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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.

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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 4×10^5 Km^2 , with a volume of approx 2×10 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.

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