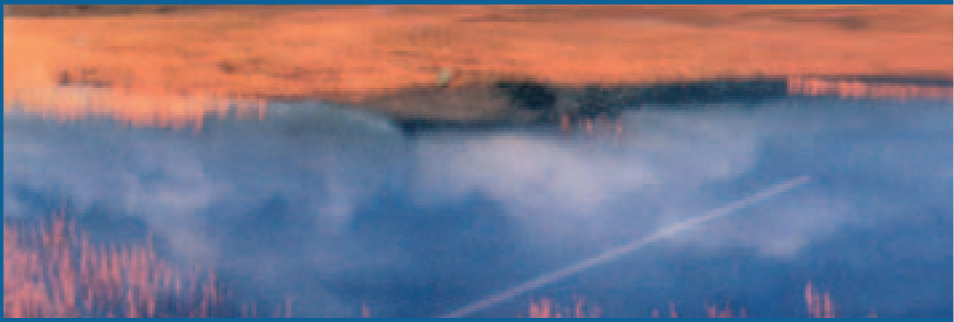
SCIENTIFIC SUPPORT PLAN FOR A SUSTAINABLE DEVELOPMENT POLICY

SPSD II

MUD ORIGIN, CHARACTERISATION AND HUMAN ACTIVITIES (MOCHA)

M. FETTWEIS, V. VAN LANCKER



PART 2

GLOBAL CHANGE, ECOSYSTEMS AND BIODIVERSITY

ATMOSPHERE AND CLIMATE

MARINE ECOSYSTEMS AND BIODIVERSITY

TERRESTRIAL ECOSYSTEMS AND BIODIVERSITY

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BELGIAN SCIENCE POLICY OFFICE
Second Multiannual Scientific Support Plan for a Sustainable Development Policy
SPSD II *Global Change, Ecosystems and Biodiversity*

Mud Origin, Characterisation and Human Activities

M. Fettweis, I. Du Four, E. Zeelmaekers, C. Baeteman, F. Francken,
J.-S. Houziaux, M. Mathys, B. Nechad, V. Pison, N. Vandenberghe,
D. Van den Eynde, V. Van Lancker, S. Wartel

Introductory Note

This report presents the final report regarding the MOCHA project (contract EV/35) for which the following partnership was set-up:

1. Royal Belgian Institute of Natural Science (RBINS), Management Unit of the North Sea Mathematical Models (MUMM); Michael Fettweis (coordinator),
   - Katholieke Universiteit Leuven, Geology Section; Noël Vandenberghe
2. Universiteit Gent, Renard Centre of Marine Geology (RCMG); Vera Van Lancker,

The project has benefit from the work of Jean-Sébastien Houziaux on the historical sediment data of the Gilson collection, of Cecile Baeteman and Mieke Mathys on the Holocene history of the Belgian coastal plain and nearshore area and of Stan Wartel on the radioactive and gamma densitometry measurements.

Addresses of authors:

1. Michael Fettweis, Frederic Francken, Bouchra Nechad, Virginie Pison, Dries Van den Eynde, Stanislas Wartel
   Royal Belgian Institute of Natural Science (RBINS), Management Unit of the North Sea Mathematical Models (MUMM), Gulledelle 100, B-1200 Brussels
   Tel: +32 (0)2 7732132, Email: m.fettweis@mumm.ac.be
2. Isabelle Du Four, Mieke Mathys, Vera Van Lancker
   Universiteit Gent, Renard Centre of Marine Geology (RCMG), Krijgslaan 281, S8, B-9000 Gent
3. Noël Vandenberghe, Edwin Zeelmaekers
   Katholieke Universiteit Leuven, Geology Section, Laboratory of Applied Geology and Mineralogy, Celestijnenlaan 200 E, B-3001 Heverlee
4. Jean-Sébastien Houziaux
   Royal Belgian Institute of Natural Science (RBINS), Invertebrate Department, rue Vautier 29, B-1000 Brussels
5. Cécile Baeteman
   Royal Belgian Institute of Natural Science (RBINS), Geological Survey of Belgium, Jennerstraat 13, B-1000 Brussels

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Abbreviations

BCS	Belgian Continental Shelf
B&W-S1	Disposal site for dredged matter north of the Vlakte van de Raan ('Bruggen & Wegen S1')
B&W-ZO	Disposal site for dredged matter east of the port of Zeebrugge ('Bruggen & Wegen Zeebrugge Oost')
B&W-O	Disposal site for dredged matter near Oostende ('Bruggen & Wegen Oostende')
MHWL	Mean High Water Level
MLLWS	Mean Low Low Water Spring
MSL	Mean Sea Level
NCS	Dutch Continental Shelf
OBS	Optical Backscatter Sensor
SPM	Suspended Particulate Matter

ABSTRACT

The cohesive sediments, which are frequently found in the Belgian nearshore zone (southern North Sea), are of different age such as tertiary clays and Holocene, modern and recently deposited muds. The area is characterised by a turbidity maximum. The source areas of the recently deposited muds and the effect of human impact vs. natural processes on the distribution and/or erosion of these sediments have been investigated using historic and recent bottom samples, in situ and remote sensing (satellite images) SPM concentration measurements, numerical modelling, GIS and clay mineral and microfossil analysis. The Schelde estuary, the potential erosion areas of cohesive sediments on the BCS and adjacent areas and the SPM transport through the Dover Strait have been considered as possible source areas.

The historic bottom samples have been collected in the beginning of the 20th century, the quality of these samples and the meta-information is very high and they have proven to be a major reference to understand the evolution of the cohesive sediment distribution. The recent bottom samples consist of box core, Reineck core and Van Veen grab samples collected during the last 10 years. The processing of the historic and recent data on cohesive sediments was mainly based on field descriptions of the samples (consolidation, thickness) and morphological evolution. On some of the recent samples radioactive and gamma densitometric measurements have been carried out. During the processing the emphasis was put on the occurrence of thick layers (>30 cm) of freshly deposited to very soft consolidated mud and of clay and mud pebbles, because these sediments are witnesses of changes.

Satellite images, in situ measurements and a 2D hydrodynamic numerical model have been combined to calculate the long term SPM transport through the Dover Strait and in the southern North Sea. The satellite images (SeaWiFS) provide synoptic views of SPM concentration. The representativness of SPM concentration maps derived from satellites for calculating long term transports has been investigated by comparing the SPM concentration variability from the in situ measurements with those of the satellite data. It is underlined that SPM concentration measurements should be carried out during at least one tidal cycle in high turbidity areas to obtain representative values of SPM concentration.

Areas where the thickness of the Quaternary cover is less than 2.5 m were defined as potential erosion areas of Palaeogene clay containing deposits. In the framework of this project, the geological data related to the BCS have been reviewed and the relevant information was compiled into a GIS. This also included a small part of the French continental shelf. Additionally information was added from vibrocores analysis and Dutch geological data. Approximately 20 % of the BCS, 6 % of the small part of the French area and only 3% of the Dutch study area could possibly serve as a source for fine suspended sediments. Quaternary muds are mostly presented in the

eastern nearshore area; on the Dutch part they occur more offshore. Their occurrence represents 11% of the BCS and approximately 35% of the Rabsbank area

Cretaceous microfossils are present in all samples and have been transported into the area with the residual water transport. Material from the east, in particular from the Eocene-Oligocene transitional strata, has been found in the eastern nearshore area up to about Oostende. This zone coincides with the extension of the Holocene mud and could indicate an erosion of these sediments and/or a transport of clay minerals from the Schelde estuary.

Clay mineral analysis has been carried by two approaches in order to determine source areas. The results of the second approach show that no systematic differences in the clay mineralogy depending on geographic location could have been found within the samples. The results clearly prove the necessity of using more elaborate sample preparation procedures in examining the provenance of the mud deposits.

Thick layers of fresh mud were deposited in the beginning of the 20th century mainly in a narrow band along the coast from about Nieuwpoort up to the mouth of the Westerschelde. These deposits were mainly the result of natural morphological changes. Today, most of the depositions of thick layers of fresh mud have been induced by anthropogenic operations, such as dumping, deepening of the navigation channels and construction and extension of the port of Zeebrugge. Comparing the actual situation with the situation 100 years ago reveals that the area around Zeebrugge where fresh mud is deposited extends more offshore today.

1 INTRODUCTION

In the Belgian nearshore zone, but mainly concentrated between Oostende and the Westerschelde estuary mud deposits and high concentrations of suspended particulate matter (SPM) occur. The presence of mud fields and high turbidity in an energetic environment such as the Belgian nearshore zone has been the subject of various studies; however the origin of the mud and the human impact on its distribution and transport remains still controversial. Knowledge on the distribution of the different cohesive sediment facies and on the different mud sources is important because of its effect on the economy (dredging and dumping), the environment and as such also for setting up a framework for a sustainable management of the area. Port extensions, deepening of navigation channels and other large scale projects (e.g. windmill farms) will continue in the future and thus the choice of e.g. efficient - from an economic and a physical point of view - dumping sites with a low environmental impact and a low recirculation to the dredging areas is essential in a sustainable management.

The data on SPM transport on the Belgian Continental Shelf (BCS) are necessary in order to answer questions on the composition, origin and residence of these sediments, the alterations of sediment characteristics due to dredging and dumping, the effects of the natural vs. human induced variability, the impact on the marine ecosystem, the estimation of the net input of hazardous substances and the possibilities to decrease this impact as well as the input. Knowledge on the mud fraction is necessary in sediment transport modelling, because clastic sediments change their erosion behaviour when they contain at least 10-15% mud. The mechanical and the grain size data together with the hydrodynamic results of numerical simulations gives an indication of the erosion behaviour of the cohesive sediments. Mud is transported by natural processes, such as tides, winds, but also human activities (dredging and dumping operations, large engineering works) have an important influence. The fine grained sediment characteristics and dynamics on the Belgian Continental Shelf have been unravelled using a combination of sedimentological, mineralogical, paleontological, geological and numerical modelling approaches. The main objectives of the project are:

- classification of cohesive sediments based on geology and consolidation;
- determination of clay mineral composition and microfossil content to trace the origin of the sediments;
- identification of the possible sources of the recent (fresh) mud;
- quantification of the anthropogenic impact during the last 100 years using historical sediment and bathymetrical data and numerical modelling;
- setting up a frame of reference for the cohesive sediment ecosystem.

The report is divided in 3 parts: chapter 2 and 3 describe regional settings and the methods used. The results on cohesive sediment distribution, SPM concentration distribution and clay mineral composition are presented in chapter 4, 5 and 6. Chapter 7 and 8 are used to discuss the possible sources of mud based on a quantitative (modelling, remote sensing, measurements) and a qualitative (microfossil content) approach and the anthropogenic impact on the cohesive sediment distribution. The major conclusion are summarised in chapter 9.

2 REGIONAL SETTINGS

The area under consideration is the southern North Sea more specific the Belgian/Dutch nearshore zone up to the mouth of the Westerschelde, see Figure 2.1. In this area different cohesive sediment types occur. These sediments are characterised by a particular rheological and/or consolidation state. The cohesive sediments have been classified as Eocene clay, consolidated mud from Holocene age, consolidated mud of modern age and freshly deposited mud. The freshly deposited mud occurs generally as thin (<2 cm) fluffy layers or locally as gradually more consolidated thicker packages (±0.2-0.5 m). The Holocene deposits, which extend over most of the foreshore area, consist of medium consolidated mud with intercalations of more sandy horizons; they are often covered by sand layers of some cm to tens of cm or fluffy layers of a few cm. The tertiary clay is outcropping in limited areas (Le Bot et al., 2003), see Figure 2.2.

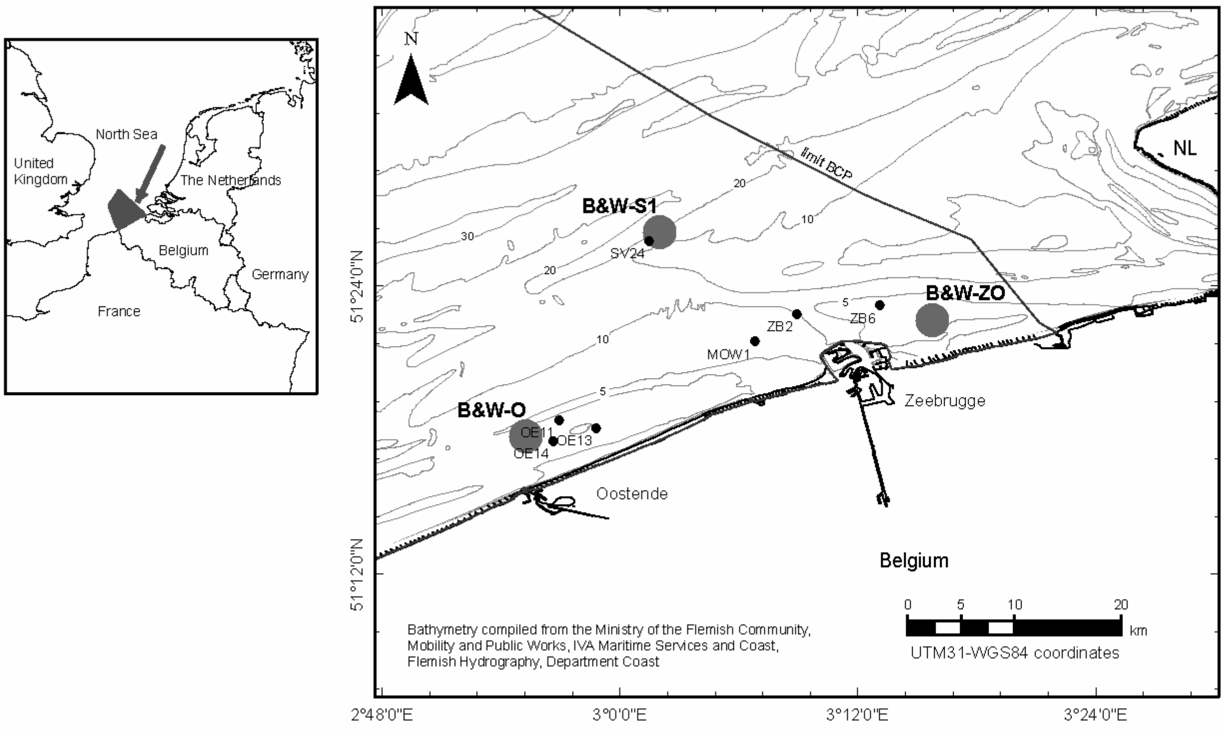


Figure 2.1: Localisation of the major dumping sites (B&W-S1; B&W-ZO, B&W-O) and the different sediment samples on the Belgian continental shelf described below.

SPM forms a turbidity maximum between Oostende and the mouth of the Westerschelde. The formation of a coastal turbidity maximum has been ascribed to the reduced residual water transport resulting in a congestion of the sediment transport in the area (Fettweis & Van den Eynde, 2003). SPM concentration measurements indicate variation in the nearshore zone between minimum 20-70 mg/l and maximum 100-1000 mg/l; low values (<10 mg/l) have been measured more offshore (Fettweis et al., 2006, 2007). Near bed layers of SPM with concentrations of more than a few 10 g/l and a non-Newtonian behaviour (i.e. fluid mud) have been reported in the bottom layer of the 'Pas van het Zand', the navigation channel towards the port of Zeebrugge (Strubbe, 1987).

2.1 Geology of the Belgian coastal area

The Belgian coast is characterised by a straight and closed coastline with a general SW-NE direction. The geological setting shows a striking difference between the western and eastern part, a difference which is already expressed in the Tertiary subsoil. The western part is characterised by compact stiff clay. In the eastern part, a vertical and lateral succession of fine sand and silt, sand and sandy clay, and clay, belonging to the Upper Eocene and Lower Oligocene, is forming the Tertiary subsoil (Maréchal, 1993) (Figure 2.2). The top of these deposits is located at depth increasing in an offshore direction and reaches about -30 m TAW (national reference level, 0 m TAW = 0.19 m below MLLWS at Zeebrugge) in the surroundings of Zeebrugge and about -20 m to -25 m TAW in the coastal plain. The thickness of the Quaternary cover in the offshore may locally be less than 2.5 m, in these areas tertiary outcrops are to be expected (Le Bot et al., 2003), see Figure 2.2 and Table 2.1.

Also in the Pleistocene, the western and eastern coastal area experienced a different evolution. Because of the presence of the IJzer, a major palaeovalley which morphology is already expressed in the top of the Tertiary subsoil (Baeteman, 2004), the western part of the plain shows a succession of fluvial and estuarine sediments formed during glacial and interglacial periods, respectively (Bogemans & Baeteman, 1993), while in the eastern part, cover sands from the Last Glacial overly coastal and open marine sediments from the Last Interglacial. In the offshore area, most of the Pleistocene deposits have been eroded during the Holocene.

The situation in the offshore zone is very much in relation with the development of the coastal plain during the Holocene. The coastal plain reaches its greatest width of about 20 km in the west, while in the east it is limited to about 10 km. Also the thickness of the Holocene deposits (exclusive the eolian deposits) at the present coastline varies in thickness between ±25 m in the west and not more than 10 m in the east, except for the young Holocene sand-filled tidal channels. The thickness and width are defined by the morphology of the pre-transgressive surface, *i.e.* the top of the Pleistocene deposits, and the occurrence of paleovalleys (Baeteman, 1999; Beets &

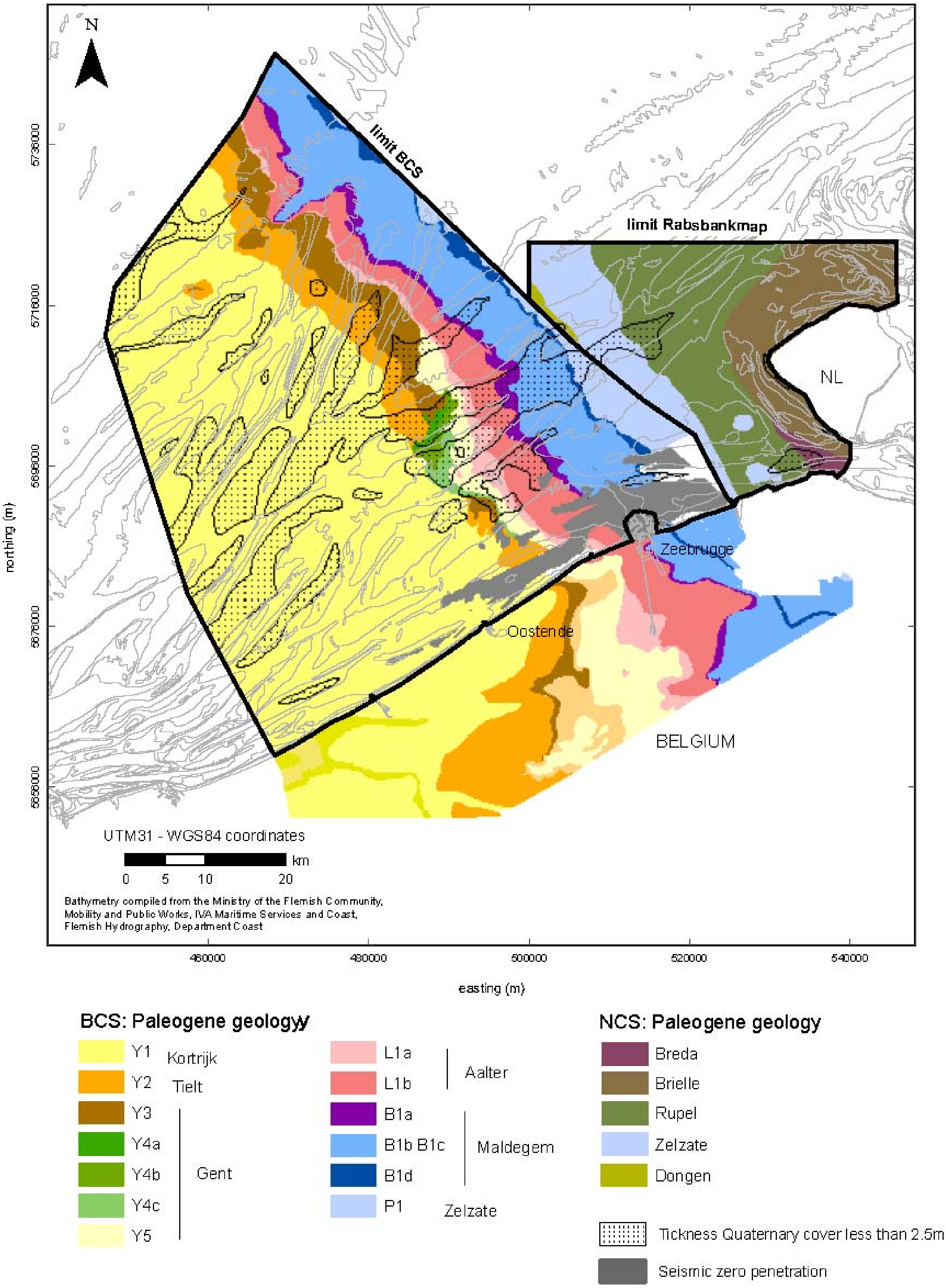


Figure 2.2: Presence of Tertiary deposits (BCS data: compilation of data of Maréchal et al. (1986), De Batist (1989), De Batist & Henriet (1995) / NCS data: Ebbing et al. (1992).

Table 2.1: Nomenclature and lithological properties of the BCS Paleogene units

Seismic Unit	Map	Formation	Member	Lithology	Thickness
P1	Ze	Zelzate		Stiff and slightly sandy, green grey **clay**	40-90m
B1d	MaOd	Maldegem	Onderdijke	Stiff to very heavy **clay**, with various amounts sand	45-60m
B1c	MaBu	Maldegem	Buisputten	Sand	
B1b	MaZo	Maldegem	Zomergem	Strongly bioturbated blue-green **clay**	
	MaOn	Maldegem	Onderdale	Moderately clayey sands	
	MaUr	Maldegem	Ursel	Blue-grey bioturbated massive **clay** with pyrite concretions	
	MaAs	Maldegem	Asse	Bioturbated clayey sands and sandy **clays**	
B1a	MaWe	Maldegem	Wemmel	Grey glauconitic slightly clayey fine sands with sandstones	
L1b	AaOe	Aalter	Oedelem	Very stiff to hard silty to sandy **clay** with sandy parts	25-30m
L1a	AaBe	Aalter	Beernem	Grey-green bioturbated glauconitic clayey fine sands	
Y5	GeVl	Gent	Vlierzele (upper)	**Clay** with a low amount of very fine sand	0-17m
Y4c	GeVl	Gent	Vlierzele (basal)	Compact **clay** to **loam**	0-25m
Y4b	GeVl	Gent	Vlierzele (basal)	Brittle to compact **clay** to **loam**, low amount of shell debris	0-20m
Y4a	GeVl	Gent	Vlierzele (basal)	Compact **clay** with high amount of silt and sand	0-21m
Y3	GePi	Gent	Pittem	Bioturbated sandy **clay** with mud drapes	0-25m
	GeMe	Gent	Merelbeke	Strongly bioturbated silty **clay**	
Y2	TtEg	Tielt	Egem	Olive-grey, stiff, sandy **loam** to silty **clay**	+/- 30m
Y1	TtKo	Tielt	Kortemark	Silty sand laminae in a poor **clay** matrix	150-180m
	Ko	Kortrijk		Massive, very heavy and hard, green-grey **clay**	

van der Spek, 2000). The western part is characterised by a major palaeovalley which was inundated by the tidal environment as from the beginning of the Holocene (Baeteman, 1999; Baeteman & Declercq, 2002). Although the Holocene deposits have not been mapped systematically in the eastern part, it is known from punctual data in literature and unpublished borehole data that the top of the Pleistocene is at an elevation of about -2 m TAW in the plain near Zeebrugge. Because of this high elevation of the Pleistocene deposits, the inundation started much later in the eastern part (at least in what is now the coastal plain).

The Holocene sequence in the plain consists mainly of alternations of intertidal mud and peat beds. The uppermost intercalated peat bed (also called surface peat) developed at about 6300-5500 cal BP in the landward part of the plain, and ca. 4700 cal BP in the more seaward areas. It accumulated almost uninterruptedly for a period of 2-3 ka years while the coast was prograding. The surface peat is generally 1 to 2 m thick and occurs between -1 and +1 m TAW. The upper peat bed is covered by a 1 to 2 m thick deposit formed by a renewed expansion of the tidal environment in the late Holocene. The expansion was associated with the formation of tidal channels which eroded deeply into the early and mid Holocene sediments, and sometimes into the underlying Pleistocene deposits. The renewed expansion of the tidal flat was also associated with shoreface erosion and a landward shift of the coastline in particular in the central and eastern part. This is very obvious in the central and eastern part of the plain. Here, the Holocene sequence at the present shoreline consists of mud and peat beds (unpublished borehole data), which continue towards offshore. Holocene muds have often been found in the eastern nearshore area. This is in contrast with the west where in a wide area in the seaward region, the Holocene sequence consists of a ca. 25 m thick sand body deposited in a coastal barrier and tidal inlet (Figure 2.3). Such a situation with a transition from barrier to back-barrier deposits (peat and mud) is the typical situation. The absence of barrier deposits in the central and eastern part of the plain indicates severe shoreface erosion and a significant landward shift of the coastline. The timing of the onset of this erosion still remains questionable, but it appears that it coincides with the period of Roman occupation (Baeteman, 2007).

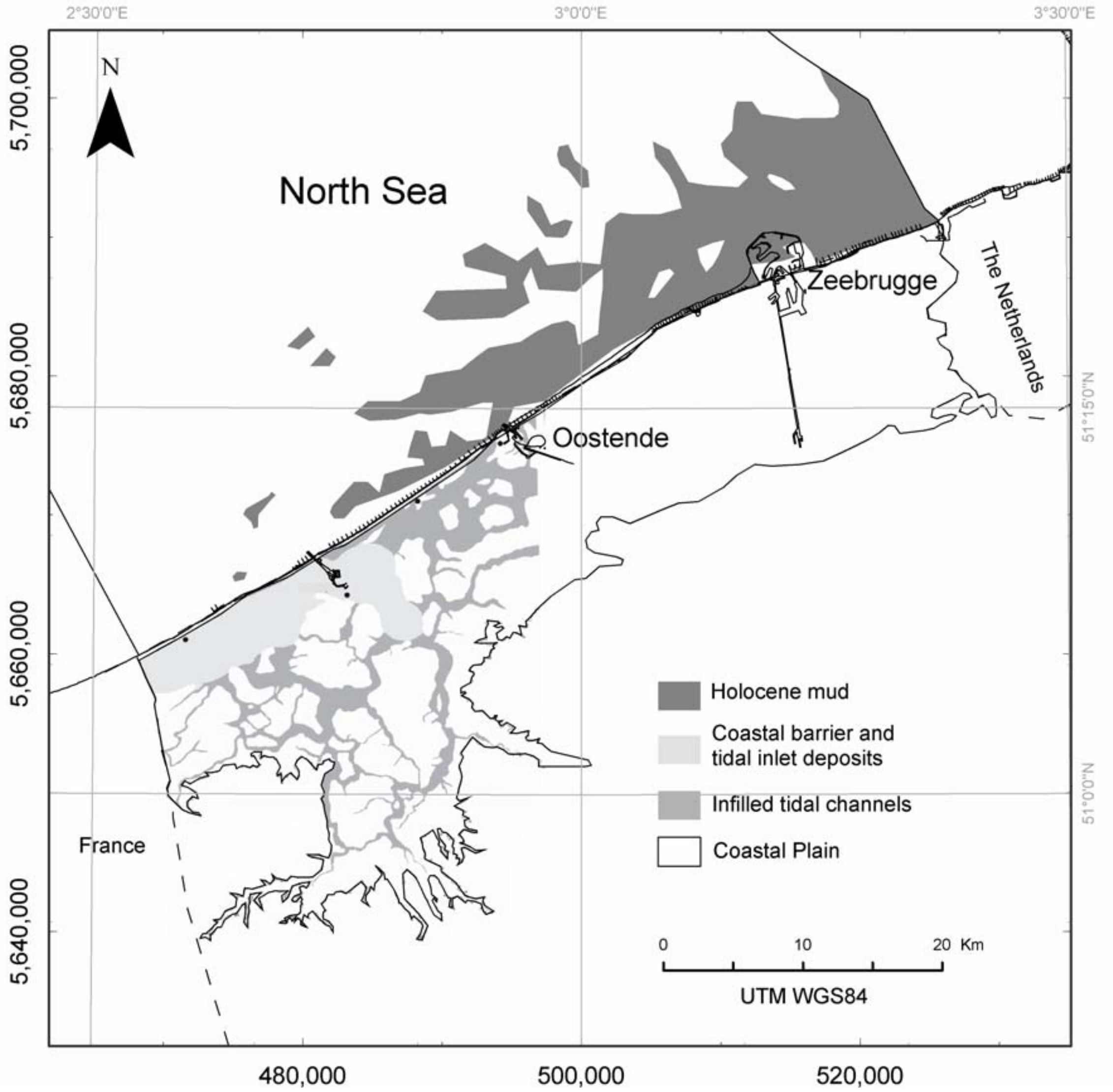


Figure 2.3: Holocene deposits of the Belgian nearshore zone and the coastal plain. The extension of the Holocene deposits in the coastal plain corresponds with the limits of the Polder. Only the Holocene deposits of the western coastal plain are shown in detail (from Baeteman, 2005).

3 METHODS AND MATERIAL

3.1 Mapping of historic and recent cohesive sediments

The cohesive sediments of the nearshore area have been mapped by Van Mierlo (1899), Bastin (1974), Missiaen et al. (2002) and Van Lancker et al. (2004). The techniques used are based on remote geophysical methods or on in situ sampling. Indications of muddy areas are also found on old hydrographical maps such as Stessels (1866). Bottom hardness as estimated by a hand-operated sounding weight is sometimes indicated on these maps and could constitute a hint to areas with freshly deposited mud. Bastin (1974) made a detailed sedimentological map using the natural radioactivity of sediments, but could not differentiate between the different cohesive sediment facies. Missiaen et al. (2002) used seismic techniques and described an area marked by poor seismic penetration due to gas formation in shallow peat layers, which corresponds with the extension of the Holocene mud. Geo-acoustical methods (multibeam, side scan sonar) have been applied by Van Lancker et al. (2004). They concluded that an acoustic seabed classification can be setup especially for very fine sand, mud and very coarse (shells) sediments, but holds many uncertainties because not only the grain size plays a role but also compactness, topography, the benthic fauna, shell cover, volume scattering and instrument settings influence the backscatter intensity.

Given the uncertainties of geophysical methods and the need of having a method enabling the comparison between historical and recent sediment samples we decided to mainly base the mapping and the comparison on the detailed field description of the samples (the results are presented in § 4.1 and 4.2). Four items related to cohesive sediment consolidation and/or erosion/deposition processes have a priori been selected as they could be found in the historic and recent dataset: clay pebbles, hard mud, soft mud and liquid mud. This approach has the advantage that the historical and the recent data are treated similarly.

The historical sedimentary situation was drawn based on sediment samples collected by G. Gilson in the early 20th century. Gilson established an ambitious sampling programme aiming to understand how environmental parameters influence the distribution of marine invertebrates (Gilson, 1900). He therefore included an exhaustive sediment sampling scheme to complement benthos sampling, but these data were never analyzed as a whole. The archived inventory of Gilson's sediment samples contains a list of 2979 sampling events between 1899 and 1939, from which 90% occurred before 1911. Gilson's cup-shaped instrument ('ground collector') was able to sample the first 10-20 cm of bottom sediments and allowed for good conservation of sediment layers in the sample, see Gilson (1901) and Van Loen et al. (2002). Gilson performed only a few grain-size analyses and only 700 sub-samples are still preserved today. However, detailed field descriptions of the sediment samples were written onboard, which enables a standardized approach to investigate sediment parameters such as mud content, sand grain-size, shell content, gravel content and others (Houziaux et al, in prep). For part of the dataset, the original field description could not be recovered, but a summarized or truncated version still exists. Where both versions are available, the summarized one is clearly less detailed, but it provides elementary information on mud content or sand grain size. In the nearshore area 1956 sediment samples are considered valid in terms of sedimentological information content and geo-referencing accuracy.

The level of detail of these sample descriptions is high and allowed a standardized aggregation of specific information to rank the samples within a mud to sand ratio scale. Other constituents like gravel or shell debris were not considered because semi-quantitative information is not always available. In a first step, mud and sand content were ranked accordingly to four basic categories: sand; muddy sand; sandy mud and mud. This basic mud/sand proportion scale was manually adjusted where possible using the additional semi-quantitative indications provided by Gilson (e.g. “mud, sand, approximately same quantity” is considered as 50% mud and sand). This adjustment is subjective and induces a bias in the ranking when semi-quantitative information is not available. Processing the data this way does not give any indication on the cohesive sediment facies, but it provides an opportunity to map relative mud content of these samples in a high resolution grid. Gilson indicated only on several occasions the vertical order of the observed layers, however, often additional information on mud appearance was provided, such as “in pieces” or “in lumps”, “hard”, “liquid”, “grey”, “black” or “superficial”, which gives clues on its age, consolidation or origin. Occasionally, additional indications on bottom hardness as recorded with a depth sounding weight are given at the sampling locations; a work commonly carried out by hydrographers by then. This information has been taken into account to identify areas with soft to medium consolidated cohesive sediments and to perform comparisons with contemporary mud samples. As aforementioned, only positive indications are considered as data, because it is not certain that such features were always appropriately recorded and their absence could thus also be due to misreporting.

3.2 Radioactivity and density measurements

As supplement to the recent sediment sample descriptions radiometric and bulk density measurements have been carried out on box core samples taken in the nearshore zone, the results can be found in § 4.1.1. The box core samples have a maximum length of 50 cm and have been kept in PVC tubes of 8 cm diameter and closed by rubber stoppers.

The radiometric measurements have been carried out with a Ge gamma detector connected to a multi-channel analyser (Canberra Series 35 Plus). Radiometric dating of sediment cores using ^{210}Pb, ^{226}Ra and ^{137}Cs activity is a widely used technique to estimate accumulation rates and age on a time scale of 10-100 years; see e.g. Carrol & Lerche (2003).

The method used to infer the density of the non-disturbed core sediments is based on the transmission of gamma-ray photons through the core (Preiss, 1968). The source of gamma rays used is ^{241}Am, with a principal γ-transition at 60 KeV. Photons emitted at this γ-transition are absorbed by the sediment rather than scattered. It is also very sensitive to small contrasts in densities, though also to chemical composition (called the soil-type effect) as can be foreseen from its very low energy level (Caillot & Courtois, 1969; Bouron-Bougé, 1972). To reduce the soil-type effect calibration standards were made of sediment from the Belgian continental shelf. Two types of sediment were used: a mud and a well-sorted medium-fine sand sample. The water of the mud was slowly evaporated while stirring the mud in order to obtain a homogenous mass that was transferred to a 12 cm long PVC tube of the same composition as used for the cores to be analysed. The radiation passing the tube was measured over the whole length in steps of 2 mm to ensure the homogeneity of the sample. After measuring the density small aliquots of mud were sampled and transferred to pre-weighed aluminium moisture cans and the water content was determined from the loss weight after evaporation at 110°C for 12 hours. The bulk density, ρ_b, was then calculated using 2600 kg/m^3 for sand and 2000 kg/m^3 for mud particle density (Bennett & Lambert, 1971).

3.3 Measurements of SPM concentration

3.3.1 SPM concentration maps derived from satellite images

The depth averaged SPM concentration maps, which are presented in § 5.1, have been derived from satellite images and in situ measurements in two steps. First the images from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) (http://oceancolor.gsfc.nasa.gov/SeaWiFS) aboard the SeaStar spacecraft have been processed. SeaWiFS measures the reflected sunlight at the Top Of Atmosphere (TOA) at 8 bands from visible to near infrared wavelengths centred at 412, 443, 490, 510, 555, 670, 765 and 865 nm. The SeaDAS software (http://oceancolor.gsfc.nasa.gov/seadas/), extended to turbid waters (Ruddick et al., 2000) is used to process these TOA into atmospherically corrected reflectance by removing atmosphere contributions (air molecules, ozone and aerosols scattering and absorption) and sea-water interface effect and finally providing the water-leaving reflectance spectrum denoted hereafter by $\rho_w^{i=412,...,865nm}$, where i refers to the ith band of SeaWiFS. A bio-optical model, which has been designed for Belgian coastal waters, is used to convert ρ_w^{670nm} into SPM concentration (Fettweis et al., 2007).

The next step in processing is to multiply the surface SPM concentration values by area-specific correction factors in order to obtain vertical averaged SPM concentrations, see Van den Eynde et al. (2006). These correction factors, which vary during a tidal cycle, represent the ratio between surface and depth-averaged SPM concentration and were derived from in situ tidal SPM concentration profiles taken on the Belgian continental shelf (BCS). In the Belgian nearshore areas the correction factors are comprised between 1.25 and 2.2, the maxima occurring at about 1 hour before high water and around low water and are related to maximum/minimum current velocity. In the offshore area, on the other hand, the ratio between the depth-averaged and the surface SPM concentration stays nearly constant over the entire tidal cycle and is limited to values below 1.1. The SPM concentration measurements also indicate that the highest correction factor corresponds generally well with the periods of high surface SPM concentration (>50 mg/l). Because we have no information outside the BCS on timing of correction factors during a tidal cycle, it was decided to neglect the relative timing during a tidal cycle and to apply correction factors as a function of SPM concentration solely. A maximum correction factor of 2 was used for high surface concentration (>50 mg/l) and the lowest for areas with low surface SPM concentration (<20 mg/l). For SPM concentration in between, a linear interpolation in correction factor was used.

3.3.2 In situ SPM concentration measurements

The in situ SPM concentration measurements (see § 5.2) have been collected from the R/V Belgica as snapshots or during tidal cycles. Tidal cycles have been measured between March 1999 and February 2005 using a Sea-Bird SBE09 SCTD carousel sampling system (containing twelve 10 litre Niskin bottles), which was kept at least 4.5 m below the surface and about 3 m above the bottom. Every 20 minutes a Niskin bottle was closed, resulting in about 40 samples per tidal cycle. Every hour the carousel was taken on board of the vessel and the water samples were filtered on board using pre-weighted GF/C filters, which were later dried and weighed to obtain SPM concentration. In the framework of MUMM’s Monitoring Program snapshots of SPM concentration were sampled at 3 m below surface. The procedure is similar, except that they are not throughout a tidal cycle.

3.4 Clay mineral analysis

For the clay mineralogical study a set of over 120 samples of both SPM and bottom sediments was collected on the BCS and in the southern North Sea, the Dover Strait, the Schelde estuary (up to Antwerp) and the port of Zeebrugge (Figure 6.1). The bottom samples consist of box cores and Van Veen grab samples. In order to estimate the tidal influence, suspension samples have been collected during a tidal cycle in the vicinity of Zeebrugge at station MOW1 (Figure 2.1). To investigate a possible variation of the clay mineral composition with time, samples were analyzed from a short core (50 cm) taken in the Paulina salt marsh, along the Westerschelde estuary. Separate sample sets were collected at and around the Nieuwpoort harbour and in the IJzer and the Ieper-IJzer canal by the ‘Afdeling Waterbouwkundig Laboratorium en Hydrologisch Onderzoek’ of the Ministry of the Flemish Community.

Clay mineral investigations were (consecutively) carried out by two approaches. The first approach (§ 3.4.1.) used limited sample preparations, qualitative interpretation methodologies mostly based on empirical descriptions (e.g. ‘v/p-ratio’) and a semi-quantitative analysis (Fontaine, 2004). This method has the advantage that large numbers of samples can be processed fast. The disadvantages are that samples are prepared in a non-standardized way (and thus more difficult to compare) and that because of the limited pre-treatment poor X-ray patterns are obtained, resulting in a limited resolution of analysis.

In a later stage a second and more refined approach was introduced (§ 3.4.2.). This method as a whole is based on an extensive sample preparation following standardized procedures and allows producing detailed qualitative and quantitative results based on state-of-the-art computer modelling. Grégoir (2005) used only the sample preparation methodology of this second approach to re-examine the conclusions of Fontaine (2004) by using the resultant higher quality X-ray patterns. The next step, which consists of detailed analyses of the qualitative and quantitative composition of the muds and samples from their potential source areas, is still in progress (IWT PhD Zeelmaekers).

3.4.1 First approach – sample preparation and data analysis

Samples were chemically treated for the removal of carbonates and organic matter, dispersed in de-ionized water, <2 µm size separated by sedimentation and dried on glass slides. The 2° to 35° 2ϑ range of these slides was registered by a Philips PW 1050/37 X-ray diffractometer (cobalt-anode) at ambient room conditions, ethylene glycol saturated and after heating to 300 °C and 500 °C. Clay mineral groups and interstratifications were identified using the peak positions and shapes as described by Thorez (1976) and Holtzapffel (1985). Semi-quantitative clay mineral compositions were reported as relative proportions of all minerals to each other using Mineral Intensity Factors (MIFs) and normalized to 100% (Moore & Reynolds, 1997; Kahle et al., 2002), with following 1/MIF values used: illite = 1, smectite = 0.25, chlorite = 0.34 and kaolinite = 0.7.

3.4.2 Second approach – sample preparation

Samples were treated largely according to the procedures described by Jackson (1975). These procedures aim at removing a maximum amount of cementing agents, allowing to separate smaller sized clay fractions and to make better oriented – and thus higher quality – slides for X-ray diffraction. A Na-acetate buffer was used to remove carbonate cements, organic matter was removed by a H_2O_2-treatment and Fe-(hydr)oxide cements were removed by Na-dithionite. Next the clays were converted to the Ca-saturated form to ensure the most homogenous swelling (Sakharov et al., 1999). By centrifugation the fractions <0.2 µm and <2 µm were separated and sedimentation slides and smearmounts respectively were made of them. Their 2° to 47° 2ϑ range was registered by a Philips PW 1050/37 X-ray diffractometer (cobalt-anode) at ambient room conditions, ethylene glycol saturated and after heating to 550 °C. The techniques and methods of the detailed qualitative and quantitative analyses of the X-ray patterns will be described in Zeelmaekers (IWT PhD).

3.5 Microfossil analysis

The microfossil content in the bottom and suspension samples was examined for nannoplankton, dinoflagellates, foraminifera and ostracods. All microfossils were extracted, prepared and analyzed according to standard micropaleontological procedures. The results are presented in § 7.3.2.

3.6 Numerical model descriptions

3.6.1 Hydrodynamic model

The hydrodynamics has been modelled using the public domain 3D COHERENS model (Luyten et al., 1999). This model has been developed between 1990 and 1998 in the framework of the EU-MAST projects PROFILE, NOMADS and COHERENS. The hydrodynamic model solves the momentum equation, the continuity equation and the equations of temperature and salinity. The equations of momentum and continuity are solved using the 'mode-splitting' technique. COHERENS disposes of different turbulence schemes, including the two equations *k-ε* turbulence model.

For the application 2D currents from 3D implementation of the COHERENS model to the Belgian continental shelf were used (see § 4.3). This model (OPTOS-BCS) covers an area between 51°N and 51.92° N in latitude and between 2.08° E and 4.2° E in longitude. The horizontal resolution is 0.01183° (longitude) and 0.007° (latitude), corresponding both to about 800 m. Boundary conditions are water elevation and depth-averaged currents, these are provided by OPTOS-NOS, which is also based on the COHERENS code, but covering the whole of the North Sea and part of the English Channel (see § 7.3). The OPTOS-NOS model is receiving boundary conditions from the OPTOS-CSM model, which covers the north-west European continental Shelf. 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) are used to force the tidal elevation on the open boundaries of the Continental Shelf Model. The current velocities of the OPTOS-BCS model have been validated using ADCP measurements (Pison & Ozer, 2003).

3.6.2 Cohesive sediment transport model

Transport of mud is determined by the settling of mud particles under the influence of gravity and by erosion and sedimentation due to the local current velocity. The cohesive transport model solves the 2D depth-averaged advection-diffusion equation for cohesive sediment transport on the same grid as the OPTOS-BCS model (Fettweis &

Van den Eynde, 2003). The model has been applied to the Belgian nearshore zone (§ 4.3). Erosion and deposition rates are calculated using the formulations of Ariathurai-Partheniades (Ariathurai, 1974) and Krone (1962), respectively. The model uses the semi-Lagrangian Second Moment Method (Egan & Mahoney, 1972; de Kok, 1994) for the advection of the material in suspension. In this method all material in each grid cell is represented by one rectangular mass, with sides parallel to the model grid, characterized by its zero order moment (total mass), first order moments (mass centre) and second order moments (extent). The diffusion of suspended matter is based on the work of Johnson et al. (1988) and calculates the enlargement of the rectangular mass assuming Fickian diffusion.

The values used in the model for the critical shear stress for erosion τ_{ce} have been set to 0.5 Pa for freshly deposited mud and 2.0 Pa for the soft to medium consolidated mud of the parent bed (Fettweis & Van den Eynde, 2003). The erosion constant for 100% mud content was set to 0.12×10^{-3} kg/m^{2}s. In sediments with lower mud content, which can only occur in the parent bed, the erosion rate is multiplied by the mud fraction. In the model a constant fall velocity of 0.001 m/s has been used. The critical shear stress for deposition τ_{cd} has been set to 0.5 Pa. The SPM concentration condition along the open boundaries of the mud transport model has been constructed using in situ measurement and satellite images.

4 COHESIVE SEDIMENT DISTRIBUTION

4.1 Actual cohesive sediment distribution

The map in Figure 4.1 is based on sediment samples, which have been collected between 2000 and 2004 and shows the mud content and the distribution of four major cohesive sediment facies as they emerge from the sample descriptions and the wet bulk density measurements; the consolidation terminology is from the Coastal Engineering Manual (2002) classification. This classification is based on bulk densities for pure cohesive sediments and should be used therefore as an indication; small amounts of sand, which often occur in the mud, may increase the bulk density. The four main facies are:

1. Clay or mud pebbles occur in a sand matrix or on top of mud layers and may indicate eroded (naturally or due to deepening dredging works) and transported tertiary clays or consolidated mud layers (Figure 4.2a).
2. Soft to medium consolidated cohesive sediments have a wet bulk density (ρ_b) of 1500-1800 kg/m^3) and indicate Holocene (Figure 4.2b) or possibly younger sediments (Figure 4.2e). Based on the consolidation of the sediment sample it is not always possible to clearly identify the age of the sediment. Holocene mud has typically a layered structure with intercalation of thin sandy layers. Other types of consolidated mud, such as the lower layer in Figure 4.2e, are sticky and no clear lay-

ering can be visually identified; it does not corresponds with the Holocene mud and it is assumed therefore to be of more recent age (up to a few centuries), it is called ‘modern mud’.

3. Freshly deposited to very soft consolidated cohesive sediments (ρ_b: 1300-1500 kg/m³) may indicate recent deposits of thick mud layers (Figure. 4.2c, 4.2e) or re-wetted older and more consolidated mud. Freshly deposited mud occurs typically in the ports below fluid mud layers (Figure 4.2f).
4. Fluid mud (ρ_b ±1100-1200 kg/m^3) flows through fingers and occurs as thin surface layers of a few cm (fluffy layers, see Figure 4.2d) or thick layers in navigation channels and ports (Figure 4.2f).

The wet bulk density of box core samples from the nearshore area near Oostende and Zeebrugge ranges between 1088 kg/m^3 and 2300 kg/m^3, two examples are shown in Figure 4.3. A clear distinction can be made in ZB6 core between the very soft layer (<1300 kg/m³) at the surface, the freshly deposited to very soft consolidated mud (±1500 kg/m³) between 2 cm and 26 cm and the very sticky soft to medium consolidated mud below 26 cm (±1600 kg/m^3) (Figures 2.1, 4.3). The organic matter content is about 5% in the lower part and 10-20% in the upper part of the ZB6 core; these differences point to a different age of both sediments. The upper part of the density profile is very irregular. These variations in wet bulk density are an indication of tidal deposits and represent an alternation of more and less muddy layers formed in sheltered areas; it is typical that these structures cannot be seen from a visual inspection of the sample. Two radiographies of Reineck core samples taken very close to the ZB6 and ZB2 box core samples show clearly these tidalites (Figure 4.4).

The wet bulk density of the upper 30 cm of the OE14 core (Figure 4.3), which has been sampled near the old dumping site of Oostende (B&W-O in Figure 2.1b) is very low (1200-1400 kg/m³). The fact that a thick layer of freshly deposited mud to soft consolidated mud can be deposited points to a protected hydrodynamic environment.

4.1.1 Age and accumulation rates based on radio-isotopes of recent samples

The radioactivity of ^{210}Pb, ^{226}Ra and ^{137}Cs has been measured to determine the age and the accumulation rate of the sediments in two box-core samples. The OE11 core has been taken in March 2004 near the old dumping place of Oostende (B&W-O in Figure 2.1) and consists of 43 cm of freshly deposited to soft consolidated mud (similar as Figure 4.2c). In the ZB6 core, which has been sampled in November 2002 northeast of the port of Zeebrugge (see Figure 2.1), two clearly different parts have been distinguished: the upper 19 cm consist of freshly deposited to soft consolidated mud and the lower 29 cm of medium consolidated mud (similar as Figures 4.2e and 4.3). The radio-isotope profiles in both box cores are irregular as can be seen from Figures 4.5 and 4.6.

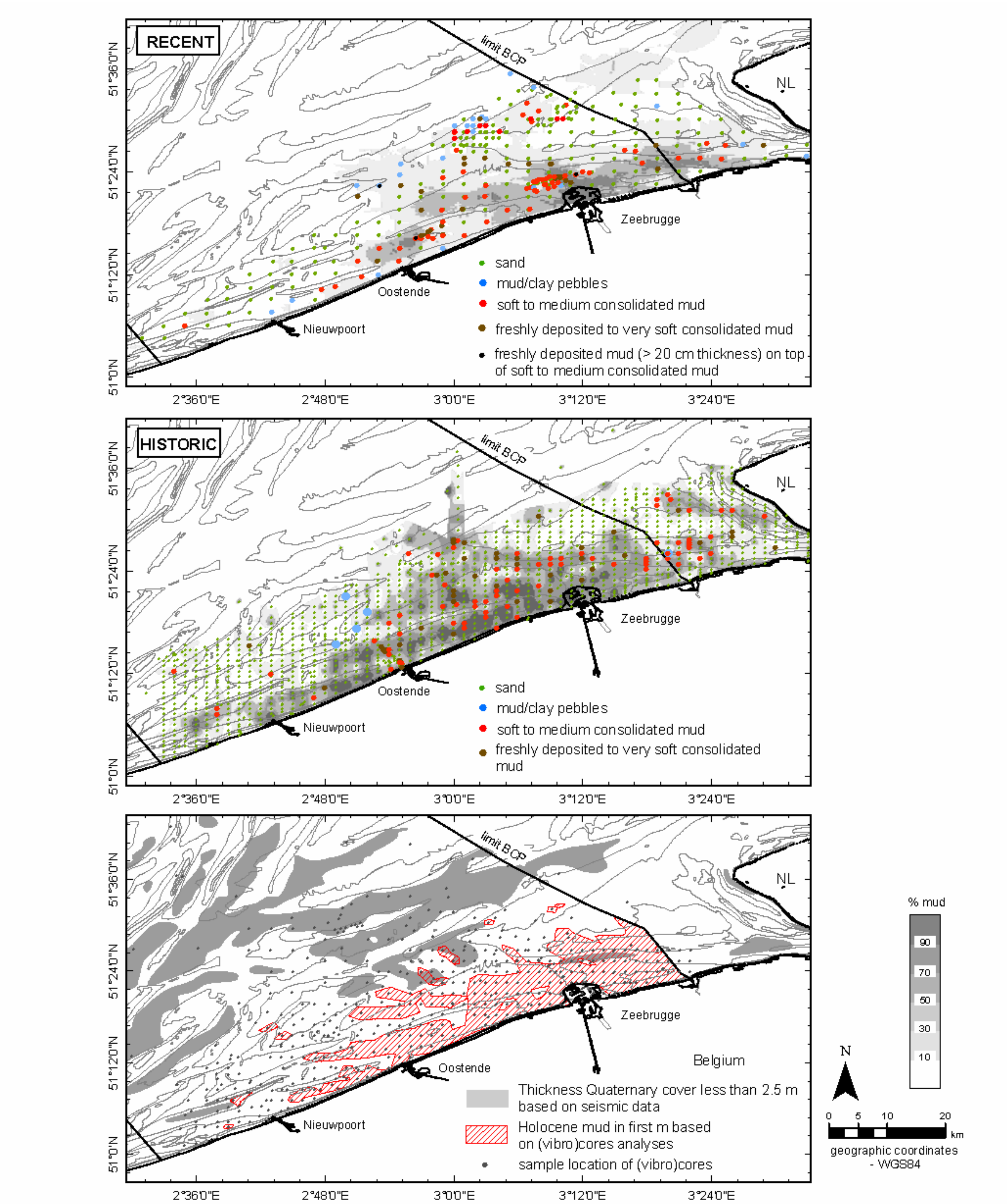


Figure 4.1: Cohesive sediment facies and mud content in the Belgian-Dutch coastal zone derived from recent (above) and historic (taken by Gilson between 1899 and 1925) (middle) sediment samples. The recent mud content is derived from grain size analysis, whereas the historic mud content distribution is based on metadata, see § 3.1. On the recent map samples consisting of freshly deposited mud have been indicated where it occurs as thick (>10 cm) layers. Areas where the Quaternary cover is less than 2.5 m thick and where Holocene mud occurs in the first meter are indicated below. Samples consisting entirely of sand are represented by green dots.

Figure 4.2: Photos of Van Veen (VV) grab (size of grab is 0.3 m × 0.2 m) and box core (BC) samples (height of core is 0.5 m), see Figure 2.1 for geographical location.
(a) BC showing mud pebbles on top (SV24, 19/02/2003), the core has been taken near the dumping place B&W-S1; the pebbles could originate from deepening dredging works.
(b) VV sample of layered Holocene mud covered by a thin ephemeral sand layer (MOW1, 04/04/2005).

(c) VV of fluid mud on top of freshly deposited mud (port of Zeebrugge, 9/11/2006).
(d) VV of fine sand covered with a thin fluffy layer, (OE13, 21/02/2003).
(e) BC of fresh mud above medium consolidated mud, (ZB2, 19/02/2003).
(f) BC (height ±45 cm) of freshly deposited to very soft mud, (OE14, 21/02/2003).

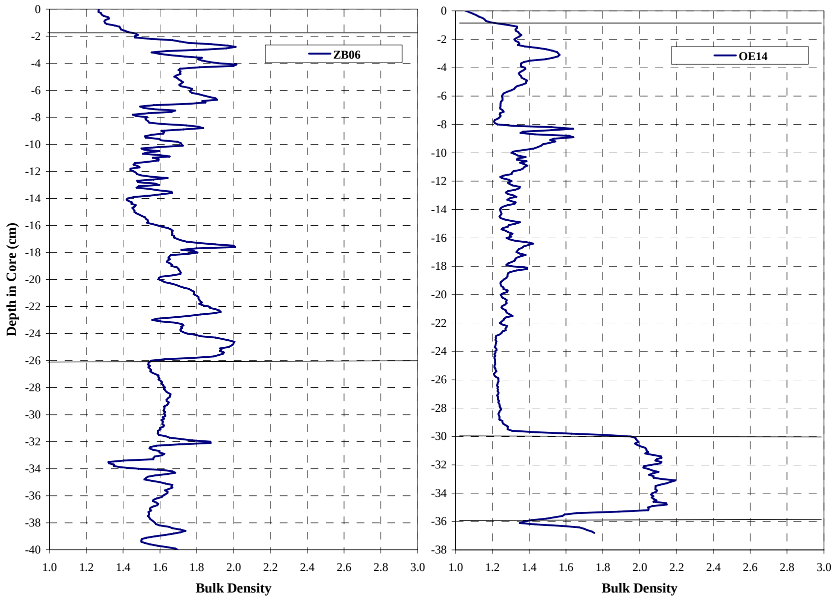


Figure 4.3: Wet bulk density profiles (kg l^{-1}) of selected box cores. The ZB6 (left) sample (27/11/2002) consist of 19 cm very soft consolidated mud (1.4-1.5 kg l^{-1}) above 29 cm of medium consolidated mud (>1.6 kg l^{-1}). On top a thin layer of freshly deposited mud (1.3 kg l^{-1}) is observed. The OE14 (right) sample (21/02/2003) consist of 30 cm of freshly deposited mud (1.2-1.4 kg l^{-1}), below is a layer of 5 cm muddy fine sand on top of medium consolidated mud.

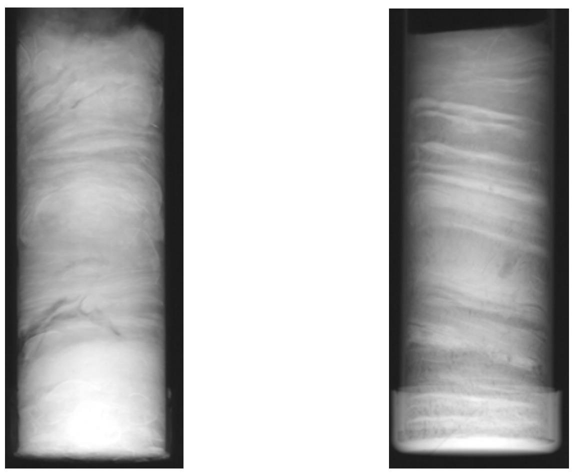


Figure 4.4: Radiography of Reineck cores (width is 5 cm). Both contain freshly deposited to soft consolidated mud with typical tidal deposition structure. RK0026-04 (24/10/2000) sample (left) has a length of 14 cm and been taken very close to ZB6 sample. RK0124-14 (24/10/2000) sample (right) has a length of 13.5 cm and has been taken in the navigation channel towards Zeebrugge near ZB2.

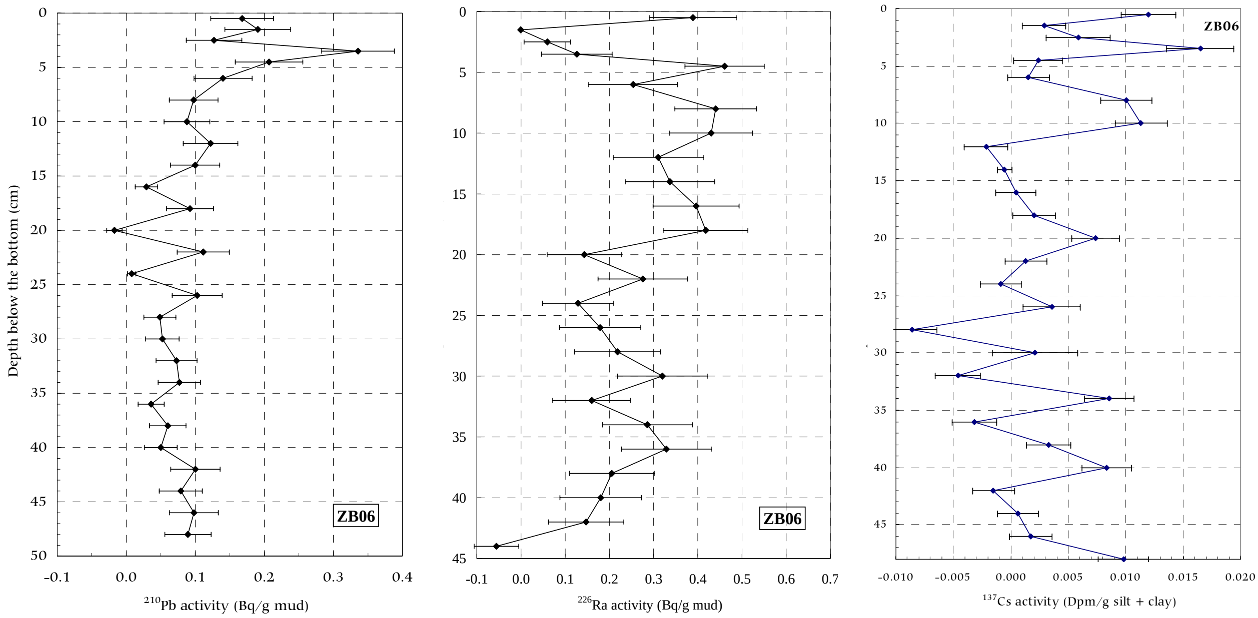


Figure 4.5: Total ^{210}Pb, ^{226}Ra and ^{137}Cs activities in ZB6 core (27/11/2002).

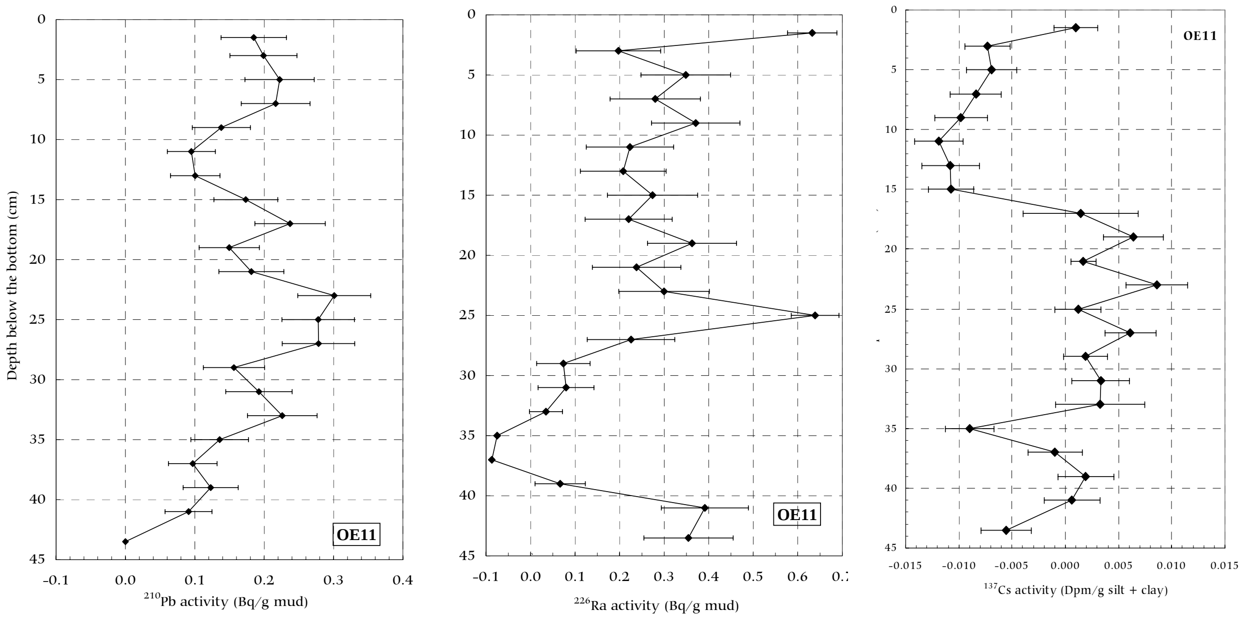


Figure 4.6: Total ^{210}Pb, ^{226}Ra and ^{137}Cs activities in OE11 core (08/03/2004).

The major source of ^{226}Ra is probably associated with the discharges of phosphate gypsum at BASF-Antwerpen between 1968 and 2002 and the ^{226}Ra discharges from 1920 on by Tessenderlo Chemie in the Grote Nete (Schelde basin), see on this subject Paridaens & Vanmarcke (2000). ^{210}Pb, which is a daughter isotope of ^{226}Ra, is formed by the decay of the industrial ^{226}Ra and thus cannot be used for dating with excess ^{210}Pb models. The sediments of the upper ZB6 and of the OE11 core can therefore be supposed to have been deposited recently (1920 - today). The study of the morphological evolution allowed to refine the age of deposition of the OE11 sediments as after 1960 (see § 4.2.1). In the beginning of the eighties large engineering works occurred near Zeebrugge (extension of the port of Zeebrugge, deepening of navigation channels). The (surface) mud northeast of Zeebrugge has probably been deposited after (during) the works and as such is probably younger than ±1980. The apparent accumulation rate of the upper 19 cm of ZB6 has been estimated as 0.86 cm/yr. The lower part of the ZB6 core can be clearly distinguished from the upper part. It has been interpreted - based on field description – as modern mud; deposition has probably occurred after 1920 and significantly before 1980.

The peak in ^{137}Cs activity between 17 cm and 33 cm below the surface in the OE11 core has been ascribed to the peak in fall out of atmospheric nuclear bomb tests during the sixties. The apparent accumulation rate for the upper part of the core is then about 0.6 cm yr^{-1}. The lower ^{137}Cs peak in this core (37-41 cm) indicates that these sediments are at least younger than 1950 when the significant releases of ^{137}Cs into the environment started.

It is clear that two samples cannot describe the complex accumulation pattern in whole the area. The measurements have however shown different isotope activity and distribution between the Oostende and Zeebrugge core, which can be explained by the recent morphological evolutions and anthropogenic influences at both sites and the age of the layers. The higher influence of the Westerschelde at Zeebrugge and thus a partially different origin of the mud could perhaps also explain the differences between the samples. The influence of the Westerschelde on the SPM concentration is for example visible in the two statistically different high turbidity zones in the nearshore area (i.c. Oostende and Zeebrugge), as is explained by Van den Eynde et al. (2006).

4.2 Historical cohesive sediment distribution

4.2.1 Distribution at the beginning of 19th century

Despite initial doubts on the accuracy of the method used to reconstruct historical mud content, the developed approach provides a coherent historic map of mud content along the Belgian coast and the Westerschelde estuary (Figure 4.1). It was not possible to unambiguously link the descriptions of Gilson’s samples to one of the four mud facies used in § 4.1, because only positive indications are considered as “data”. A morphological analysis has therefore been carried out comparing the bathymetrical maps of Stessels (1866) and Urbain (1909) in order to link the occurrence of cohesive sediments with an increase (erosion) or a decrease (accumulation) in bathymetry. If Gilson’s sample is situated in an area where the depth has decreased, then the mud has been deposited recently (maximum 35 years before sampling). If the sample is situated in an eroded or stable area then the surface mud is most probably old (Holocene of modern). Fresh mud may however occur in all areas (usually thin surface layers) through tidal and spring-neap tidal driven deposition such as described in the metadata.

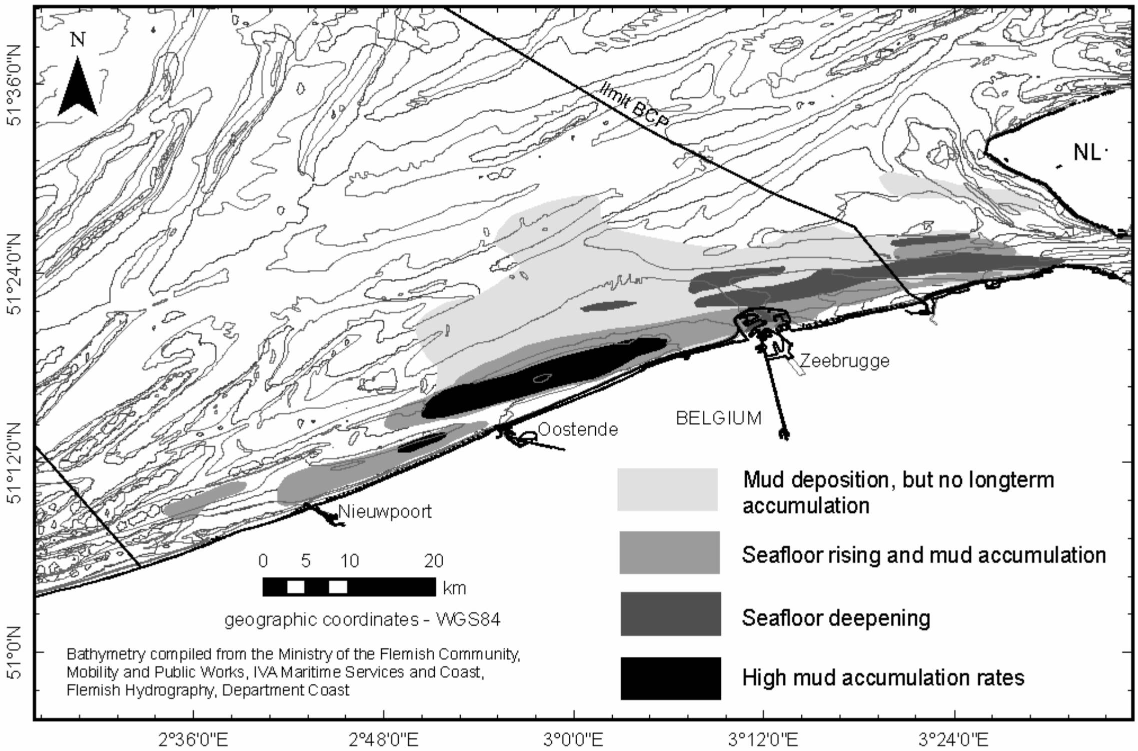


Figure 4.7: Aggregated trends in mud deposition and seafloor morphology inferred from detailed visual inspection of bathymetric changes (period 1866-1911) and mud content information derived from the historic sediment samples (see Figure 4.1).

Areas where an accumulation of sediment is observed are found in a parallel band of 5 km width along the coast line (Figure 4.7). The highest accumulation (±3 m) occurs between Oostende and Zeebrugge, an area which corresponds with high mud contents at the end of the 19th and the beginning of the 20th century (Figure 4.1) just before and during the construction works. The hydrographic chart of Stessels (1866) shows the occurrence of pure mud in the same area. East of the port mainly sandy sediments were deposited; important morphological changes in the area continue until today. Comparison between the hydrographical maps of 1866 and 1911 (Figure 4.7) indicates that these changes have started before the construction of the port and could thus be the result of a natural morphological evolution. However, human influences such as the construction of coastal defence structures in the 19th century along the eastern Belgian coast cannot totally be excluded to explain at least partly these morphological changes. These changes resulted in the formation of a sand bank (called "Het Zand") at the place where the port is situated (Van Mierlo, 1899). The most direct impact of the first infrastructure has possibly been to locally reinforce natural morphological trends in decreasing depth, as predicted by Van Mierlo (1897).

Areas where the seafloor has deepened (>1 m) are partly artificial, such is the case in the 'Pas van het Zand' and the navigation channel towards the Westerschelde (Scheur). In these areas freshly deposited mud is expected to be found, as these environments are artificial sinks for fine-grained sediments. Further offshore, deepening is probably natural and must correspond with erosion processes. It is thus most likely that the mud observed in these areas coincide with outcrops of Holocene mud. The cohesive sediments in the offshore zone (>10 m MLLWS) where the bathymetry has not changed are most probably also of ancient age (Holocene).

4.2.2 Distribution in the 1960ties

Bastin (1974) made a detailed sedimentological map using the natural radioactivity of sediments, see Figure 4.8. He differentiated between mud (clay_mud), a cohesive sediment characterised by its loose packaging and clay a soft to medium consolidated cohesive sediment. Sand_mud correspond with a fluffy layer of mud on sand or a mixture of sand and mud.

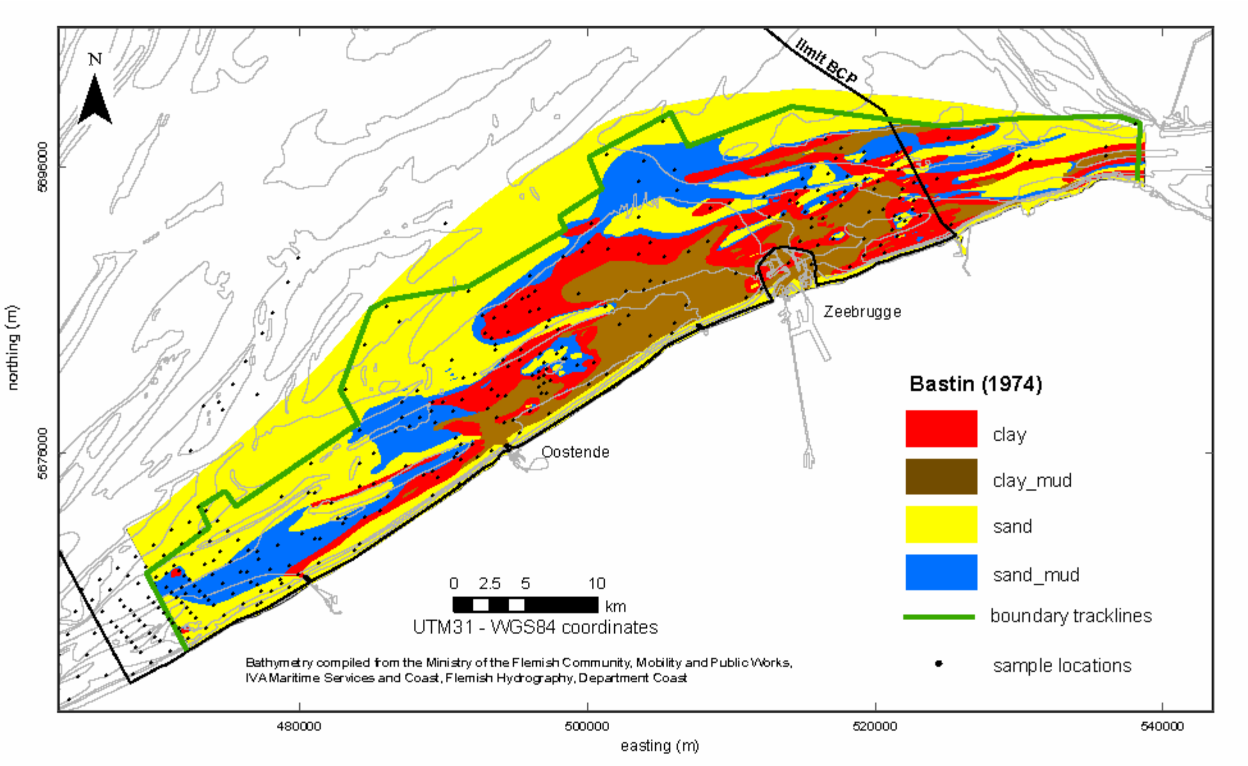


Figure 4.8 Mud distribution after Bastin (1974). The lithology is based on measurements of natural radioactivity.

4.3 Sediment transport simulations for 2003 and 1959 situation

The aim of the model simulations was to simulate the transport and deposition of fine grained sediments using a bathymetry before (i.c. bathymetry of 1959, without port of Zeebrugge) and after the major engineering works have been carried out (bathymetry of 2003, with port of Zeebrugge) and to quantify the anthropogenic impact on the SPM concentration and on the mud deposition (Figure 4.9). The simulations have been carried out during calm weather and lasted one spring-neap tidal cycle. It is assumed that the SPM concentration along the open boundaries of the OPTOS-BCS model is the same for the recent and historic situation. The critical shear stress for erosion and deposition are both 0.5 Pa, the fall velocity was set to 1 mm/s and the erosion constant to 0.12×10^{-3} kg/m²s. The results are presented in Figure 4.10 (2003 situation) and Figure 4.11 (1959 situation, without Zeebrugge). The figures show that the Belgian and southern Dutch coastal waters are an effective trap for suspended sediments, resulting in the formation of an area of high SPM concentration. During spring tide the SPM concentration reaches a maximum, whereas during neap tide the mud deposition is highest.

Permanent mud deposits are those, which are not eroded during spring tide; they occur in the navigation channels and – for the recent situation – around Zeebrugge. Not withstanding the limitations of the model, the results indicate that despite the occurrence of a turbidity maximum in the nearshore zone only few permanent deposits of cohesive sediments exist and that most of them are situated in areas with high anthropogenic impact. The model results show further – as a consequence of mass conservation in the model and without inclusion of dredging and dumping – that SPM concentration is on average lower and mud deposition higher today than in 1959.

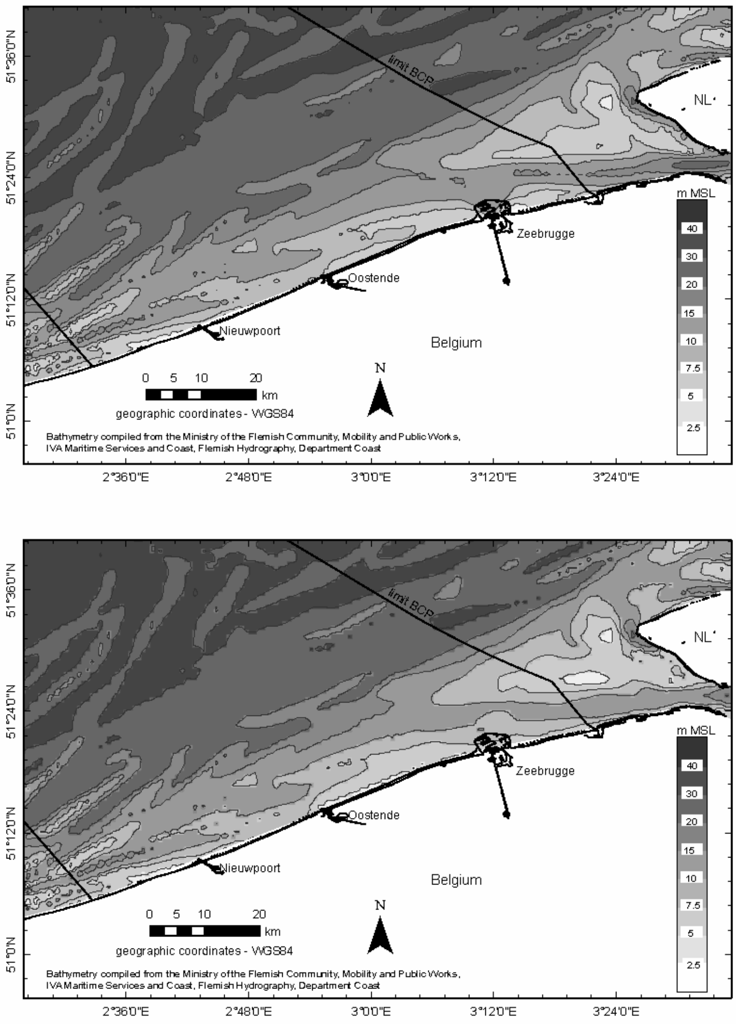


Figure 4.9: Bathymetry derived from 2003 surveys (above) and surveys before 1959 (below). Significant differences occur in the coastal zone and navigation channels. The port of Zeebrugge is not included in the '1959' model grid.

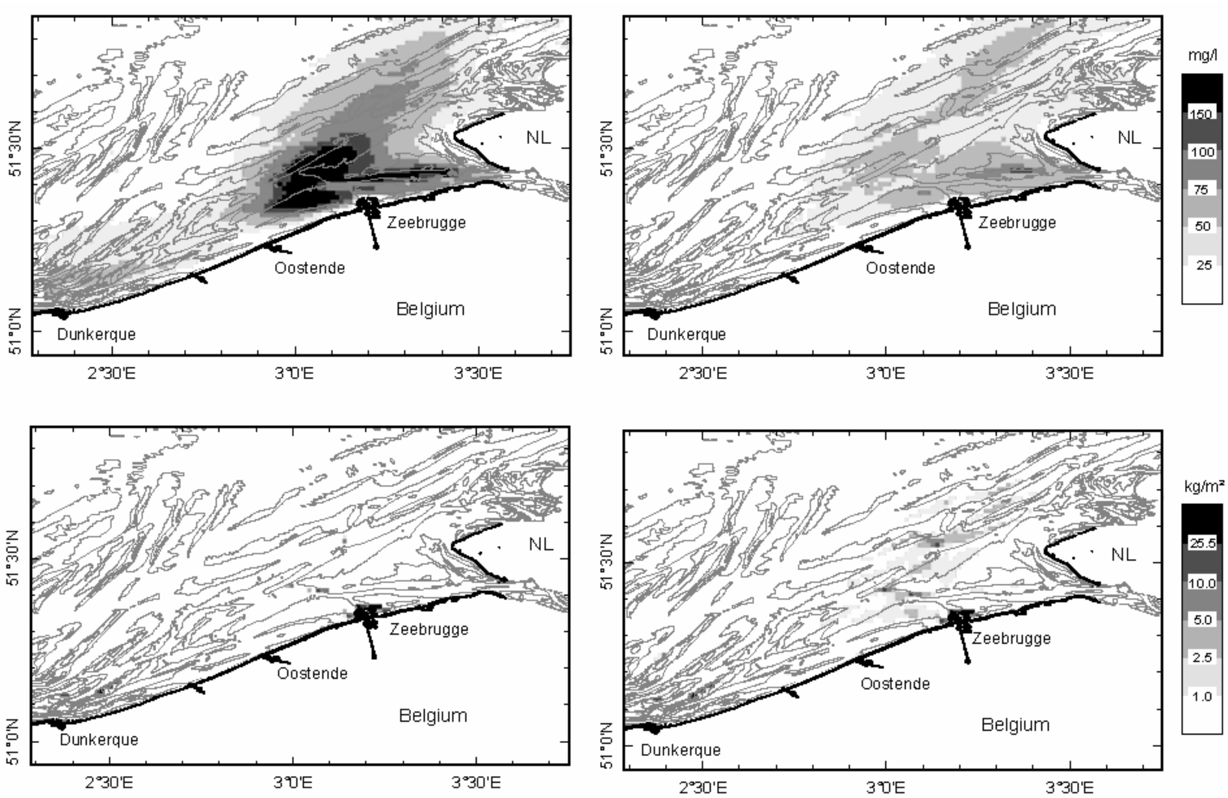


Figure 4.10: Tidal averaged SPM concentration (above) and mud deposition (below) during a spring tide (left) and a neap tide (right) respectively for the2003 situation.

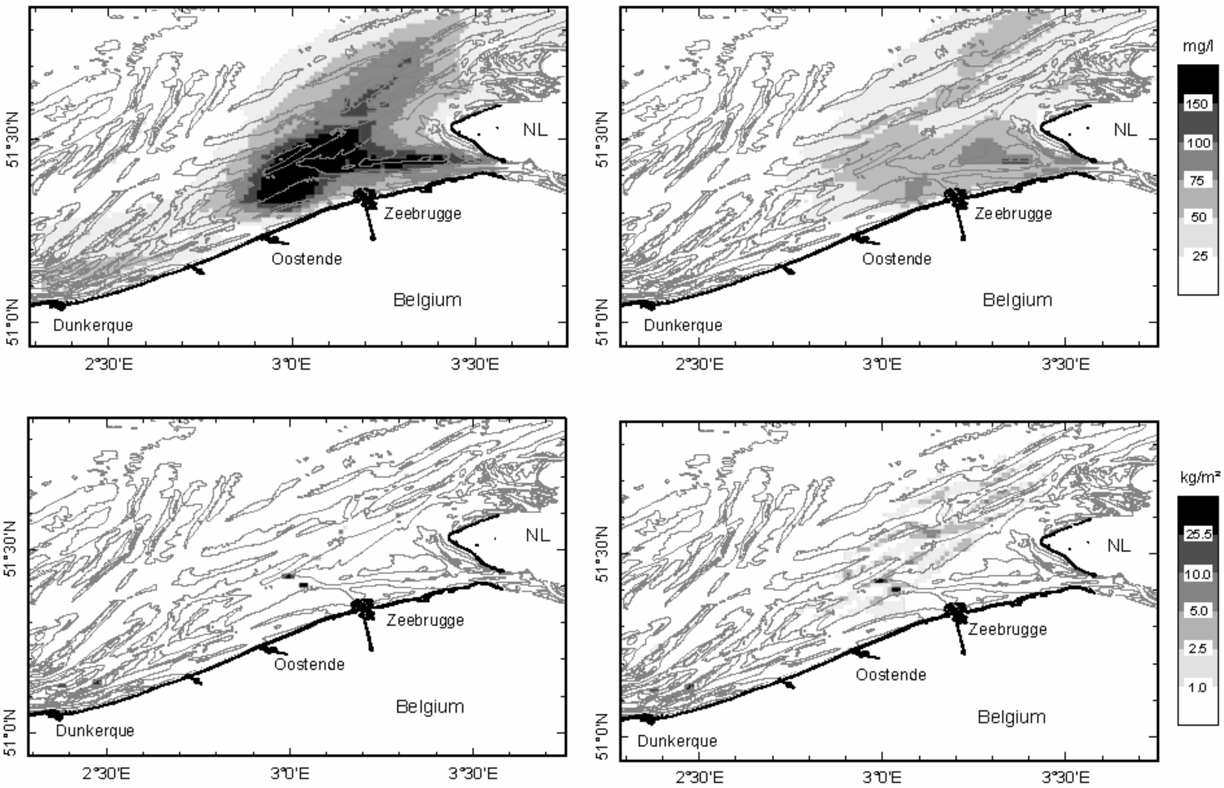


Figure 4.11: Tidal averaged SPM concentration (above) and mud deposition (below) during a spring tide (left) and a neap tide (right) respectively for the 1959 situation. The port of Zeebrugge is not included in the model grid.

5 SPM CONCENTRATION DISTRIBUTION

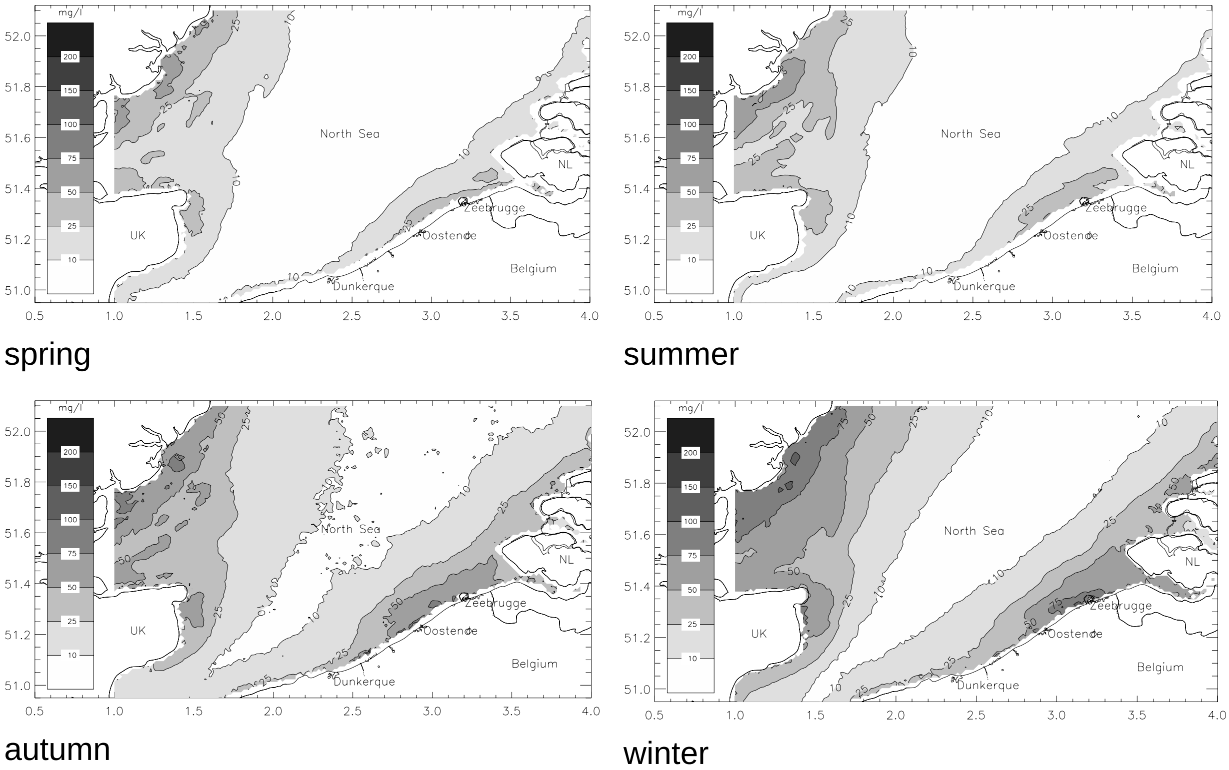
5.1 SPM concentration derived from satellite data

In total 362 SeaWiFS images were collected from September 1997 to April 2004. Among these images, 172 scenes are entirely cloud-free. Most of the 362 images have been affected by less than 30 % of clouds which were flagged during the processing of SPM concentration maps. The images have been grouped per season and have been processed to obtain vertical averaged SPM concentration, 37% of the images are from spring, 27% from summer, 13% from autumn and 23% from winter. A map of the seasonal surface and vertical averaged SPM concentration is given in Figures 5.1 and 5.2 respectively. The maximum surface SPM concentrations in the southern North Sea are situated between 75-100 mg/l during autumn and winter and 25-50 mg/l during spring and summer. The highest values are found in the Belgian-Dutch nearshore zone and in the mouth of the Thames estuary. In the Dover Strait the maxima are limited to about 15 mg/l (summer) up to 50 mg/l (winter). The meteorological data from the UKMO together with information on cloud cover from the satellite pictures have been used to calculate the mean wind speed in station 330 during clouded and cloud-free sky conditions in the satellite pictures. No clouds are present in the pixel in 83% of the images with the other 17% being cloudy. The mean wind speed during cloud-free conditions was 3.7 m/s (maximum 11.3 m/s), which is a little lower than the 4.8 m/s mean wind speed during clouded conditions.

5.2 In situ measurements of SPM concentration

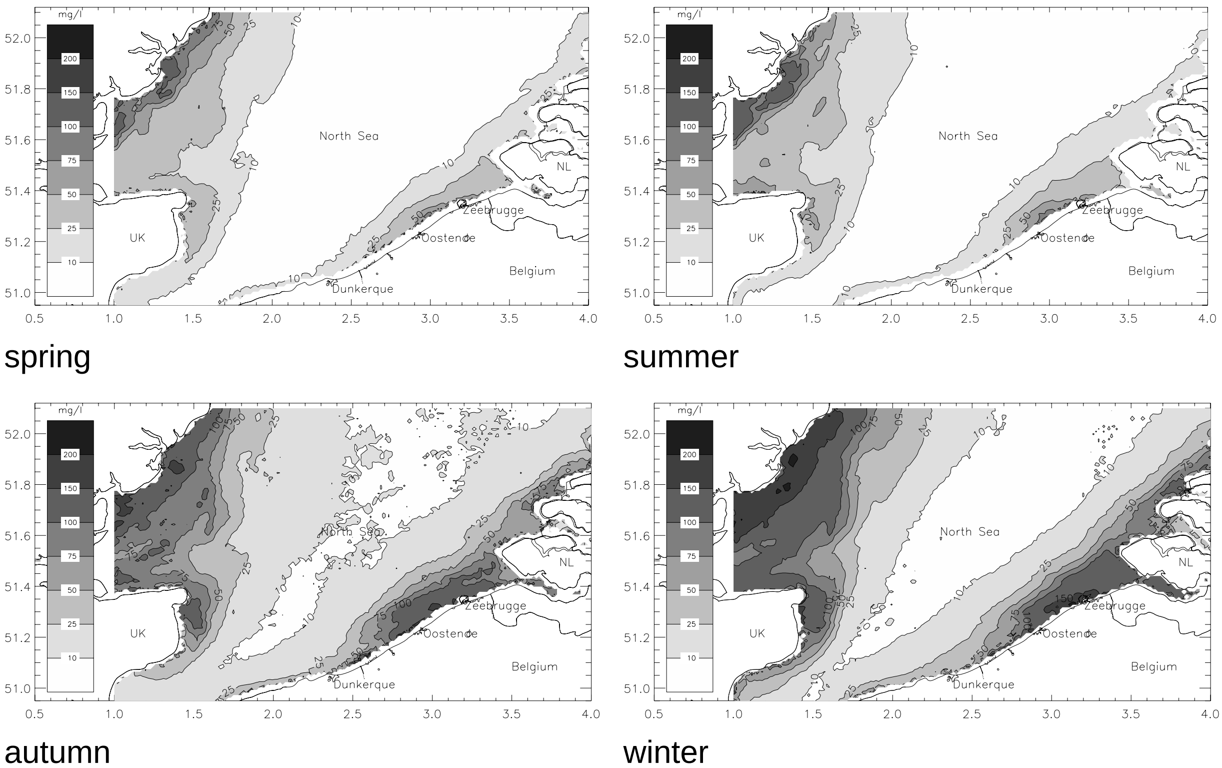
The SPM concentration has been measured during 38 tidal cycles between March 1999 and February 2005 from the R/V Belgica in the framework of the SEBAB and MOMO projects (Ministry of the Flemish community). 14% of the measurements were made during spring, 23% during summer, 26% during autumn and 37% during winter. The mean wind speed during all measurements was 6.7 m/s. The results presented in Figure 5.3 show the mean SPM concentration distribution.

The SPM concentration has also been measured in the framework of MUMM's Monitoring Program; these data are snapshots of SPM concentration at 3 m below surface and have thus not been measured throughout the tidal cycle. The data have been extracted from the BMDC database (http://www.mumm.ac.be/datacentre) for the period 1987-2004 and in the stations where at least 10 samples exist. In total 719 samples are available from which 35% during spring, 4% during summer, 34% during autumn and 27% during winter. In Figure 5.3 the mean SPM concentration distribution is shown.



spring summer
autumn winter

Figure 5.1: Seasonal averages of SPM surface concentration in the southern North Sea derived from 362 SeaWiFS images (1997-2004).



spring summer
autumn winter

Figure 5.2: Seasonal averages of vertically corrected SPM concentration (vertically averaged) in the southern North Sea derived from 362 SeaWiFS images (1997-2004).

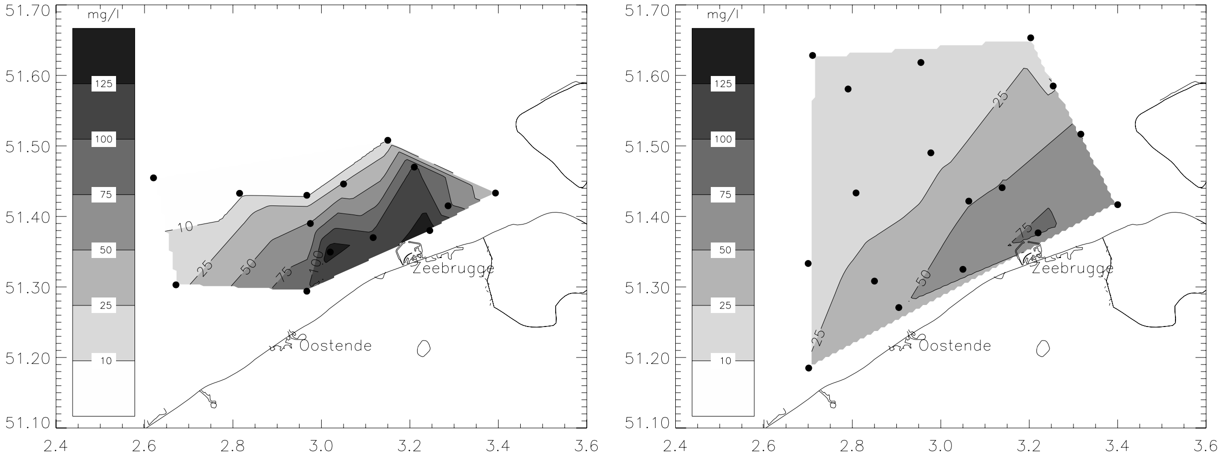
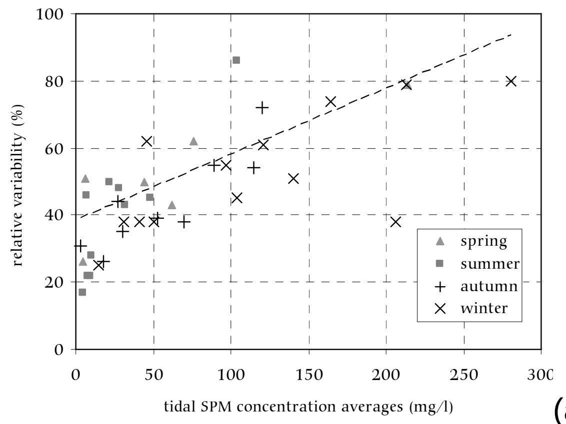


Figure 5.3: Mean SPM concentration (mg/l); (left) in the tidal cycle stations (1999-2005), the samples have been taken at ±3 m from the bottom; (right) from 'snapshot' samples collected in MUMM's monitoring stations (1987-2004), the samples have been taken at 3 m below the surface. Axes are in longitude (°E) and latitude (°N).

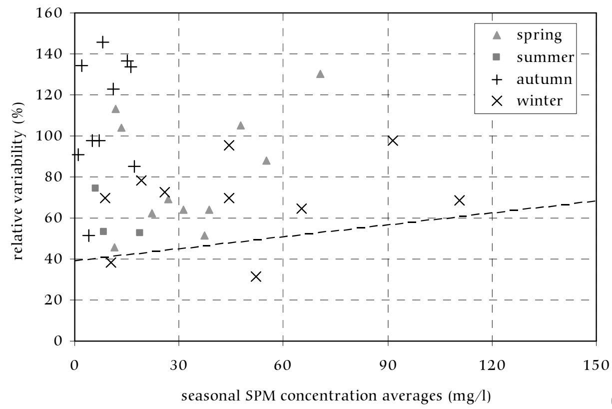
5.3 Variability of SPM concentration

The satellite images provide synoptic views of SPM concentration distribution but do not take away the uncertainty of SPM transport calculation, i.e. the accuracy of SPM concentration in a cross section. This is due to the fact that (1) not enough long term SPM concentration measurements are available to correct the satellite images and to derive the long term residual SPM transport and (2) SPM concentration varies as a function of tide, wind, spring-neap tidal cycles and - because winds (storm surges) are not equally distributed during a year - also depends on the seasonal time scale (Jones et al., 1994; Fettweis et al., 2005, 2006). The short term variations (tidal, spring-neap tidal cycle) have not been found back in the satellite images, however seasonal variations are clearly visible. The satellite images have been taken during cloud-free conditions and low mean wind speeds (about 3.7 m/s) and are correlated with good weather conditions; increased SPM concentration due to higher wave erosion is seldom to be expected in these images.

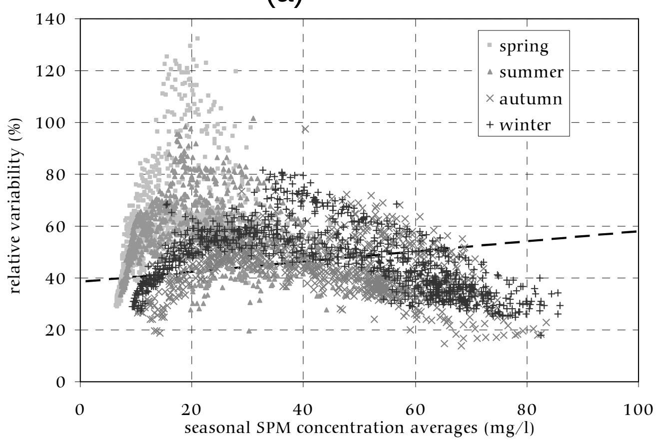
The representativeness of SPM concentration maps derived from satellites for calculating long term averaged transports has been investigated by comparing the SPM concentration variability from in situ measurements with those of remote sensing data. In Figure 5.4 the relative variability in the in situ measurements and in the satellite data is shown as a function of the averaged SPM concentration. Figure 5.4a shows that the relative variability in the tidal cycle measurements (standard deviation of SPM concentration during a tidal cycle divided by tidally averaged SPM concentration) increases with increasing tidal averaged SPM concentration. This means that in the coastal turbidity maximum zone the SPM concentration variations are high during a tidal cycle, whereas outside or at the edge of the turbidity maximum, where the SPM concentrations are low, the tidal variability is also low. The 'snapshot' SPM concentration at MUMM's monitoring stations (Figure 5.4b) is generally lower and the variability higher when compared with the tidal cycle measurements. Figure 5.4c shows the variability in the pixels of the satellite images situated in the Belgian near-shore area as a function of the seasonally averaged SPM concentration The figure indicates that (1) the SPM concentrations are generally lower from satellite data than from in situ tidal cycle measurements, (2) the relative variability decreases for lower and higher SPM concentrations and has a maximum at about 20 mg/l during spring and summer and at about 40 mg/l during autumn and winter, (3) the relative variability is of the same order of magnitude in most pixels as in the in situ tidal measurements (20-80%) except during spring and summer when relative variability's of up to 140% have been calculated and (4) the very high variability at low concentrations is also found in the in situ 'snapshot' measurements at MUMM's monitoring stations.



(a)



(b)



(c)

Figure 5.4: (a) Relative variability in the tidal cycle stations (1999-2005) as a function of tidal averages of SPM concentration. The samples have been taken at ±3 m from the bottom. (b) Relative variability in MUMM's monitoring stations (1987-2004) as a function of seasonal averaged SPM concentration. Only stations with at least 10 samples have been selected. The samples have been taken at 3 m below the surface. (c) Relative variability in the pixels of 362 SeaWiFS surface SPM concentration maps (1997-2004) situated in the Belgian-Dutch nearshore zone (51.1°N - 51.5°N and 2.7°E-3.5°E) as a function of seasonal averaged SPM concentration. The trend line in (b) and (c) is from in situ tidal measurements.

The maximum SPM concentration from the satellite images is 75-100 mg/l (surface) and 150-200 mg/l (depth averaged correction), whereas the maximum from the in situ ‘snapshot’ measurements is 680 mg/l (3 m below surface) and from the tidal cycle measurements ±1000 mg/l (3 m above bottom). Satellite images and the in situ measurements in MUMM’s monitoring stations are both snapshots of the SPM concentration and have been sampled at the surface or near the surface (3 m below). The decreasing variability in satellite images and in the ‘snapshot’ in situ measurements with increasing SPM concentration could be explained if most of the SPM in the nearshore zone during a tidal cycle would occur in the bottom layer of the water column and would thus be invisible for satellites or near surface sampling. Tidal measurements however indicate that strong vertical gradients and high SPM concentrations only occur during about 1/3 of the tidal cycle (2h per ebb and flood) and that during the rest of the cycle the SPM stratification and concentration is much lower (Van den Eynde et al., 2006). The low variability at higher concentration is probably an artefact of the fact that the algorithm for processing the satellite images underestimates the high SPM concentrations. The very high variability at low concentrations could be due to short-lived events, such as storms or high river runoff, which increase locally the SPM concentration and move the turbidity maximum zone coastward or towards offshore, as found in the salinity variations in the nearshore area (Lacroix et al., 2004). During winter and autumn, the SPM concentration is high and these events are therefore statistically less significant.

Measurements in the Dover Strait, where the SPM concentration is generally low (<10 mg/l) indicates that the vertical gradient is negligible (Van Alphen, 1990). The tidal cycle measurements in the nearshore zone show that the SPM concentration stratification is low in low SPM concentration areas, therefore satellite images may give a good estimate of the total SPM concentration. In high turbidity areas the vertical variation during a tidal cycle is important and corrections have to be applied to obtain depth averaged values.

6 CLAY MINERALS

6.1 Results and conclusions of the first approach

To detect mud provenance indicators Fontaine (2004) examined the clay mineralogy of over 70 samples taken on the BCS, its estuaries (Schelde and IJzer), its ports and harbours (Zeebrugge and Nieuwpoort) and close-by areas (Dover Strait), see Figure 6.1. Samples were taken in the mud dominated areas as well as beyond and include the different mud types as presented in § 4.1, i.e. Holocene mud, freshly deposited to very soft consolidated mud (thick mud and fluffy layers), sandy samples and SPM. Since this was a reconnaissance study a preparation and interpretation methodology was used that allowed to process fast large numbers of samples, but that was limited in its resolution and produces only semi-quantitative results (see § 3.4.1).

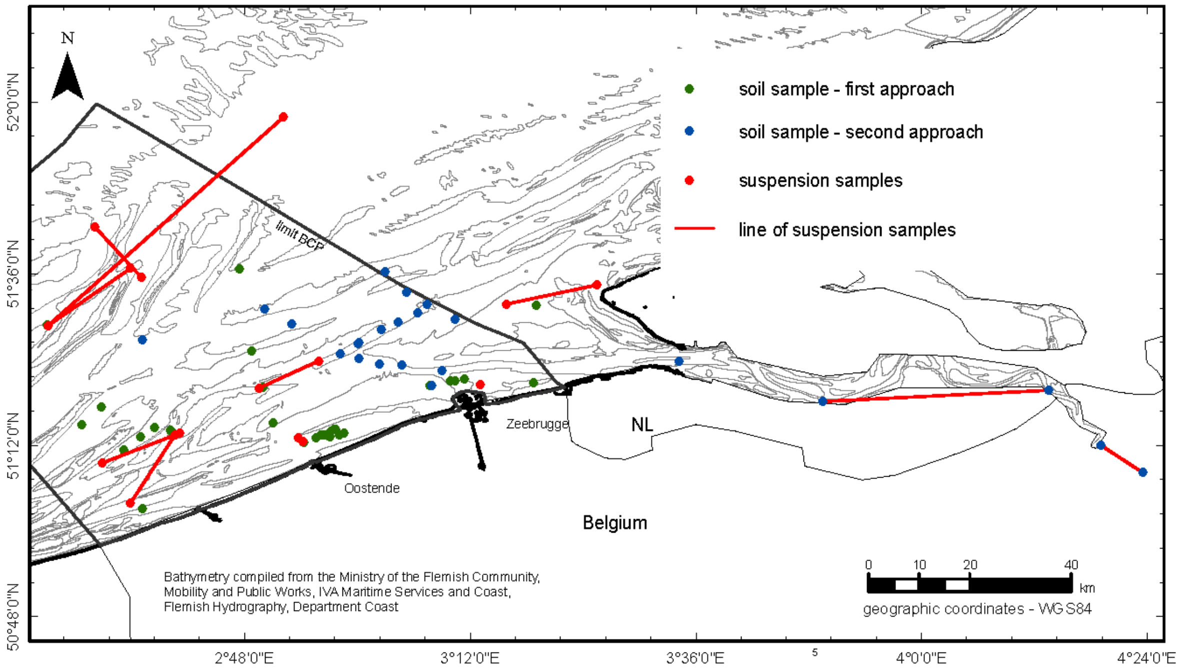


Figure 6.1: Location of samples used for clay mineral analysis; bottom samples (above), suspension samples (below), some have been sampled along track lines. Yellow dots: first approach, black dots: only second approach.

The methods, the examined parameters (e.g. v/p-ratio) and the results, including detailed tables and graphic representations, have been extensively reported in Fettweis et al. (2005). The summarized conclusions are that:

Clay mineral proportions vary on the BCS and in the estuaries leading to the North Sea with estimated differences for illite between 15 and 83%, for smectite between 1 and 80%, for kaolinite between 1 and 36% and minimal differences for chlorite. A trend seems to be present in the bottom sediments. More smectite occurs in the northern and eastern sectors of the North Sea, and more illite in the south-western sector. This difference is not observed in the mineralogy of suspended matter which seems to have a more homogeneous composition. A distinct difference in the v/p ratio (an empirical description of the smectitic phases) was found between bottom and suspension samples, with the latter having the lowest v/p ratios. The sampling at MOW1 (1 to 7) during a tidal cycle does not show any trend and the differences between the samples are limited. Suspension samples in the Dover Strait show very low smectite proportions (3 and 13%). This is somewhat unexpected as the erosion of the chalks exposed along the coast in this area would normally produce relatively high smectite proportions. This result suggests that the coastal erosion of chalk is not a major contributor to the suspended matter. The IJzer and the canal samples have lower illite and higher smectite contents than in the harbour mud of Nieuwpoort. The mud mineralogy of the harbour samples is similar in composition to the muds in the vicinity of Nieuwpoort. Also the smectite v/p ratio in the harbour mud is different from the IJzer *a*nd canal samples. Therefore, the clay mineralogy suggests that the excessive mud sedimentation in the Nieuwpoort harbour is derived from the precipitation of sea water suspended matter and not from river influx.

The data for the Schelde bottom samples show a trend. From Antwerp towards downstream the smectite content increases, from 18% to 77% while the illite and kaolinite content decreases respectively from 51 to 15% and from 31 to 8%. The increase in smectite content is accompanied by an increase in v/p ratio. The smectite increase in suspension samples is much more limited. The core samples from the Paulina salt marsh seem to document a clay mineral compositional trend with time. Illite increases with depth from 46 to 71 %, while smectite and kaolinite decrease with depth, respectively from 18 to 2% and from 36 to 26%. Decreasing smectite content with depth is also accompanied by decreasing v/p ratio. Apparently one century ago there was more illite and less smectite and kaolinite in the Schelde mud. An explanation could be the deepening works carried out in the Schelde estuary during the last century, which have resulted in a higher MHWL, an increasing tidal amplitude and a higher import of fine-grained sediments from the North Sea. The tidal flats in the Schelde estuary follow this sea level rise and have accumulated an increasing fraction of these marine sediments during the last century (Temmerman et al., 2004).

In general Fontaine (2004) concluded that the use of clay mineralogical analyses in the provenance study of the North Sea muds could be a promising tool. However, at the same time was concluded that the used methodology was not detailed enough and implied too many uncertainties (e.g. only semi-quantitative results) to draw final conclusions about the composition and provenance of the muds. It was also recommended to examine the clay mineralogy with denser sampling.

6.2 Results of the second approach

Following these conclusions and recommendations a second study was undertaken by Grégoir (2005), this time a much more refined approach to clay mineral research was used (see § 3.4.2). In this study only the sample preparation methodology of this approach was used to re-examine the main conclusions of Fontaine (2004) and at the same time prove the value of these much more detailed - but also more time-consuming – procedures in studying the provenance of the North Sea muds. For this purpose three main hypotheses were put forward:

- Can it be confirmed that there are systematic differences in the clay mineralogy of sediments on the BCS between the east and the west near-shore zone?
- Can it be confirmed that there is a substantial difference between the clay mineralogy of suspension and bottom samples?
- Is there a difference in clay mineralogy between samples taken in areas with high mud content and in the sandy areas further offshore?

For this second study 45 additional samples were taken (Figure 6.1). Unlike for the first study, samples were mainly taken on the BCS. The Schelde estuary, the Dover

Strait and the Nieuwpoort harbour were not considered this time. Also, for comparison a few of the samples of Fontaine (2004) were re-examined.

As a direct effect of the more extensive sample preparation, considerably better X-ray diffraction patterns than in the first study were obtained. The complete removal of cementing agents allowed for the extraction of the extremely fine fraction <0.2µm (in addition to the fraction <2µm). In this fraction the important group of mixed-layered minerals (mainly illite-smectite) is concentrated and thus visualized. In addition, the clay crystals can be oriented better on the slides, resulting in higher intensities and a less 'noisy' pattern, both strongly enhance peak resolution. Also, saturating the samples with one exchange cation (Ca) substantially increased the quality of the patterns (more pronounced peaks). When comparing X-ray diffraction patterns of samples also analyzed using the first approach, the increase in quality is apparent immediately. Especially in the low angle region, peaks of mixed-layered minerals are much more pronounced (Figure 6.2). Another major benefit is that all samples are prepared in a standardized way and therefore can be easily compared.

Because of the high quality X-ray patterns a qualitative examination was sufficient to check the 3 hypotheses put forward. It was found that none of the hypotheses could be confirmed. A (limited) variability in the samples could be observed, but there is no systematic variability in the clay mineralogy between 1) samples from the east or the west of the BCS, 2) suspension and bottom samples and 3) mud dominated or sand dominated sediments (Figure 6.3).

6.3 Conclusions after the second approach

The results of the second approach imply for the conclusions of Fontaine (2004) that at least the observed difference between suspension and bottom samples cannot be confirmed. Grégoir (2005) also did not detect systematic differences in the clay mineralogy depending on geographic location, but it needs to be remarked that in the results of Fontaine (2004) samples from the Schelde river and a larger number of samples from the west BCS (including the Nieuwpoort harbour) were included. So a definite conclusion is not possible. Nevertheless, the more extensive procedures used showed that non-standardized sample preparations were responsible for a substantial part of the observed differences. Therefore it is to be expected that potential differences will be substantially smaller than reported after the first approach.

The results of the second approach clearly prove the necessity of using more elaborate sample preparation procedures in examining the provenance of the mud deposits. Another advantage of these procedures is that because of standardized preparations and the much higher resolution of the results, the study of the provenance of the muds can be extended to analyzing and comparing samples from possible source areas. Such a study, in combination with detailed qualitative and quantitative analyses, is currently in progress (IWT PhD Zeelmaekers).

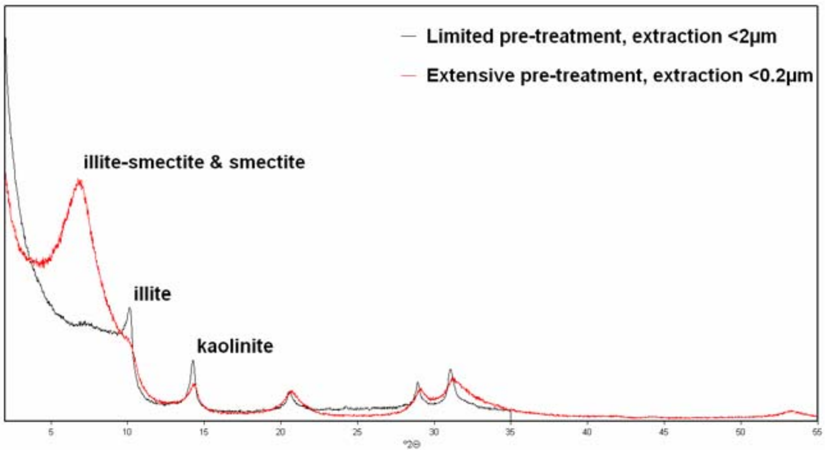


Figure 6.2: Comparison the maximum possible resolution of the first approach (black pattern) and the second approach (red pattern) <u>on the same sample</u>. As a result of the more extensive pre-treatment and the extraction of a smaller fraction the mixed-layered illite-smectite components can also be examined. X-ray patterns were recorded in the air-dry state. (Note: in this example most peaks of the red pattern are broader and less pronounced than in the black pattern because of a smaller crystal size, not because of sample preparation!).

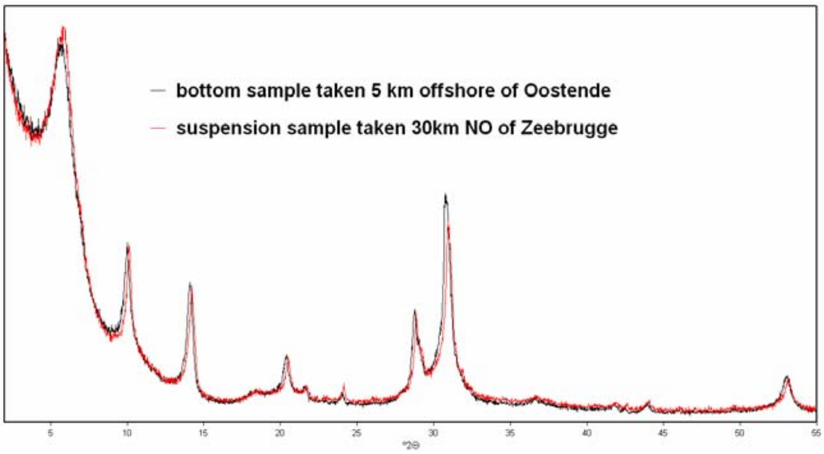


Figure 6.3: Quasi identical X-ray patterns from two very distinct samples (bottom vs. suspension) taken at considerable distance of each other. X-ray patterns were recorded in the ethylene glycol solvated state.

7 SOURCES OF COHESIVE SEDIMENTS

Globally the predominant sediment inputs into the North Sea are from the Channel, sea floor erosion and the North Atlantic, the rivers and estuaries come only at the fourth place (Eisma & Irion, 1988). There is evidence of long-term net inflow of water through the Dover Strait and thus also of SPM transport into the North Sea (Prandle et al., 1993, 1996). Gerritsen et al. (2001) underline that this transport is the major source of recent fine-grained sediments in the North Sea. An extensive scientific literature on the SPM transport through the Dover Strait exists; the values vary between [2.5-57.8]$\times10^6$ t/yr (Eisma, 1981; Eisma & Irion, 1988; van Alphen, 1990; Lafite et al., 1993; Velegrakis et al., 1997; McManus & Prandle, 1997, Lafite et al., 2000). Sediment accumulation measurements in the Kattegat and the Skagerrak resulted in a four times higher accumulation rate than previously accepted (de Haas, 1997); this would imply a SPM transport through the Dover Strait of at least 46×10^6 t/yr. The big differences in SPM transport through the Dover Strait found in literature reflect partially the high temporal and spatial variability of the influx but have their origin also in the way the SPM measurements have been carried out, in the small number of SPM concentration measurements on which the calculations were based as well as the differences in the way the residual SPM transport was calculated. Velegrekakis, et al. (1999) mention as predominant sediment inputs into the English Channel cliff erosion (in particular the Chalk outcrops) in the eastern English Channel, the Seine river (the remainder of the French and UK rivers have much lower SPM discharges) and the Atlantic ocean (western English channel). They suggest that on balance and in the long term, the eastern Channel might represent an area of fine-grained sediment 'by-passes'. The following possible sources have been considered during the project:

- the Schelde estuary;
- the potential erosion areas of cohesive sediments on the BCS;
- the SPM transport in the southern North Sea and through the Dover Strait.

7.1 The Schelde estuary

Estuaries and related tide-dominated environments are supposed to be subject to long-term sediment infilling (Billeaud, et al., 2005) and are thus not considered as net sediment suppliers. The contribution of the Schelde estuary to the fine grained sediment supply in the nearshore zone is therefore assumed to be small. Based on empirical data and numerical modelling a net residual input of marine mud of 0.6×10^6 t/yr into the estuary was calculated by Van Alphen (1990). Van Maldegem & Vroon (1995) reported an even smaller value ($0.1\times10^6 \pm 0.2\times10^6$ t/yr). The amount of terrestrial mud input at Rupelmonde was estimated by Wollast & Marijns (1981) and Sas & De Jonghe (1993) as 0.75×10^6 and 0.80×10^6 t/yr, respectively. The MHWL has risen during the past century at rates varying between 3 mm/yr at the mouth and 15 mm/yr in the inner estuary (Temmerman et al., 2004). This sea level rise has increased the tidal range and the flood volume, which favour an import of fine-grained sediments from the North Sea. The tidal flats in the Zeeschelde are accumulating and follow the sea level rise. Salden (2000) has calculated the mud balance in the estuary using 3D numerical sediment transport model. The numerical results show a doubling of marine mud input into the estuary due to the deepening of the navigation channel. This result is confirmed by the measurements of the fluvial fraction of suspended organic matter, which indicate an increase of the marine SPM component between 1992 and 1998 at 58 and 92 km from the mouth (Chen et al., 2005).

7.2 Quaternary mud and Tertiary clays: erosion

7.2.1 Potential erosion areas of Paleogene sediments

Areas where the thickness of the Quaternary cover is less than 2.5 m were defined as potential erosion areas of Paleogene clay containing deposits (Figure 7.1). In some cases the Tertiary sediments are even outcropping (e.g. south and northeast of the Gootebank, the Westdiep swale and west of the Kwintebank (Le Bot et al., 2005). In the framework of this project, the geological data related to the BCS, and synthesized in Le Bot et al. (2005), have been reviewed and the relevant information was compiled into a GIS. This also included a small part of the French continental shelf. Additionally data was added from vibrocores analysis (compilation of Mathys, FWO PhD) and Dutch geological data, compiled by Ebbing et al. (1992), was gathered. The western part of the BCS is characterised by compact stiff clay (more information can be found in Le Bot et al., 2005). In the eastern part, a vertical and lateral succession of fine sand and silt, sand and sandy clay, and clay, belonging to the Upper Eocene and Lower Oligocene, is forming the Tertiary subsoil (Maréchal, 1993) (Figure 2.2). The Dutch study area is mainly characterised by stiff clay. Only in the outermost eastern part Tertiary sand occurs. The possible erosion capacity is represented in Table 7.1.

Approximately 20 % of the BCS, 6 % of the small part of the French area and only 3% of the Dutch study area could possibly serve as a source for fine suspended sediments. Nevertheless, one has to keep in mind that (1) the erosion resistance of Tertiary clay under the present-day hydrodynamic regime is still unknown, (2) the percentages are maximum values and probably only smaller areas will undergo erosion, (3) muddy sediments with a mixture of sand, or vice versa, have a higher erosion resistance within certain limits (Williamson & Torfs, 1996) and (4) the clays are mainly situated outside the turbidity maximum area in a zone where the SPM concentration is low (<5 mg/l), which indicates thus that the local erosion is very low. Consequently, the estimates of the erosion capacity of Tertiary clayey sediments remain purely indicative.

Table 7.1: Possible erosion capacity of Paleogene clays.

ID Area	Type sed.	Area (km²)	% with respect to total area
BCS	clay	465	13
	clayey sand	31	1
	sandy clay	113	3
	alternation of sand & clay layers	73	2
Rabsbankmap	clay	24	2
	clayey sand	4	0
	alternation of sand & clay layers	14	1
Northern France	clay	30	6

7.2.2 Potential erosion areas of Pleistocene/Holocene sediments

Descriptions of vibrocores, mostly collected by the former Rijks Geologische Dienst (NL) and the Belgische Geologische Dienst, have been used to derive the presence of Pleistocene/Holocene mud in the first meter of the seabed. On the Dutch part also seismic data were evaluated (Ebbing et al., 1992). Finally results of Reineck and Van Veen samples were used for further validation. Quaternary muds are mostly present in the eastern nearshore area; on the Dutch part they occur more offshore (Figure 7.2). Their occurrence represents 11% of the BCS and approximately 35% of the Rabsbank area (Table 7.2).

Table 7.2: Possible erosion capacity of Holocene clays (mud).

Type of clay	ID Area	Area (km²)	% tov total area
Holocene clay	BCS	368	11
	Rabsbankmap	376	35

7.2.3 Hydrodynamic conditions

The bulk density gives an indication of the consolidation and of the erosion behaviour of the cohesive sediment. Measurements of the bulk density of sediments from the BCS have been used by Fettweis et al. (2005) to estimate the erosion behaviour following Williamson & Torfs (1996). The critical erosion shear stress was calculated as <1 Pa for the freshly deposited to very soft mud and between 1.4 Pa and 2 Pa for the soft to medium consolidated mud.

The maximum and minimum bottom shear stress during a typical neap and spring tide are shown in Figures 7.3 and 7.4. The maximum bottom shear stresses during a neap tide are <0.5 Pa except in the navigation channel ‘Scheur‘ and ‘Pas van het Zand’ (<1 Pa). The results affirm that during neap tide favourable conditions for mud deposition exist. During spring tide (Figure 7.3) the bottom shear stresses are much higher and reach peak values of more than 3 Pa. These values indicate that fresh mud layers are not stable and that the hydrodynamics during extreme conditions are possibly strong enough to erode the Holocene mud.

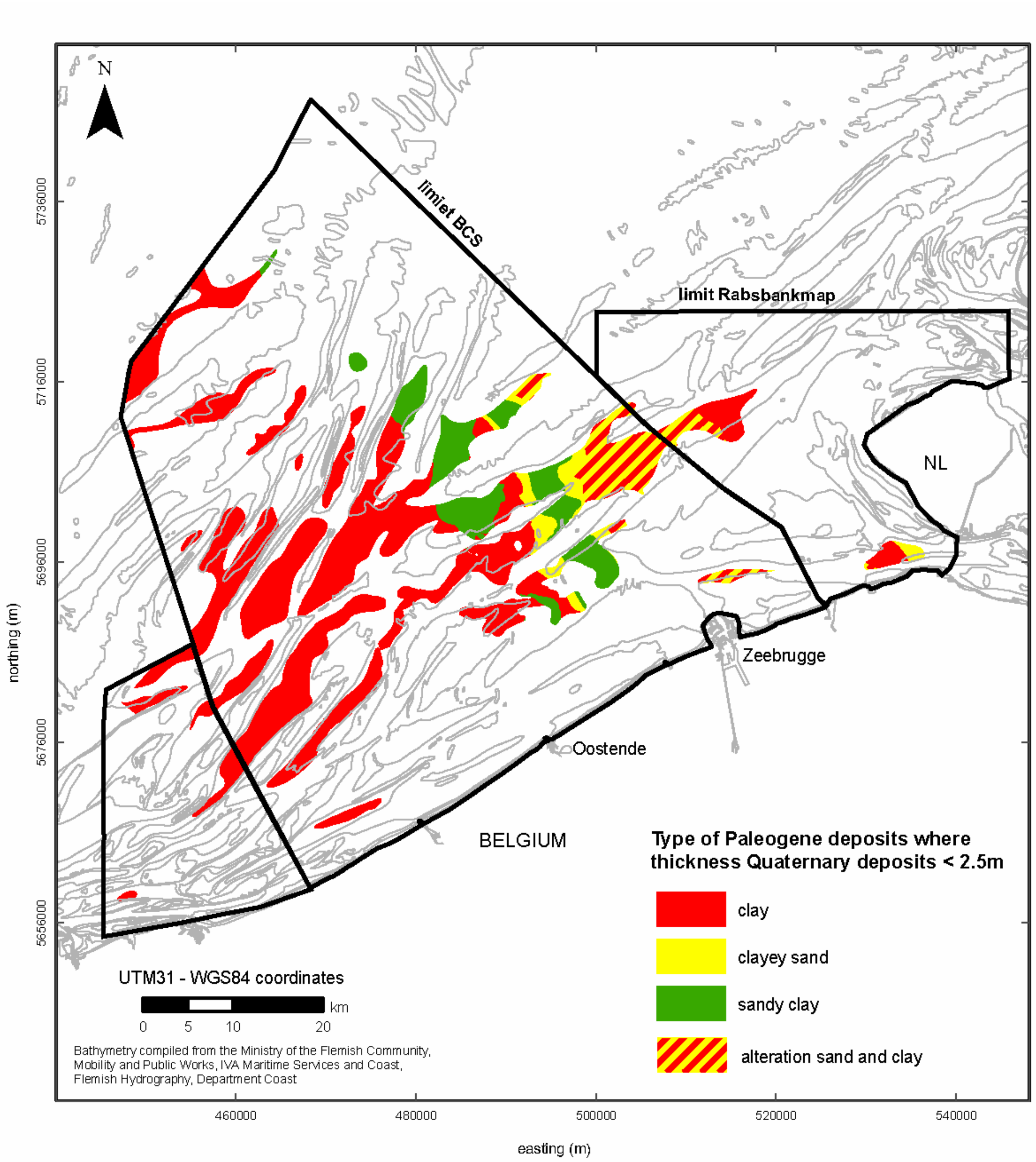


Figure 7.1: Sediment type of the Paleogene deposits at locations where the thickness of the Quaternary cover is less than 2.5m.

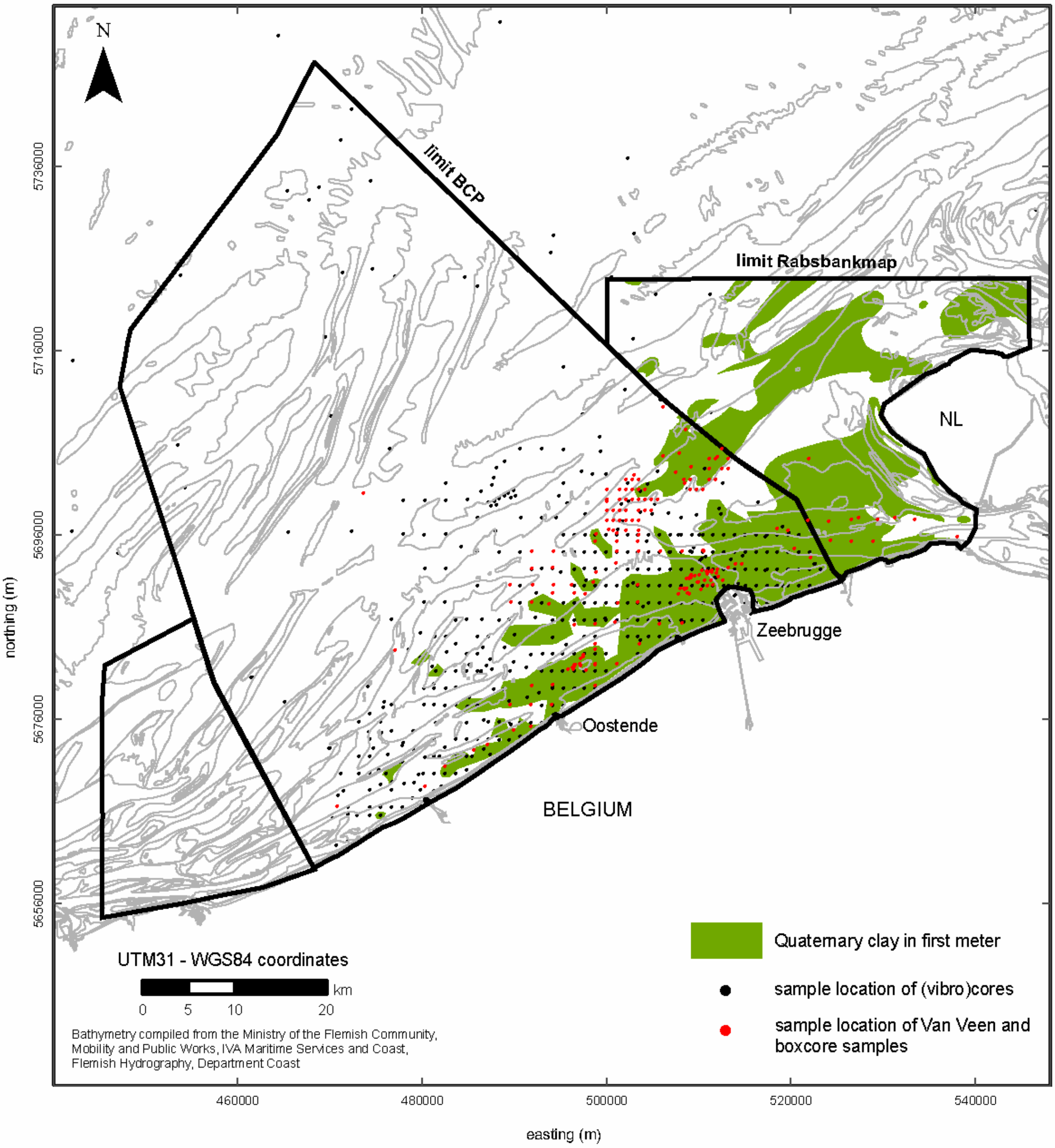
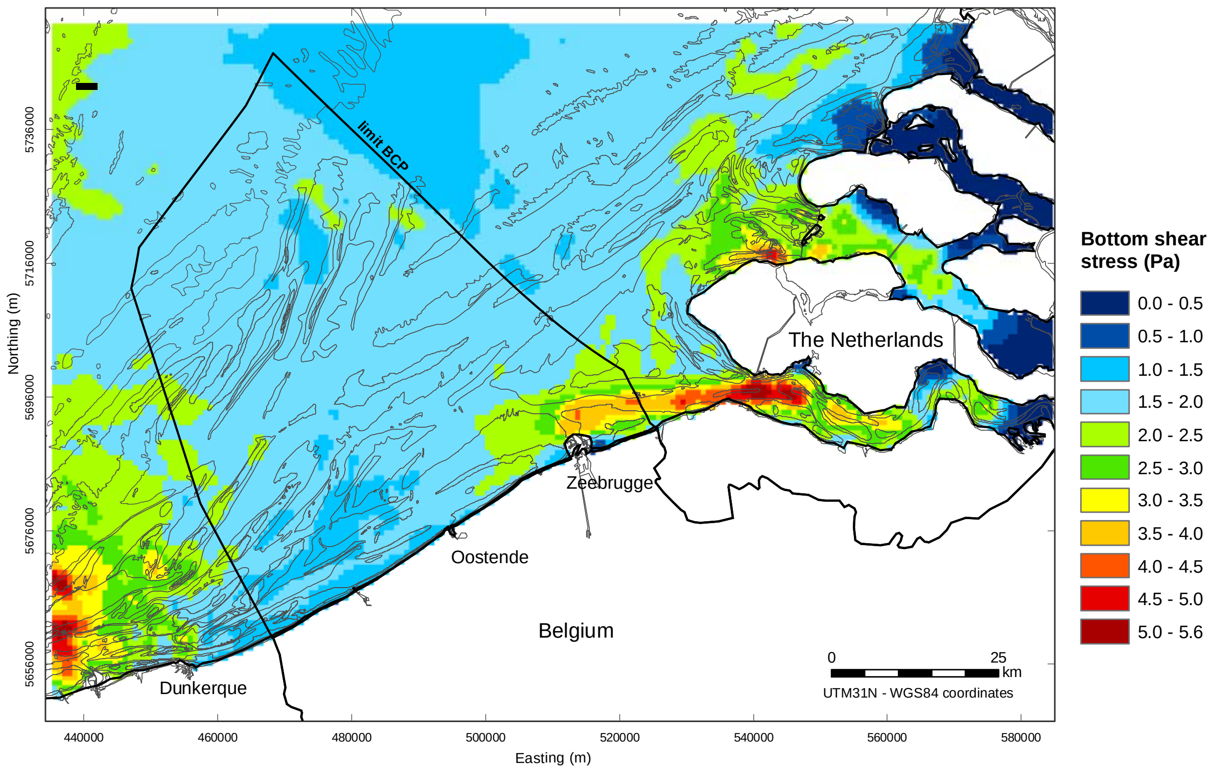


Figure 7.2: Presence of Quaternary clay in the first meter of the seabed. Sample locations of vibrocores, Van Veen grabs and box core samples are also shown.



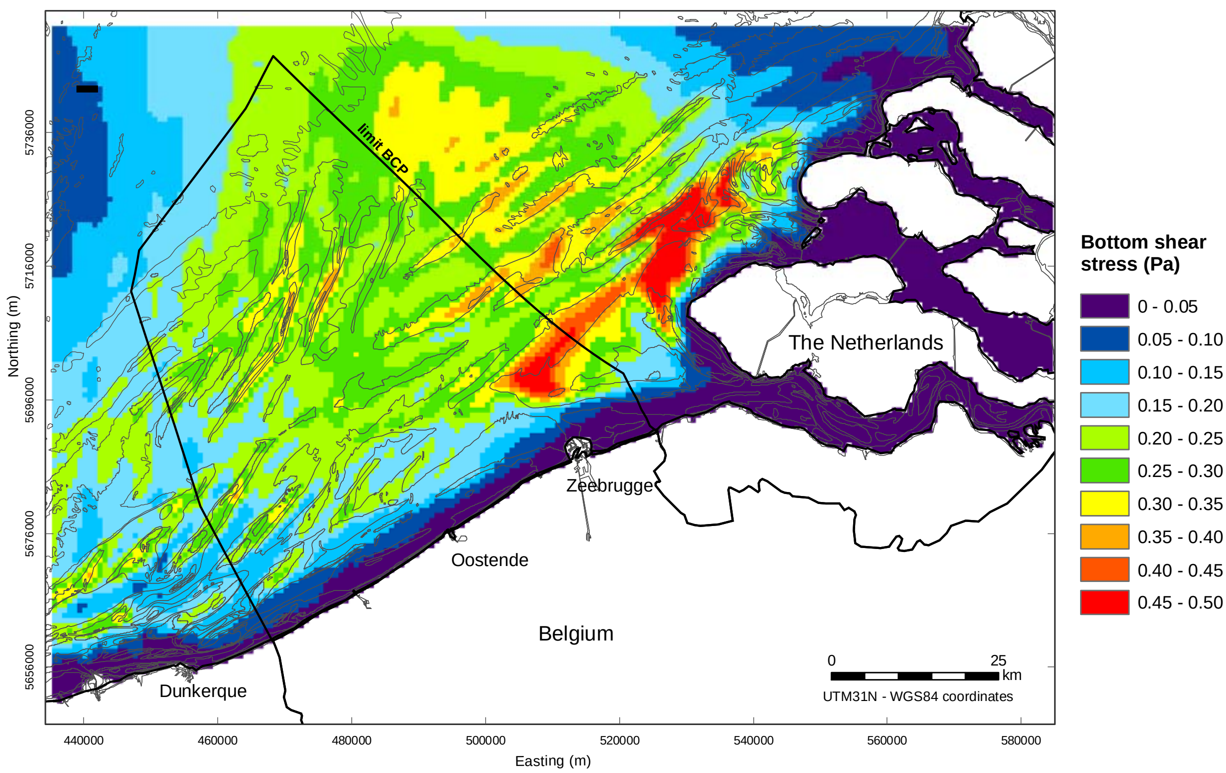
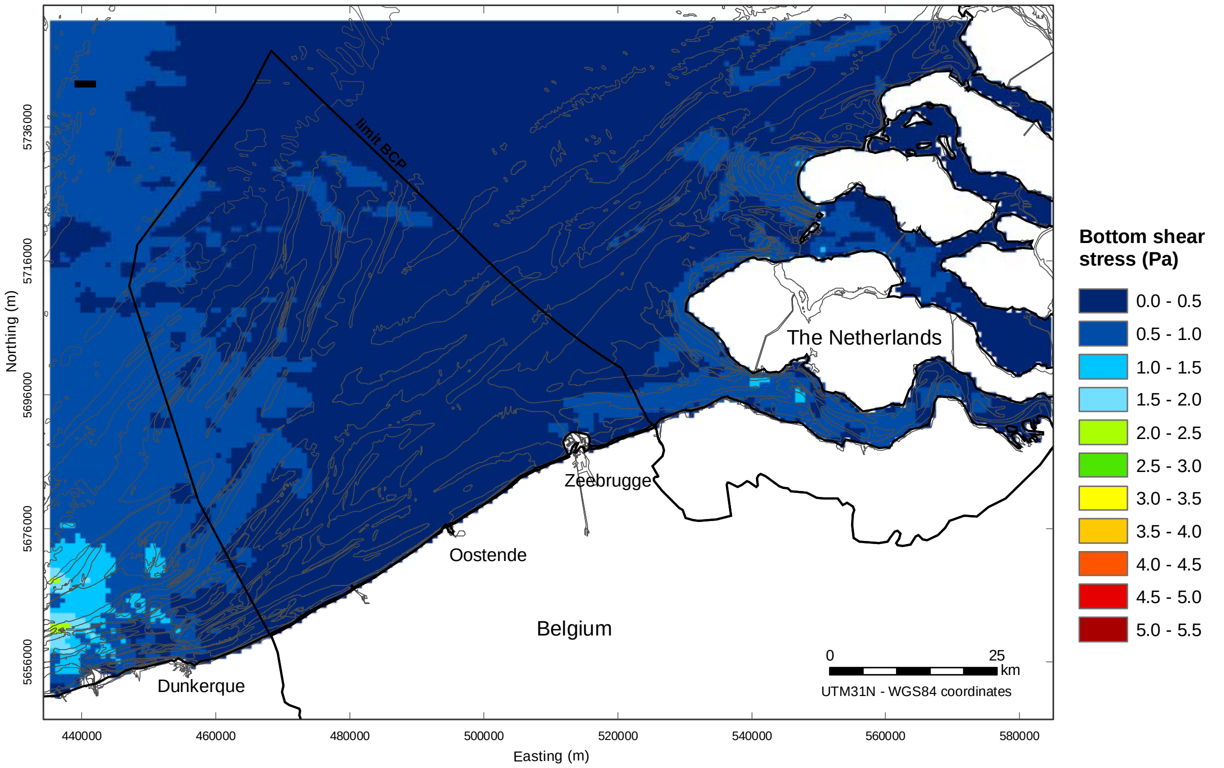


Figure 7.3: Maximum (above) and minimum (below) bottom stress during spring tide (without wind effects), simulated by the OPTOS-NOS model.



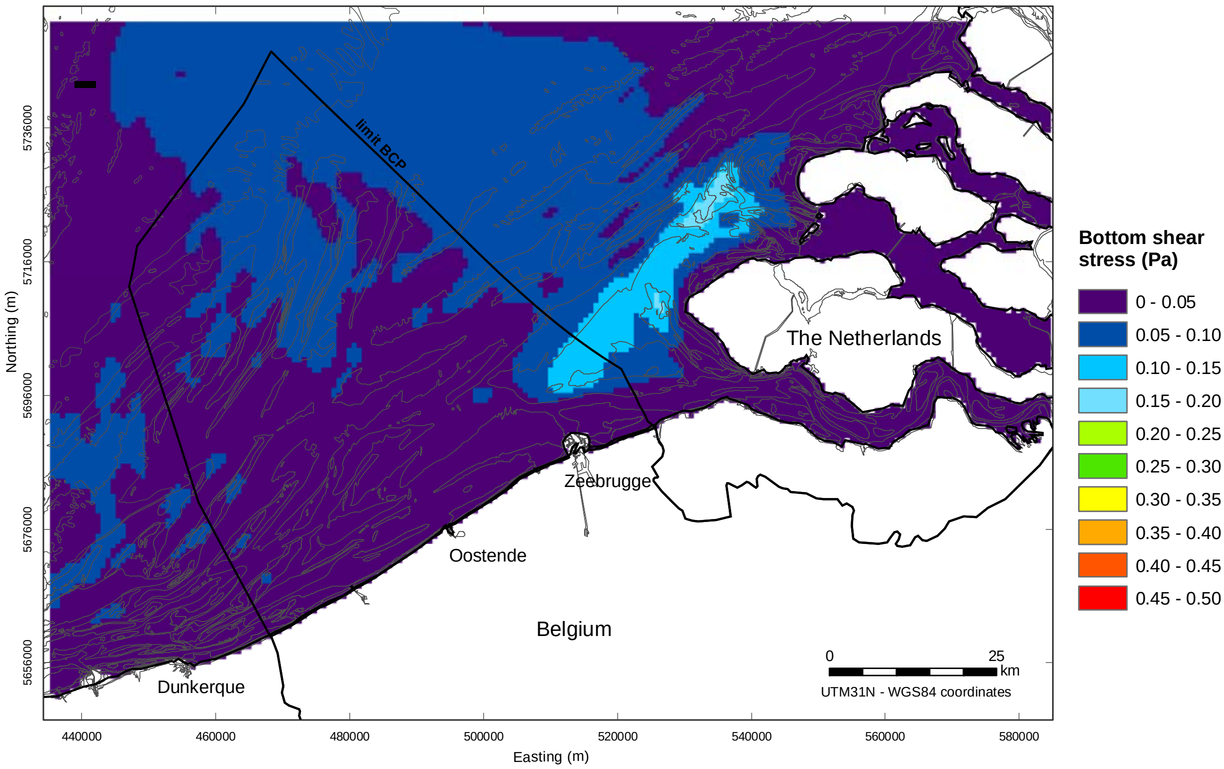


Figure 7.4: Maximum (above) and minimum (below) bottom stress during neap tide (without wind effects), simulated by the OPTOS-NOS model.

7.3 SPM transport in the southern North Sea

7.3.1 Quantitative approach using satellite images and numerical modelling

The SPM transport in the southern North Sea has been calculated by combining satellite images (SeaWiFS), in situ measurements and a hydrodynamic numerical model. The use of optical remote sensing methods to produce SPM concentration maps benefits from the satellite capabilities to picture wide area and to provide synoptic views of SPM concentration distribution. The disadvantages are mainly that the data are limited to the surface layer, that good data exist only during cloud-free daytime and that the time resolution is low. For the BCS about 60 (partially) cloud free images per year are available. In order to cope with the fact that only surface values are available, the method of Van den Eynde et al. (2006) has been applied in which in situ measurements of SPM concentrations have been used to calculate the depth averaged SPM concentration distribution in the satellite image. The low time resolution prevents an accurate computation of the sediment flux when using:

$$T = \int_0^t \int_0^h u(z,t)c(z,t)dzdt \tag{7.1}$$

where T is the sediment flux per unit width, h is the water depth, $u(z,t)$ is the current velocity normal to the section and c(z,t) the SPM concentration. Prandle et al. (1996) wrote that the SPM dynamics in tidal waters are mainly determined by water depth, eddy diffusivity K_z and settling velocity w and that the residual transport closely approximates

$$T \approx \int_0^t \int_0^h u(z,t)dzdt \int_0^t \int_0^h c(z,t)dzdt \tag{7.2}$$

when $K_z > wh$. In coastal waters, such as the southern North Sea, with water depth between 10-50 m and a K_z of 0.01 m²/s the settling velocity must be <1 mm/s. This is a value in agreement with measured settling velocities of flocs and aggregates in estuaries and in the North Sea (van Leussen, 1994; Mikkelsen & Pejrup, 2001).

The net sediment flux has been calculated through the Dover Strait (51.0° N) and through a cross section at 51.9° N using Eq. 7.1 and Eq. 7.2. Eq. 7.1 has been applied in two ways. First the 362 SPM concentration fields derived from satellite pictures have been multiplied by the velocity field at that same moment and summed (method 1); second the velocity fields at every model time step (10 minutes) have been multiplied with the linearly interpolated SPM concentration at that time and also summed (method 2). For Eq. 7.2 the seasonally averaged velocity fields and SPM concentration maps have been used (method 3). The results show clearly that differences exist between the methods (Fettweis et al., 2007). The results of method 2 and 3 are qualitatively similar in that SPM enters the southern North Sea through the Dover Strait where it bifurcates along the English and continental nearshore zone and flows towards the north. Using solely the 362 satellite pictures and the corresponding velocity fields (method 1) gives a transport direction, which does not correspond with the typical long term residual circulation.

Table 7.3: Residual SPM transport (10^6 ton/season or year) through the Dover Strait and through a cross section at 51.9° N for the period January 1997 - December 2003 (positive is towards the north) for method 2 and 3. The SPM concentrations have been vertically corrected to obtain depth averaged concentrations. 'Dover Strait – 51.9°N' is the difference between inflow and outflow at both section, positive means a higher SPM flux into the southern North Sea than out of it.

		spring	summer	autumn	winter	**year**
Method 2	Dover Strait	3.36	2.50	9.18	7.22	**22.26**
	51.9°N	7.32	7.83	23.55	21.87	**60.57**
	Dover Strait – 51.9°N	-3.96	-5.33	-14.37	-14.65	**-38.31**
Method 3	Dover Strait	3.00	4.19	14.02	10.53	**31.74**
	51.9°N	6.30	4.45	14.80	15.57	**41.12**
	Dover Strait – 51.9°N	-3.00	-0.26	-0.78	-5.04	**-9.08**

The residual SPM transport through the Dover Strait and through a cross section at 51.9° N are given for method 2 and 3 in Table 7.3. The value of the SPM transport is depending on the method. Using method 2 the highest SPM transport occurs during autumn and the lowest during summer (Dover Strait) and spring (51.9° N). Using method 3 the highest SPM transport is calculated during autumn and the lowest during spring (Dover Strait) and summer (51.9° N), the seasonal transports are shown in Figure 7.5. The SPM transport per year through the Dover Strait amounts to 31.74×10^6 t (method 3); from which about 40% flows through the English and 60% through the French part of the Strait. The results are about 60% smaller when method 2 is applied (22.26×10^6 t/yr). Despite the big differences in the results, it can be seen that the SPM transport values are of the same order of magnitude as most of the recently published ones: $[22–30]\times10^6$ t/yr (Eisma & Irion, 1988), 17×10^6 t/yr (Van Alphen, 1990); 19.2×10^6 t/yr (Lafite et al., 1993) and $[21.6\pm2.1]\times10^6$ t/yr (Velegrakis et al., 1997).

The transport through the Dover Strait and the 51.9° N section have to be more or less in equilibrium, because no significant deposition areas of mud exist in the Southern Bight (Eisma, 1981). Important local sources of SPM are the rivers (Thames, Rhine-Meuse, Schelde), seafloor and coastal erosion and primary production. Accurate values however do not exist; the Thames supplies about 0.7×10^6 t/yr (Dyer & Moffat, 1998), the Rhine about 1.7×10^6 t/yr (Eisma, 1981) and erosion of the Holocene mud layers off the Belgian coast is estimated as $0\text{-}2.4\times10^6$ t/yr (Bastin, 1974) or about 3.0×10^6 t/yr (Fettweis & Van den Eynde, 2003). The total input of

SPM from these local sources is thus situated between 2.2×10^6 and 5.2×10^6 t/yr. The SPM input is probably higher because primary production, seafloor erosion outside the Belgian nearshore area and coastal erosion are not included. The difference between inflow and outflow is 38.31×10^6 t/yr for method 2 and 9.08×10^6 t/yr for method 3. The latter is closer to the sum of the local SPM sources, which indicates that method 3 is – with the available data - the most accurate one.

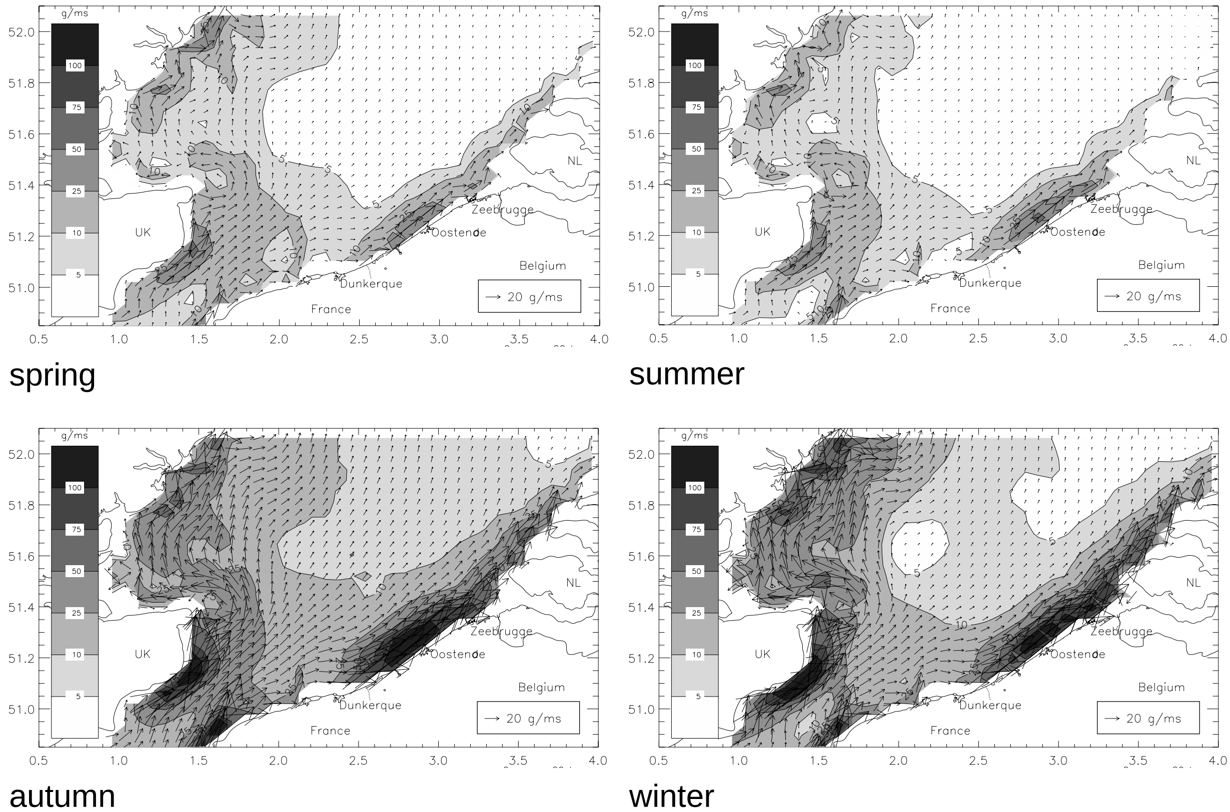


Figure 7.5: Seasonal averaged SPM transport per unit width (g/ms) in the southern North Sea, the x- and y-coordinates are in longitude (°E) and latitude (°N) respectively. The SPM transport has been calculated using method 3. The SPM concentration from the satellite pictures has been corrected vertically to obtain depth averaged values.

7.3.2 Qualitative approach based on microfossils

Since it is reasonable to expect that with the (clay) minerals also microfossils have been eroded from the source rocks Fontaine (2004) also examined on a limited scale the microfossil content of part of the samples used for clay mineralogical analyses. Even though these microfossils are more fragile than minerals, some survived and leave a trace of the origin of the sediment. Most microfossils in the sediment will however be of recent origin. Extensive descriptions, tables and graphic representations of the results were presented in Fettweis et al. (2005). The most important results are summarized below.

For the port of Zeebrugge, including the dumping sites, it can be stated that the majority of nannofossils are reworked from Cretaceous chalks. A few percentages of the nannofossils are derived from the 'Bassevelde 3' marine Tongrian and the 'Ruisbroek' sequences sensu Vandenberghe et al. (2003) and described from the Doel 2b well. This earliest Oligocene is located definitely to the east of the samples, while the Cretaceous chalks are located west (Dover Strait, English Channel). Dinoflagellates show associations from the Ruisbroek Sands, outcropping just to the east of the Bassevelde 3 sequence, and eventually even from the Boom Clay, younger than the S90 level. Also in the Oostende area mostly Cretaceous microfossils occur in the bottom sediments, pointing to currents coming from the west, but also some Earliest Oligocene specimens are present coming from the east. In the suspension samples Cretaceous forms derived from the west dominate but also eastern derived Earliest Oligocene specimens are present. This implies that in the eastern nearshore zone between the mouth of the Westerschelde and about Oostende, suspensions must be transferred both from the west (Cretaceous nannoplankton) and from the east (nannoplankton and dinoflagellates) and possibly also from the Schelde basin.

In the Flemish bank area (including the Nieuwpoort harbour) along the west coast, significant amounts of reworked Cretaceous nannofossils occur suspended in the sea water without almost any Paleogene forms. Also in the bottom samples, the majority of the nannofossils are Cretaceous. In one sample, a Lower Eocene dinoflagellate specimen was found, almost untransported seen its well preserved form. These observations are in agreement with the residual currents from the west, which are bringing in the Cretaceous microfossils. Possibly local erosion of the Lower Eocene Ieper Group Clay may occur, this has however still to be confirmed.

A suspension sample just north of the mouth of the Westerschelde shows half of the nannoplankton to be of Cretaceous origin and hence to be of a western origin and not derived from the Schelde estuary. Some specimens are of the Earliest Oligocene NP21 zone sediments and therefore either locally eroded - slightly to the west of the sample - or transported from the Schelde estuary. The latter is less likely as in that case also nannoplankton from other Eocene and Oligocene bio-zones would be expected to be mixed in the Schelde water.

In conclusion it can be said that on all sites Cretaceous nannoplankton is present, which has been transported into the area with the residual water transport. In addition material from the east, in particular from the Eocene-Oligocene transitional strata, has been found in the eastern nearshore area up to about Oostende. Remarkably the zone of east-derived material coincides with the extension of the Holocene mud (Figure 4.1) and could indicate an erosion of these sediments and/or a transport of clay minerals from the Schelde estuary. It should be mentioned here that it is not possible to use the quantitative microfossil results to estimate the proportion of mud coming from the west and the east. The reason is that the Cretaceous chalks predominantly consist of nannofossils, while the dinoflagellates (or nannofossils) from the Paleogene clay layers are much less abundant.

8 ANTHROPOGENIC IMPACT VS NATURAL DYNAMICS

The Belgian-Dutch nearshore zone is naturally a very dynamic area as can be seen e.g. from bathymetrical differences in nautical charts from 1866 on. The construction of the port of Zeebrugge in the 20th century and the dredging or deepening of navigation channels represent the most conspicuous anthropogenic impact in the Belgian nearshore zone. The construction of the port started at the end of the nineteenth century when the Belgian government decided to build a new outer port on a location where there was little more than a beach and a row of dunes. Van Mierlo (1897) predicted already a fast siltation of the port before the beginning of the construction. The first port was constructed between 1899 and 1903 and was modest in size; the embankment had a length of 1.7 km and a maximum distance from the coast of 1.1 km (Figure 2.1). The navigation channel 'Pas van het Zand' was dredged in 1903 through a recently and naturally formed sand bank (Van Mierlo, 1897); the channel had a length of 2.8 km, a width of 0.3 km and a depth of 9 m below MLLWS. Since then many adjustments were carried out in order to deepen the access channels and finally to extend the outer port (photos of the port of Zeebrugge can be found on: www.portofzeebrugge.be).

Significant expansion works were carried out between 1980 and 1985 with the construction of two longitudinal harbour moles with a length of 4 km and extension of about 3 km in sea. The outer port has a depth up to 16 m below MLLWS and its connection towards the open sea ('Pas van het Zand') of 14 m below MLLWS; they are significantly deeper than the nearshore area, which has a water depth of less than 10 m below MLLWS. The construction and extension of the port of Zeebrugge and its connections to the open sea, the dumping of dredged matter and the morphological evolutions induced by these operations have had and still have an influence on the fine grained sediment system. The comparison between the recent and the historic data (Figure 4.1) shows that the distribution of freshly deposited to very soft consolidated mud and of clay pebbles has changed. The possible explanations such as natural or human induced morphological changes, dredging and dumping, increased erosion of clayey sediments and changes in storminess are discussed below.

8.1 Deposition of fine grained sediments

The coastal turbidity maximum is responsible for the availability of fine grained sediments and thus also for the deposition of fresh mud. On most places in the nearshore zone the occurrence of fresh mud is limited to thin layers of maximum a few cm on top of the sediment bed (liquid layer or fluffy layer). The erosion resistance is small and they are resuspended during high currents. The occurrence of fluffy layers cannot be used as indication of variation in cohesive sediment distribution between the past (100 years ago) and today. Thick layers (±0.5 m) of freshly deposited to very soft consolidated mud (Figure 4.2c) however are a good indicator of changes. They occur today in environments which are or have been strongly influenced by human activities such as near dumping places (B&W-O in Figure 2.1), navigation channels, inside ports and harbours, and in the area around the port of Zeebrugge, see Figure 4.1. These mud layers can easily be distinguished from the older more consolidated cohesive sediments (Figure 4.2e) or the fluffy layers (Figure 4.2d). The fact that Gilson did not mentioned the occurrence of thick freshly deposited to very soft mud layers could indicate that they did not occur 100 years ago and that they are a result of human impact into the system. This reasoning is however unbalanced. First, the functioning of Gilson's ground sampler could lead to a washing out of the fresh mud. The sampler is able to penetrate the substratum to about 20 cm when it lies on its side, but its vertical height is limited to about 10 cm so that when hauled back, the heavy closing lid may have expelled a more or less large part of the soft to fluid matter; this has been reported once. Second, field description of the samples does often not encompass details on compaction of the sample. Occurrence of thick layers of freshly deposited to very soft consolidated mud have probably occurred in the eastern nearshore area where the sediments consist of mud and the depth soundings indicate "soft" and/or "sticky" bottoms.

From a combination of historic content (Figure 4.1 and the morphological changes between 1866 and 1911 (Figure 4.7) it can be seen that the surface layer consists of mainly mud in a narrow band along the coastline and corresponds most probably with the freshly deposited to very soft consolidated mud of § 4.1. No information is available on the thickness of these layers, but the fact that Gilson sampled the area on several occasions and that he found most of the time muddy sediments leads to the conclusions that the deposits were permanent during the considered interval and that they could resist the strong currents during spring-tide. Furthermore the metadata of several sampling occasions clearly mentions 'very soft' bottom in the area, possibly indicating freshly deposited mud on top; it is however not possible to give a thickness to these deposits, thus it could also indicate a fluffy layer of a few cm or more. Van Mierlo (1908) wrote that after the construction of the first port of Zeebrugge the water depth west of the harbour mole decreased by 2 m due to the deposition of cohesive sediments. The same author wrote that before the port construction, a layer of 60 cm of mud was deposited in the same area over a period of 10 years, corresponding thus with a accumulation rate of 6 cm/yr). If these sediments still exist today, then it is expected that they fit the class 'soft to medium consolidated' and correspond thus with modern mud. Although the recent sampling resolution is generally lower than Gilson's one, freshly deposited to very soft consolidated thick mud layers (>30 cm) in this narrow coastal band have only been found today near the old dumping place of Oostende (B&W-O). In some samples this mud is deposited on soft to medium consolidated mud (see box core OE14 in Figure 4.3), the latter corresponds possibly with the freshly deposited mud layers of the beginning of the 20th century. The deposition of these mud layers near B&W-O started after the 1950ties as was detected from the radiometric measurements of the OE11 box core (see § 4.1.1) and was only possible because the modification of the bathymetry created a hydrodynamic protected area. Van Lancker et al. (2004) have studied using different bathymetrical maps from 1955 up to 1997 the morphological evolution of the area around B&W-O. They conclude that the water depth decreased on the dumping place and that north and south of the dumping place two channels were formed. The decrease in water depth was initiated by the dumping activities and was followed by morphological changes.

Other areas today with important depositions of fresh mud are the navigation channels, the ports and harbours and – more interesting - the area situated a few km north of the port of Zeebrugge (see Figure 4.1), such as the recent mud found at ZB6. This deposition is probably related to the extension of port of Zeebrugge in the 1980ties, as was deduced from the radiometric measurements (§ 4.1.1). Accumulation of mainly sand east and west of the harbour moles continued after the extension in the 1980ties; and the bathymetry is today (2003) about 3 m higher (2-3 m MLLWS). The results of the numerical model simulations (see § 4.3) suggest that solely the deepening of the bathymetry and the extension of the outer port of Zeebrugge are responsible for a decrease in SPM concentration and an increase in mud deposition between the 1959 and the 2003 situation in the area around Zeebrugge. Keeping in mind the limitation of the model (resolution, 2D simulation) they also show that the extension of the port of Zeebrugge results in mud deposition near the port; a feature not occurring in the 1959 model.

The results suggest that in the beginning of the 20th century permanent deposition of cohesive sediments occurred mainly in a narrow band along the coast from about Nieuwpoort up to the mouth of the Westerschelde. These depositions were mainly the result of natural occurring morphological changes. Today, permanent fresh mud deposits are found in the same area only near the dumping place B&W-O and in the outer port of Zeebrugge and the navigation channel ‘Pas van het Zand’. Deposition of fresh mud seems to have shifted towards more offshore and occur today in the navigation channels ‘Scheur’ and ‘Pas van het Zand’ and in the area north of the port of Zeebrugge.

8.2 Increased erosion of Holocene or Tertiary mud?

Clay and mud pebbles of a few cm up to 10 cm in size and with different rounded shapes have been found regularly in sandy sediments 100 years ago and today. The roundness is an indication that these pebbles have been transported; the flattened shape may indicate that they originate from erosion of the layered Holocene mud. Figure 4.1 shows that they are more frequently recorded today, despite the lower sampling resolution.

The higher frequency today of clay and mud pebbles in the vicinity of the dumping places B&W-S1 and B&W-O is probably a result of the dumping of dredged sediments from mainly deepening dredging works. Tertiary clay and Holocene mud are, e.g. outcropping in the navigation channel towards the Westerschelde and in the 'Pas van het Zand' (Figure 4.1a).

On other places the occurrence of mud or clay pebbles may indicate erosion of old mud (Holocene or modern) or tertiary clay. Near MOW1 (Figure 2.1) Holocene mud is outcropping, where it is covered by a 0-10 cm thick ephemeral sand layer. Mud lenses have been observed in the sand indicating probably erosion of the underlying Holocene mud. Interesting in the OE11 core is the lower ^{210}Pb activity in the upper part (Figure 4.6). The observed profile could be explained by assuming a supply and deposition of mud with a low ^{210}Pb content. Possible sources are from the erosion of the Holocene mud and from capital dredging works, which may bring Holocene and Tertiary fine grained sediments in suspension. Similar observations from elsewhere have been reported by Ten Brinke et al. (1995) and Andersen et al. (2000). Variation in industrial ^{226}Ra discharges and the closing down of the BASF-Antwerpen discharges in 2002 could also give an explanation for the decreasing ^{210}Pb activity. Quantitative information on transport and diffusion of ^{226}Ra from the Schelde estuary towards the southern North Sea is however not known to confirm this explanation.

8.3 Dredging and dumping effects

The port of Zeebrugge and its connection to the open sea as well as the navigation channels towards the Westerschelde estuary are efficient sinks for cohesive sediments. Maintenance dredging and dumping amount today to about 12 millions tons of dry matter yearly (average over the period 1999-2004), from which more than 70% is silt and clay. 48% of the total quantity is dredged in the navigation channels towards the Westerschelde and the port of Zeebrugge, 45% in the port itself and 7% in the smaller harbours (Oostende, Blankenberge and Nieuwpoort). 52% of the dredged matter is dumped on dumping place B&W-S1, 33% on B&W-ZO and 5% on B&W-O. Comparison between the SPM transport entering and leaving the BCS and the quantities dredged and dumped at sea shows that an important part of the SPM is involved in the dredging/dumping cycle (Fettweis & Van den Eynde, 2003).

The deposition of mud in the dredging areas should be seen as a temporarily storage and it does not affect the global sediment balance on a scale of the BCS. In these areas the human impact is however massive and the deposition is the results of the engineering works, which have been carried out (deepening, port construction). The fact that high amounts of fine grained sediments are deposited and dredged shows that the nearshore zone has become more muddy since the beginning of the 20th century when dredging was significantly smaller.

The dumping of fine grained sediment increases temporarily the SPM concentration by 50-100 mg/l in a diameter of 20-40 km around dumping place B&W-S1 and increase the deposition of mud north of the dumping place (Van den Eynde & Fettweis, 2004). The seasonal averaged SPM concentration in this area as derived from satellite images and in situ measurements amounts to 25 mg/l ± 100% in summer up to 100 mg/l ± 70% in winter (see chapter 5). If the assumption that the SPM transport has not changed globally in the southern North Sea in the last 100 years is valid, then it can be concluded from these results and from the model results of § 4.4 that the turbidity maximum area has shifted in the last 100 years more off shore, because SPM concentration near the dredging areas has slightly decreased due to deposition, while around the dumping places it has increased.

8.4 Changes in storminess

The occurrence and frequency of storms are important for the distribution of cohesive sediments. Indications of changing storminess in the North Sea have been frequently reported, see e.g. Wasa Group (1998) and Weisse et al. (2005). The Wasa Group (1998) mentions that the storm- and wave climate in most of the North Sea has undergone variations on time scales of decades; these variations are related to variations in the North Atlantic Oscillation index. Interesting to note is that the intensity of the storm- and wave-climate in the 1990ties seems to compare with the intensity at the beginning of the 20th century (WASA Group, 1998; Dawson et al., 2002). Nevertheless the decadal variation in storminess no statistical significant long-term trends (>100 years) could have been found, see De Jong et al. (1999) for the German Bight and Verwaest (pers comm.) for the BCS. It is therefore concluded that variations in meteorological conditions cannot explain at least partly the differences in cohesive sediment distribution today and 100 years ago.

9 CONCLUSIONS

9.1 Sources of mud on the BCS

The different sources of fine grained sediments (SPM, freshly deposited to very soft consolidated mud) have been investigated. The results indicate that:

1. In approximately 20 % of the BCS, 6 % of the French and only 3% of the Dutch study area outcrops of Paleogene clays could possibly serve as a source for fine suspended sediments. The estimates of the erosion capacity of these sediments remain however purely indicative, because the erosion resistance under the present-day hydrodynamic regime is still unknown, the percentages are maximum values and probably only smaller areas will undergo erosion and because the clays are mainly situated outside the turbidity maximum area in a zone where the

SPM concentration is low (<5 mg/l), which indicates that erosion is probably very low.

2. The occurrence of Holocene muds represents 11% of the BCS and approximately 35% of the Rabsbank area. The critical erosion shear stress, which has been estimated based on bulk density measurements, indicates that erosion of these sediments under the given hydrodynamics regime could be possible.
3. Literature indicates that input of SPM from the erosion of Holocene mud and from the Schelde estuary is situated between 2.2×10^6 and 5.2×10^6 t/yr.
4. Vertically corrected SPM concentrations derived from satellite images, in situ measurements and hydrodynamic model results have been combined to calculate a long term SPM flux through the Dover Strait of 31.74×10^6 t/yr.
5. Microfossils analyses (on a limited scale) show that Cretaceous nannofossils are present in all examined bottom and suspension samples taken on the BCS. These nannofossils can only originate from the chalk cliffs bordering the Dover Strait. Microfossils from Eocene-Oligocene transition layers are only found between Oostende and the mouth of the Westerschelde. Such microfossils can only originate from the Schelde Estuary or layers outcropping on the seabottom near its mouth. These results indicate (at least) two sources of the muds on the BCS: a western source (Dover Strait) that has an influence over the entire BCS and an eastern source (Schelde Estuary) that has an influence until the vicinity of Oostende. It is not possible to draw quantitative conclusions about the mud sources using these microfossil results.

9.2 Clay minerals as tracer for mud sources on a local scale

Clay mineral analyses were done consecutively by two approaches.

1. In a first approach fast, but not very refined procedures were used. By comparing the results with those from the more detailed procedure used during the second approach, it was found that no clear conclusions can be drawn from these results.
2. The previous results were re-examined during the second approach and it was concluded that:
   - There is no systematic variation in the clay mineralogy between sediments of the east and the west of the BCS on the examined scale.
   - There is no systematic variation in the clay mineralogy between bottom and suspension samples.
   - There is no systematic variation in the clay mineralogy between samples from mud dominated and more sandy areas.
   - The used detailed procedures are suited to study the provenance of the cohesive sediments and by using them the study can be extended to analyse sediments from the possible source areas as well (Zeelmaekers, IWT PhD).

9.3 Anthropogenic impact and reference framework

The effects of engineering works or natural processes have been investigated by comparing the distribution of freshly deposited to very soft consolidated mud and clay pebbles 100 years ago and today. The historic data of Gilson have been used to describe the cohesive sediment distribution as it occurred in the beginning of the 20th century in the Belgian nearshore area. The quality of these samples is very high regarding the available metadata and the data have proven to be a major reference to understand the evolution of the local cohesive sediment distributions. The processing of the historic and recent data was mainly based on field descriptions of the samples (consolidation, thickness) and on morphological evolution; emphasis was put on the occurrence of thick layers (>30cm) of freshly deposited to very soft consolidated mud and on the distribution of clay and mud pebbles. The major conclusions are:

1. Thick layers of fresh mud were deposited in the beginning of the 20th century mainly in a narrow band along the coast from about Nieuwpoort up to the mouth of the Westerschelde. These depositions were mainly the result of natural morphological changes. Today, deposition of permanent layers of fresh mud is concentrated around the old dumping site of Oostende, in the outer port of Zeebrugge, in the navigation channels ‘Scheur’ and ‘Pas van het Zand’ and in the area north to northeast of the port of Zeebrugge. Comparing the actual situation with the situation 100 years ago it seems that around Zeebrugge the area where fresh mud is deposited extends more offshore.
2. Most of the actual depositions of thick layers of fresh mud (>30 cm) have been induced by anthropogenic operations, such as dumping of dredged material, deepening of the navigation channels and construction and extension of the port of Zeebrugge.
3. If the assumption that the SPM transport has not changed globally in the southern North Sea in the last 100 years is valid, then it can be concluded that the centre of the turbidity maximum area has shifted in the last 100 years offshore. This is explained by the slight decrease in SPM concentration near the dredging areas due to high siltation rates and the increase in SPM concentration on dumping places situated more offshore (such as B&W-S1).
4. The higher frequency of clay and mud pebbles today compared with 100 years ago is mainly related to deepening dredging works. However, radiometric measurements also indicate a possible erosion of Holocene mud.
5. The historical and recent datasets show both that the Belgian coastal waters east of Oostende are naturally subject to high siltation rates, resulting in the deposition of fresh to very soft consolidated mud layers of more than 30 cm, but also in the deposition of tidal driven ephemeral fluffy layers of a few cm. The effects of variation in SPM concentration and cohesive sediment distribution through time on the habitat of benthic invertebrates are therefore probably minor and not a key to ex-

plain temporal changes in the composition of the benthic communities since the early 20th century.

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