occur more easily in low-energy seas, such as the Baltic Sea. However, as relevant measurements are rare, this effect might have been overlooked in previous studies.

The accumulation of fine sediment enriched in organic material and oxygen deficiencies, during summer, can be regarded as a local pattern ascribed usually to eutrophication (BOESCH, 1985). According to local monitoring programmes (LUNG, 1999; LUNG, 2001), these alterations occurred in an area previously affected less by eutrophication (see also RUMOHR, BONSDORFF and PEARSON, 1996). Whereas eutrophication is often widespread, the observed dredging effects were restricted locally and disturbed areas were located adjacent to less disturbed, or undisturbed, areas.

Physical and biological recovery is interlinked and the recolonisation of benthic communities can be expected to differ, depending upon: (a) the nature of the physical impact; (b) the physical recovery stages; and (c) the regional structure of the benthic community. Typically for the Western Baltic Sea, the original fauna was structured mostly by the physical environment, characterised as a marginal sea with estuarine circulation, low salinity, an annual high temperature fluctuation, and stochastic events such as saltwater intrusions (PRENA *et al.*, 1997). The salinity gradient from south to north, in combination with the geological youth of the Baltic Sea, are considered to be the primary factors for the poor taxon richness (BONSDORFF and PEARSON, 1999; REMANE, 1940). The benthic communities in such an environment are considered to be able to cope well with additional physical stress factors (WILSON, 1994). In their classical model, PEARSON and ROSENBERG (1978) have described different successional states of macrofauna, under increasing eutrophication levels. At the extraction site studied here, the common species of the western Baltic Sea, e.g. the bivalve *Mytilus edulis*, were collected regularly after dredging. Conversely, sensitive species such as the polychaete *Travisia forbesii* and the amphipod *Bathyporeia pilosa,* present continuously at the control sites, were not recorded at the impact sites after dredging (Figure 6). According to the concepts of sensitive and non-vulnerable species (ICES, 1994, 1995; KRAUSE, VON NORDHEIM and GOSSELCK, 1996) and the Pearson-Rosenberg model, that at least 3 distinct categories of macrobenthic species population recovery are proposed.

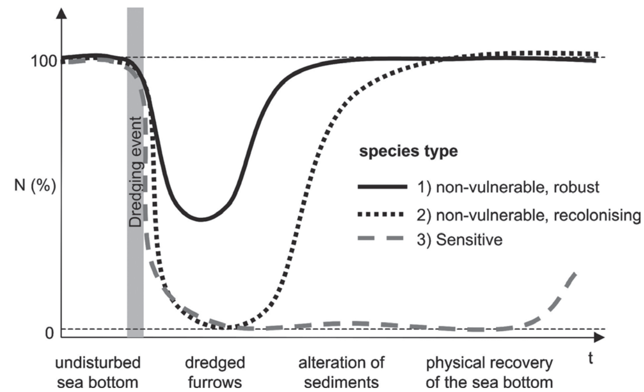


Figure 8. Conceptual model of the changes in the relative abundance (N), throughout time (t) of: (1) a `non-vulnerable´ species having the ability to cope with direct alterations of the physical conditions after dredging (i.e. robust); (2) a `non-vulnerable´ species that recolonises very rapidly after extraction, due to high reproduction rates (non-vulnerable, recolonising); and (3) a `sensitive´ species which cannot cope with post-dredging physical alterations and having limited migration and reproductive abilities, respectively.

(1) Robust non-vulnerable species: species for which occurrence and abundance decrease only slightly after dredging, due to the robustness of individuals to physical disturbances and post-dredging alterations of sediments and water column characteristics (e.g. oxygen conditions). Additionally, such species are omnipresent in the surrounding area, and, as such, larvae and adults can migrate easily into the dredged area (e.g. *Mytilus edulis*, Figure 6)

(2) Recolonising non-vulnerable species: species which are removed almost completely from the sediment, due to dredging and which cannot cope with post-dredging alterations of sediment and water column characteristics. However, due to their omnipresence in the region and rapidly migrating adults and larvae, these species are able to recolonise a dredged site rapidly (e.g. *Pygospio elegans*, *Macoma balthica*; Figure 6).

(3) Sensitive species: species which cannot cope with post-dredging, grain size alterations and oxygen depletion and cannot recolonise an area rapidly, due to low migrating abilities of the adults and larvae (e.g. *Travisia forbesii*; Figure 6).

In Figure 8, idealised development curves of relative abundances are proposed, for the species types described above. Species Type 1, due to its robustness, never disappears from the dredged area. Species Type 2 disappears but, due to well-developed migrating abilities of the larval and adult forms, reappears rapidly in the area. Species Type 3, without the abilities of the two first types, can only recolonise the region after a long phase (time) lag, in which the physical conditions of the sediments and water column have recovered and naturally-sporadic larvae settlements appear.

It should be noted that non-vulnerable species contribute most to the overall abundance of the local benthic community: non-vulnerable species types dominate the fluctuation of total abundance, within a given community. Therefore, population trends, following sediment extraction of the sensitive species and which are equivalent parts of the local biodiversity, might be overseen when using the SAB-approach only. Even multivariate analyses, which reduce the dominance of abundant species in statistic analyses, could be misleading.

CONCLUSIONS

The dredging operation has been tend to have had varied effects on the seabed. The response of areas with isolated furrows differed from areas with dense furrows, or pits. The impacts did not leave with the cessation of dredging. The sediment composition continued to change and oxygen deficiency developed, at the base of the dredged furrows. For a complete evaluation of the biological effects, it is insufficient to analyse only the overall richness, abundance, and biomass, as any effects on less abundant species can be overlooked. Such species may be characteristic and sensitive indicators for the region. Therefore, analysis at multiple scales is required, to detect any changes.

Dredging-induced impacts on benthic communities can be only minimal and short-lived, when the physical impact is limited and the site recovers rapidly to pre-dredging conditions. However, when the physical alteration cascades into subsequent prolonged harsh conditions, e.g. oxygen deficiency in summer time, a potentially rapid recovery is interrupted, until physical recovery occurs.

The planning and licensing of extraction areas and methods used in the western Baltic Sea need to be based upon solid guidelines, to retain the physical impact at a minimum, in space and time. Likewise, they need to consider the different regional conditions of the physical and biological environmental parameters, of the various sea regions.

ACKNOWLEDGEMENTS

The authors would like to thank the crew of RV *Littorina* (Adam Kubicki, Kay Vopel and Elke Körner) for cooperation during this study. The reviews of the manuscript by Brian Paavo and 3 unknown referees are acknowledged. We thank also Franziska Tanneberger, Herminia Castro and Keith Cooper for their critical reading of the manuscript. The work of the first author (JCK) was funded by the German Environmental Foundation (DBU) and supported by the German Federal Agency for Nature Conservation (BfN).

LITERATURE CITED

Boers, M., 2005. Effects of a deep sand extraction pit*; Final report of the PUTMOR measurements at the Lowered Dump Site*. Rijkswaterstaat, report RIKZ/2005.001, 87p.

Boesch, D.F., 1985. Effects on benthos of oxygen depletion in estuarine and coastal waters. *Estuaries*, 8, 43-55.

Bonsdorff, E., 1980. Macrozoobenthic recolonisation of a dredged brackish water bay in SW Finland. *Ophelia. Supplement*, 1, 145-155.

Bonsdorff, E. and Pearson, T.H., 1999. Variation in the sublittoral macrozoobenthos of the Baltic Sea along environmental gradients: A functional-group approach. *Australian Journal of Ecology,* 24, 312-326.

Boyd, S.E.; Limpenny, D.S.; Rees, H.L.; Cooper, K.M., and Campbell, S., 2003. Preliminary observations of the effects of dredging intensity on the re-colonisation of dredged sediments off the south-east coast of England (Area 222). *Estuarine, Coastal and Shelf Science*, 57, 209-223.

Boyd, S.E.; Cooper, K.M.; Limpenny, D.S.; Kilbride, R.; Rees, H.L.; Dearnaley, M.P.; Stevenson, J.; Meadows, W.J., and Morris, C.D., 2004. Assessment of the re-habilitation of the seabed following marine aggregate dredging. Sci. Ser. Tech. Rep., CEFAS Lowestoft, 121, 154p.

Boyd, S.E.; Limpenny, D.S.; Rees, H.L., and Cooper, K.M., 2005. The effects of marine sand and gravel extraction on the macrobenthos at a commercial dredging site (results 6 years post-dredging). *ICES Journal of Marine Science*, 62, 145-162.

Bortz, J.; Lienert, G.V., and Boehnke, K., 1990. *Verteilungsfreie Statistik Methoden in der Biostatistik.* Springer, Berlin, 935p.

Clarke, K.R. and Warwick, R.M., 1994. *Change in marine communities: an approach to statistical analysis and interpretation.* Natural Environment Research Council, Plymouth, UK, 144p.

Cooper, K.; Boyd, S.; Eggleton, J.; Limpenny, D.; Rees, H., and Vanstaen, K., 2007. Recovery of the seabed following marine aggregate dredging on the Hastings Shingle Bank off the southeast coast of England. *Estuarine, Coastal and Shelf Science*, 75, 547-558.

Desprez, M., 2000. Physical and biological impact of marine aggregate extraction along the French coast of the Eastern English Channel: short- and long-term post-dredging restoration. ICES, *Journal of Marine Science,* 57, 1428-1438.

Diesing, M., 2007. What does "physical regeneration" of marine aggregate dredging sites mean? Coastal Sediments '07, *Proceedings of the Sixth International Symposium on Coastal Engineering and Science of Coastal Sediment Processes* (New Orleans, Louisiana), pp2394-2401.

Diesing, M.; Schwarzer, K.; Zeiler, M., and Klein, H., 2006. Comparison of marine sediment extraction sites by means of shoreface zonation. *Journal of Coastal Research, Special Issue* 39, 783-788.

Dyer, K.R., 1986. The sediment. *In:* Wiley, J. and Sons ltd (eds.), *Coastal and estuarine sediment dynamics*, pp.13-46.

Essink, K., 1998. *Risk analysis of coastal nourishment techniques (RIACON):* Final evaluation report. National Institute for Coastal and Marine Management (RIKZ). Haren. *RIKZ-97.031*, 98p.

Fauchald, K. and Jumars, P.A., 1979. The diet of worms: a study of polychaete feeding guilds. *Oceanography and Marine Biology: an Annual Review*, 17, 193-284.

Gray, J.S., 1979. Pollution - induced changes in populations. *Philosophical Transaction of the Royal Society of London*, Part B 286, 545-561.

Hartmann-Schroeder, g., 1996. *Annelida, Borstenwürmer, Polychaeta.* 2nd edn., Jena, Fischer, , 648p.

HAYWARD, P.J. AND RYLAND, J.S. (eds), 1990. *The marine fauna of the British Isles and North-West Europe*. Vol.1 and Vol.2., New York, Oxford University Press.

HELCOM, 1988. *Guidelines for the Baltic Monitoring Programme for the third stage (1988)*: Helsinki Commission (HELCOM). Baltic Sea Environmental Proceedings (Biological Determinants), 27D, 91-100.

HELCOM, 1998. *Red list of marine and coastal biotopes and biotope complexes of the Baltic Sea, Belt Sea and Kattegat*. Baltic Sea Environmental Proceedings, 75, 115p.

HEWITT, J.E.; THRUSH, S.E., and CUMMINGS, V.J., 2001. Assessing environmental impacts: Effects of spatial and temporal variability at likely impact scales. *Ecological Applications*, 11, 1502-1516.

HINTZE, J., 2001. *NCSS and PASS. Number cruncher statistical systems.* NCSS softwareICES, 1990. *Soft bottom macrofauna: collection and treatment of samples.* Copenhagen, International Council for the Exploration of the Sea (ICES). Techniques in marine environmental sciences. (ICES) 8, 18p.

ICES, 1994. *Benthos issues - Indicator species with reference to physical disturbance of the seabed.* Cooperative research report. Copenhagen, International Council for the Exploration of the Sea. (ICES) 204, pp.55-57.

ICES, 1995. *Environmental effects monitoring of extraction of marine aggregates.* ICES. ACME Copenhagen, International Council for the Exploration of the Sea (ICES). Report, pp.73-76.

ICES, 2001. *Effects of extraction of marine sediments on the marine ecosystem.* WGEXT. Copenhagen, International Council for the Exploration of the Sea (ICES), 247, 80p.

JONES, G. and CANDY, S., 1981. Effects of dredging on the macrobenthic infauna of Botany Bay. *Australian Journal of Marine Freshwater Research*, 32, 379-398.

KAPLAN, E. H.; WELKER, J. R.; KRAUS, M. G., and MCCOURT, S., 1975. Some factors affecting the colonisation of a dredged channel. *Marine Biology*, 32, 193–204.

KENNY, A.J. and REES, H.L., 1994. The effects of marine gravel extraction on the macrobenthos - early post-dredging recolonization. *Marine Pollution Bulletin*, 28, 442-447.

KENNY, A.J. and REES, H.L., 1996. The effects of marine gravel extraction on the macrobenthos: Results 2 years post-dredging. *Marine Pollution Bulletin*, 32, 615-622.

KINNE, O., 1971. I*nvertebrates. In:* KINNE, O.(ed.), *Marine Ecology* 1 (2), 683-1244.

KRAUSE, J.C.; VON NORDHEIM, H., and GOSSELCK, F., 1996. Effects of submarine sand and gravel extraction on benthic macrofauna in the Baltic Sea, Mecklenburg-Vorpommern, Germany. Actual problems of the marine environment. Lectures at the 6th Scientific Symposium 14 and 15 May 1996 in Hamburg, *Deutsche Hydrographische Zeitschrift,* Supplement 6, pp.189-199.

KUBICKI, A. and DIESING, M., 2006. Can old analogue sidescan sonar data still be useful? An example of a sonograph mosaic geo-coded by the DECCA Navigation System. *Continental Shelf Research*, 26, 1858-1867.

LEGENDRE, P. and LEGENDRE, L., 1998. *Numerical Ecology*, 2nd edn. Amsterdam, Elsevier Science, 853p.

LUNG, 1999. *Gewässergütebericht 1996/1997: Ergebnisse der Güteüberwachung der Fließ-, Stand- und Küstengewässer und des Grundwassers in Mecklenburg-Vorpommern.* (Water quality report Mecklenburg-Vorpommern). Landesamt f. Umwelt, Natur und Geologie (LUNG), Güstrow, 124p.

LUNG, 2001. *Gewässergütebericht 1998/1999: Ergebnisse der Güteüberwachung der Fließ-, Stand- und Küstengewässer und des Grundwassers in Mecklenburg-Vorpommern.* (Water quality report Mecklenburg-Vorpommern). Landesamt f. Umwelt, Natur und Geologie (LUNG), Güstrow, 106p.

MCCUNE, B. and MEFFORD, M.J., 1999. *Multivariate analysis of ecological data.* Gleneden Beach, MJM Software Design, 237p.

MERCK, T. and VON NORDHEIM, H., 1996. Rote Listen und Artenlisten der Tiere und Pflanzen des deutschen Meeres- und Küstenbereichs der Ostsee (Red data book for animals and plants fort the German Baltic Sea). Bundesamt f. Naturschutz (BfN), *Schriftenreihe für Landschaftspflege und Naturschutz*, Bonn-Bad Godesberg, 48, 1-108.

NORDEN ANDERSEN, O.G.; NIELSEN, P.E., and LETH J., 1992. Effects on sea bed, benthic fauna and hydrography of sand dredging in Køge Bay, Denmark. *In: Proceedings of the 12th Baltic Marine Biologists Symposium* (Helsingør, Denmark) ,International Symposium Series, 16p.

ØRESUNDKONSORTIET, 1998. *The Øresund Link. Assessment of the Impacts on the Marine Environment of the Øresund Link. Report*, Update March 1998. Øresundkonsortiet, Malmö & Copenhagen, 175p. unpublished.

PEARSON, T.H. and ROSENBERG, R., 1978. Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. *Oceanographic Marine Biological Annual Review,* 16, 229-311.

PIRAINO, S.; FANELLI, G., and BOERO, F., 2002. Variability of species' roles in marine communities: change of paradigms for conservation priorities. *Marine Biology*, 140, 1067-1074.

PRENA, J.; GOSSELCK, F.; SCHROEREN, V., and VOSS, J., 1997. Periodic and episodic benthos recruitment in southwest Mecklenburg Bay (western Baltic Sea). *Helgoländer Meeresuntersuchungen*, 51, 1-21.

REMANE, A., 1940. Einführung in die zoologische Ökologie der Nord- und Ostsee. *In:* GRIMPE, G. and (WAGLER, E.) REMANE, A. (eds.), *Die Tierwelt der Nord- und Ostsee*. Leipzig: Akademische Verlagsgesellschaft Becker & Erler,. 238p.

RUMOHR, H.; BONSDORFF, E., and PEARSON, T.H., 1996. Zoobenthic succession in Baltic sedimentary habitats. *Archive of Fishery and Marine Research*, 44, 179-213.

SCHWARZER, K., this volume. Aggregate resources and extraction in the Baltic Sea – An Introduction. *Journal of Coastal Research.*

TAUBER, F. and LEMKE, W., 1995. Map of sediment distribution in the western Baltic Sea (1:100,000), Sheet "Darß". *Deutsche Hydrographische Zeitschrift*, 47(3), 171-178.

THATJE, S.; GERDES, D., and RACHOR, E., 1999. A seafloor crater in the German Bight and its effects on the benthos. *Helgoland Marine Research*, 53, 36-44.

VAN DALFSEN, J. and ESSINK, K., 1997. *RIACON – Risk analysis of coastal nourishment techniques in The Netherlands.* Part A, Part B, Part C. EC DG XII, Mast II. (*No. MAST2-CT94-0084*), National Institute for Coastal and Marine Management / RIKZ, Haren, pp1-98.

VAN DER VEER, H.W.; BERGMAN, M.J.N., and BEUKEMA, J.J., 1985. Dredging activities in the Dutch Wadden Sea: effects on macrobenthic infauna. *Netherlands Journal of Sea Research*, 19, 183-190.

VAN GEMERDEN, H.; TUGHAN, C.S.; DE WIT, R., and HERBERT, R.A., 1989. Laminated microbial ecosystems on sheltered beaches in Scapa Flow, Orkney Islands. *Fems Microbiology Ecology*, 62, 87-102.

VISSCHER, P.; BEUKEMA, J.J., and VAN GEMERDEN, H., 1991. In situ characterization of sediments: Measurements of oxygen and sulfide profiles with a novel combined needle electrode. *Limnology and Oceanography,* 36, 1476-1480.

VOPEL, K.; DEHMLOW, J.; JOHANSSON, M., and ARLT, G., 1996. Effects of anoxia and sulphide on populations of *Cletocamptus confluens* (Copepoda, Harpacticoida). *Marine Ecology Progress Series*, 175, 121-128.

WILSON, J.G., 1994. The role of bioindicators in estuarine management. *Estuaries,* 17(1a), 94-101.

WILSON, J.G. and ELKAIM, B., 1991. The toxicity of freshwater: Estuarine bioindicators. *In:* JEFFREY, D.W. and MADDEN, B. (eds.), *Bioindicators and Environmental Management*. London: Academic Press, pp311-322.

ZEILER, M.; FIGGE, K.; GRIEWATSCH, K.; DIESING, M., and SCHWARZER, K., 2004. Regenerierung von Materialentnahmestellen in Nord- und Ostsee. *Die Küste*, 68, 67-98.

ZETTLER, M.; BÖNSCH, R., and GOSSELCK, F., 2000. Verbreitung des Makrozoobenthos in der Mecklenburger Bucht (südliche Ostsee) - rezent und im historischen Vergleich. *Meereswissenschaftliche Berichte*, 42, 1-144.