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QUANTIFICATION OF EROSION/SEDIMENTATION TO TRACE NATURALLY - FROM ANTHROPOGENICALLY-INDUCED SEDIMENT DYNAMICS

"QUEST4D"

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North Sea

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QUANTIFICATION OF EROSION/SEDIMENTATION TO TRACE NATURALLY- FROM ANTHROPOGENICALLY-INDUCED SEDIMENT DYNAMICS
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ACRONYMS, ABBREVIATIONS AND UNITS

ADCP, ADP:	Acoustic Doppler Current Profiler
ADV:	Acoustic Doppler Velocimeter
BCS:	Belgian Continental Shelf
BPNS:	Belgian part of the North Sea
CTD:	Conductivity, Temperature and Pressure Sensor
DTM:	Digital terrain model
GIS:	Geographic information system
HCMS	High Concentrated Mud Suspension
LISST:	Laser In-Situ Scattering and Transmissometer
mab:	Meter above bed
MLLWS	Mean Lowest Low Water at Spring tide
OBS	Optical Backscatter Sensor
PSD	Particle Size Distribution
SPM:	Suspended particulate matter

SUMMARY

Context

Seabed, living and non-living resources are exploited increasingly: sand and gravel is needed for beach nourishment and for construction purposes, the accessibility of harbours requires regular dredging and disposal operations, offshore windmills contribute to our future energy supply and pipelines and cables transport gas and electricity to the mainland. The interaction of these activities with seabed and water column nature and processes needs careful consideration. However, present-day impact studies remain often inconclusive because of: the lack of a 'non-disturbed' reference situation, the interference of both naturally and anthropogenically-induced changes and the role of climate change on seabed processes. Moreover, the range of human activities may result in cumulative effects affecting the magnitude and extent of the impact on the seabed. A more sustainable ecosystem-based approach to management is needed, based on an overall marine environmental status and its possible degradation. Setting-up environmental targets and well-balanced monitoring programs have become timely. These will help in ensuring a sustainable use of our marine environment.

Objectives

The Belgian part of the North Sea (BPNS) has been targeted to investigate the marine ecosystem over the past 100 years. Main objectives include: (1) Increase in knowledge on natural variability of sediment processes; (2) Establish historic baselines, to set environmental targets; (3) Quantification of ecosystem changes, on the medium- to long-term; (4) Demonstration of human impact, with case studies relating seabed and water column changes to both naturally- and anthropogenically-induced sediment dynamics; (5) Assessing climate change scenarios and their effect on seabed processes; and (6) Recommendations of more sustainable exploitation strategies of non-living seabed resources.

Conclusions

The BPNS is a typical sandbank-swale environment, though the coastal zone comprises of large mud fields, associated with a turbidity maximum. The complexity of processes involved is high and required both small- and large-scale investigations. A combined suite of tools was used, comprising *in situ* measurements, seabed mapping and modelling.

Natural variability of sediment processes

Data from quasi-continuous multi-sensor tripod measurements increased significantly our knowledge on the nature and dynamics of suspended particulate matter (SPM).

Time series of SPM concentration, current velocity (and turbulence) and *in situ* particle sizes were analysed. Variations in the particle size distributions are primarily caused by flocculation and break-up processes, due to tidal forcing. The long-term data showed also the influence of hydro-meteorological conditions and of storms on the size and composition of SPM; new insights were obtained in the nature and behaviour of mixed sediments. These, in combination with the effects of waves on the failure of consolidated mud beds and the erosion effects of sand on top of consolidated mud are main drivers of sediment transport in the coastal zone. Significant increases in SPM have been correlated with the formation of high concentrated mud suspensions (HCMS) during or after a storm, hitherto never investigated. Under these conditions, about 3 times more mass of SPM was observed in the water column, as compared to calm weather conditions. The disposal grounds of dredged material, navigation channels and adjacent areas, with freshly deposited mud, have been found to be the major source of fine-grained sediments during storms. This result is important, as it suggests that dredging and the associated disposal of sediments have made available fine-grained matter that contributes significantly to the formation of those HCMS. The effect of hydro-meteorological forcing on SPM (tidally- and

wind-induced flows), has been studied through data classification according to variations in sub-tidal alongshore currents, with the direction of sub-tidal flow depending on wind direction. This influences the position of the turbidity maximum; as such also the origin of SPM. For a very near shore location, winds blowing from the NE increased SPM concentration, whilst SW winds induced a decrease. The latter is related to advection of less turbid English Channel water, inducing a shift of the turbidity maximum towards the NE and the Westerschelde estuary. Under these conditions, marine mud will be imported and buffered in the estuary. Under persistent NE winds, HCMS were formed and remained present during several tidal cycles. Data show that SPM consists of a mixture of flocs and locally eroded sand grains during high currents.

Detailed 3D substrate characterisation was performed using very high resolution acoustic seabed mapping, in combination with sediment and macrobenthos sampling. The main disposal ground of dredged material and its possible influence area, up to 12 km to the Belgian-Dutch border, was targeted. Present disposal activities take place in the trough of a sandbank, displaying a flood-dominated morphology. Where this trough ends and shallows, dense aggregations of the tubeworm and bio-engineer *Owenia fusiformis* were observed, as also high abundances of other macrobenthos species (e.g., the invasive species *Ensis directus*). Causal relationships are being established between the disposal activities and benthic habitats. Large bed forms are present, both near the disposal ground and near the areas with high biodiversity occur. A bed load convergence is identified with a dominant NE transport in the flood-dominated trough, but consistent ebb-dominant transport just north of it, as also near the disposal ground. This has important implications for the management of the disposal activities; disposed sands are transported in a SW direction, back towards the navigation channels. From repetitive multibeam echo sounding recordings in the area, in combination with current and turbidity data along transects, natural variability is being assessed and evaluated against anthropogenically-steered dynamics.

For impact predictions and more integral assessments, modelling remains challenging. Improved bed models have been incorporated to account for erosion of old sediments (Holocene and outcropping Tertiary clays) distinguishing between active layers and a more passive buffer layer. It has been shown that flocculation models, based on an empirical approach, are not able to satisfactorily reproduce measurement data and more physical based models (simple models and bimodal size class based models) have been implemented and evaluated. A break through progress has been made in the development of a low-Reynolds turbulence model, needed for the simulation of the highly concentrated near bottom sediment transport. Present-day sediment transport models are, yet, not able to simulate the likely formation of fluid mud layers. The influence of the Westerschelde estuary on sediment- and morphodynamics of the BPNS and vice versa has been addressed and identified through satellite and in situ data. Finally, wave induced turbulence and wave energy dissipation, and their importance in the turbulence part of hydrodynamic models are being modelled. The coupled wave-current model has been implemented and tested on High Performance Computer facilities. The coupled system has been successfully applied to obtain long-term modelling results on hydrodynamic forcing and sediment transport (1999-2010) and for the assessment of possible impacts of large scale sand extraction on waves in the coastal zone.

Establishing historical baselines, in view of setting environmental targets

A sediment and macrobenthos dataset of the period 1899-1910 (G. Gilson collection) has been reconstructed, in view of establishing a historical baseline. The dataset is unique for the period, due to its consistent and dense sampling approach. After calibration of the data, the spatial distribution of sediment types could be mapped. Background information is provided for the former distribution of 'mud fields', fine and coarse sands, high shell debris contents and gravel grounds. The historical distribution of macrobenthos richness and abundance was reconstructed using data acquired on bivalves, polychaetes and amphipods; the baseline maps for macrobenthic diversity extend across the Belgian-Dutch border.

Quantification of ecosystem changes during the last century

Long- to medium-term morphological trend analyses allowed defining areas with significant erosion or deposition. Those areas with a clear and strong trend could be associated with human intervention (e.g., large-scale infrastructure works, dredging of navigation channels and disposal of dredged material). However, some of the observed long-term changes are most likely caused by natural processes. This is most prominent on the Coastal Banks, with erosion along their gentle side and sedimentation along their steep side (i.e. landward migration). Also, the troughs of those sandbanks tend to be erosive on the long-term. The medium-term morphological analysis revealed a clear erosion trend of the foot of the shoreface, consistently appearing along almost the whole Belgian coast, and only absent on locations where the erosion-sedimentation pattern is dominated by distinct local features (e.g. breakwaters, tidal gullies). From the medium-term morphological trend analysis of beach and shoreface west of Zeebrugge harbour, the magnitude of the littoral drift was estimated. A net transport of 395.000 m^3/year in a NE direction is inferred.

Long-term changes in the distribution and dynamics of cohesive sediments indicate that nowadays, very high levels of poorly consolidated mud occur in and around areas, altered by human activities (navigation channels, disposal sites). However, decreased mud content is observed where, historically, coastal mud fields were present. This may be due to increased erosion of older Holocene mud; as a consequence, higher amounts of fine-grained sediments are being released into the southern North Sea today. This may well be reinforced by long-term beam trawling. Analyses along sandbanks reveal very high fishing intensities along the slopes and locally, fully fragmented seafloors have been observed.

Long-term change analyses of distributions and relative abundances of 12 common bivalve species were performed for the periods 1899-1908 and 1994-2008. The observed expansion of some species, tolerant to higher mud contents (*Abra alba*, *Tellina fabula*, *Macoma balthica*, *Venerupis senegalensis*) is significant and contrasts with the regression of some clean sand species (significant for *Donax vittatus*). These findings agree well with the suggestion of a human-induced increase of turbidity, which likely result in transient deposition of higher amounts of fluffy layers and very soft consolidated mud. Results also point at a higher amount of species contributing more evenly to bivalve species richness, as compared to the historical situation. This points at a probable effect of eutrophication of the area, during the second half of the 20th century. No significant statistical correlation could be found between NAO cyclicity and the discharge of the river Scheldt. Still, correlations were found between NAO and the concentration and distribution of suspended particulate matter.

Medium-term impact of disposal of dredged material on substrate characteristics was studied along the main disposal ground of dredged material. Based on vibrocores analyses, a clear difference was observed in sedimentation patterns between the old and present disposal site of dredged material, respectively on a sand shoal and in a trough. On the sand shoal, sand remained on the bottom and fines were actively washed out; in the trough, vibrocores show that both sand and mud remain *in situ* and accumulation rates are much higher. This shows the importance of morphological setting for the final estimation of environmental impact; however, also the type of disposed material determines seabed recovery rates, after cessation of activities.

Short-term impact of continuous disposal of fine-grained sediments on SPM concentration was investigated during a dredging experiment. Before, during and after the experiment monitoring of SPM concentration was carried out at a location 5 km west of the disposal site. Analyses revealed that the SPM concentration near the bed was on average more than 2 times higher during the dredging experiment. The disposed material was mainly transported in the benthic layer and resulted in a long-term increase of SPM concentration and formation of fluid mud layers. As the heterogeneity and complexity of the SPM concentrations are high naturally, statistical methods have been used to characterize temporal SPM concentration variation in a way that it can be used as indicator for changes, induced by human activities.

***Exogenic forces:* Climate Change**

Analyses have shown that high sea surges along the Belgian coast occur when a low pressure system remains stationary over the Baltic Sea and is associated with a reinforced Azores high. This sea-level pressure (SLP) pattern shows a strong SW-NE pressure gradient leading to onshore winds along the Belgian coast. Wintertime highest sea surges (99th percentile) at Ostend have increased at a rate of + 1 mm/yr from 1925 to 2000. This increase is associated with a SLP rise over the Azores, leading to an increase of the frequency of strong surge-related pressure gradients. High surges are expected to stay stationary during the 21st century, associated with no significant changes in SLP conditions over the Baltic Sea and over the Azores. It is not expected that climate change for the 21st century will significantly modify the highest surges or highest waves. Nevertheless, the mean sea-level rise, associated thermal dilatation and ice melting, will ineluctably increase the peak sea level during storm events.

Towards sustainable management of human activities

Results evidence the importance of SPM as a driver in the ecology of the Belgian coastal waters, but its effect remains largely elusive due to its variability. Hence, the recommendation arises to monitor SPM as an indicator of environmental changes. This can be established provided sufficiently long time-series and spatially distributed data are available, representative of the natural variability. Due to the climate-induced temporal and spatial variability of SPM concentration in such high turbidity coastal areas an increased sampling effort is necessary, as compared to offshore systems with low SPM concentration. Such large data sets can originate from *in situ* (e.g., tidal cycle, tripod measurements) and remote sensing (MODIS) samplings. Their combination can be used to statistically assess heterogeneity by comparing SPM concentration frequency distributions (e.g., due to meteorological forcing or human activities). Further implementation of coastal and seafloor observatories would facilitate continuous measurements more efficiently. SPM was evaluated as driver of habitat and benthos changes. Within mostly medium-grained sediments, intermediate levels of SPM (average 4 mg/l) were correlated with higher species richness and macrobenthic densities, though no thresholds of change could be established. Seabed erosion/deposition rates were evaluated as possible indicator to discriminate natural from anthropogenically-induced change, though without success. Though, in the coastal zone, areas with sedimentation are due to human activities.

More sustainable practices of human activities

Continuing efforts are being made to advice on *reducing the recirculation of disposed fine-grained matter* towards the dredging areas. Natural dynamics around the sites should be taken into account and the choice of the disposal ground can vary according to the ruling hydro-meteorological conditions. This was demonstrated with numerical results. Operational models which predict the advection and diffusion of the disposed material could make the dredging more efficient. Also, consideration of bed load transport is important. On the medium- to long term, sediment accumulates significantly, but is also transported away from the sites. The importance of this process on neighbouring habitats, as also on other functions of the seabed, should be considered when selecting new locations.

Related *to aggregate extraction*, modelling results are presented of the impact of large-scale extraction at an offshore site (at more than 35km) on the safety level of the Belgian coast. Under storm conditions, model results show a logical increase in wave height in the aggregate extraction area, consequently leading to a significant increase in wave dissipation processes when waves propagate further towards the coastal zone. Along the beaches, there is no (model) indication of an increase in wave energy dissipation. It is tempting to conclude that safety levels at the coast will therefore not be affected by large-scale aggregate extraction; however, it is clear that there will be an indirect effect, due to possible morphological changes towards the coastal zone, induced by changes in wave energy dissipation. Those changes will in turn invoke changes in areas closer to the beaches. Such morphological changes are slow and it is still not possible to predict them reliably at this moment.

Scientific support to a sustainable development policy

In an era of increasing needs from marine living and non-living resources, a more sustainable development should focus, also, on finding ways to optimize present-day practices of human activities. On the one hand, increasing awareness is needed on how humans affect sediment processes (both water column and seabed) and their implications to marine life; on the other hand, synergies with industry are needed to come to more sustainable practices. With increasing sea-level, coastal safety will demand huge quantities of sand. Research has shown that resources are not renewed, and will become depleted on the long-term. This project has demonstrated long-term and far field effects from past human activities, also on the benthos. Changes in sedimentation and/or SPM concentration can be predicted, though uncertainty margins will be high on the long-term (50-100 yrs). Careful consideration when intensifying human activities is hence needed.

Meanwhile, we anticipate by providing a scientific knowledge base, together with modelling tools, and indicators on how sediment processes may affect ecosystem functioning. More integrative monitoring and long-term data series, preferably along ecological continua, are indeed prerequisite, even more so now that seas and oceans are considered one of the grand challenges of the 21st century (Ostend Declaration, EurOCEAN 2010).

Keywords
Natural variability; Human fingerprint; Suspended Particulate matter (SPM); Historic data; Long-term morphological evolution; Seabed erosion and sedimentation; Climate forcing; Ecosystem changes; Eutrophication; European Marine Strategy Framework Directive; Seafloor Integrity; Environmental targets

1. INTRODUCTION

1.1 Context

Seabed, living and non-living resources are exploited increasingly: sand and gravel is needed for beach nourishment and for construction purposes, the accessibility of harbours requires regular dredging and disposal operations, offshore windmills contribute to our future energy supply and pipelines and cables transport gas and electricity to the mainland. The interaction of these activities with the seabed nature and processes needs careful consideration. However, present-day impact studies remain often inconclusive because of: the lack of a 'non-disturbed' reference situation, the interference of both naturally and anthropogenically induced changes and, the hitherto unknown, role of climate change on seabed processes. Moreover, the range of human activities may result in cumulative effects affecting the magnitude and extent of the impact on the seabed. A sustainable management, based on an overall marine environmental status and its possible degradation, is therefore needed. Setting-up environmental targets and well-balanced monitoring programs have become timely. These will help in protecting and preserving the marine environment and safeguard our seas for future generations.

1.2 Objectives

Quest4D targets the Belgian part of the North Sea (BPNS) to investigate the seabed ecosystem over the past 100 years. Main objectives include: (1) Increase in knowledge on natural variability of seabed nature and processes; (2) Establish historic baselines, as reference situations for impact studies; (3) Quantification of ecosystem changes, on the medium- to long-term; (4) Demonstration of human impact, with case studies relating seabed changes to both naturally and anthropogenically induced sediment dynamics; (5) Assessing climate change scenarios and their effect on seabed management; and (6) Development of more sustainable exploitation strategies of non-living seabed resources.

1.3 The Belgian part of the North Sea – a complex environmental setting, heavily occupied by human activities and facing climate change

The Belgian part of the North Sea (BPNS) (3600 km²) is a siliciclastic macro-tidal environment comprising several groups of sandbanks. The sandbanks represent a thin and patchy Holocene cover, which overlies Tertiary clayey sediments that outcrop locally in troughs. The tidal regime is semi-diurnal, with tidal ranges that diminish towards the northeast. The mean tidal range at Zeebrugge is 4.3 m and 2.8 m at spring and neap tide, respectively. Sediment transport is mainly driven by tidal currents (max 1.2 m/s), though wind-induced currents and waves may have a direct effect on sediment resuspension and bedform morphology. Winds blow dominantly from the southwest and the highest waves occur during north-western winds.

Human activities take place mainly in the shallow coastal zone (0-20 m MLLWS) with beam trawling, harbour infrastructure works, navigation channels, coastal defence, and dredging and disposal of dredged material ($\sim 10 \times 10^6$ tonnes dry matter/yr) being the main drivers of potential changes. Marine aggregate extraction ($\sim 2 \times 10^6$ m³/yr, at present) and windmill farm construction takes place further offshore. Alterations of the cohesive and non-cohesive sediment distribution are to be expected, because infrastructure works, together with dredging and disposal of sediments, often result in hydrodynamic conditions which are not in equilibrium with the present-day bathymetry.

Surficial sediments in the coastal zone are characterised by the occurrence of cohesive and non-cohesive sediments; fine sands with variable mud content dominate. The cohesive sediments occur mainly in the eastern nearshore part and are characterised by a particular rheological and/or consolidation state. Four different types are distinguished, namely Eocene clay, Holocene mud (+/- 3000 yr BP), modern mud (<100 yr BP) and freshly deposited mud (Fettweis *et al.* 2009). Generally, the freshly deposited mud occurs as thin fluffy layers, or locally as gradually soft consolidated thicker packages (±0.2-1 m). The mud:sand ratio influences the transition between cohesive and non-cohesive behaviour and has a major influence on erosion, suspended particulate matter (SPM) concentration, SPM composition and benthic ecological properties (Williamson and Torfs 1996; Panagiotopulos *et al.* 1997; Flemming and Delafontaine 2000; van Ledden *et al.* 2004; Waeles *et al.* 2007). Natural SPM comprises many different substances with time and site specific concentrations. In mixed sediment areas, SPM reflects the bed composition and may consist of a mixture of cohesive and non-cohesive mineral particles (Manning *et al.* 2010). Close to a sandy seabed, SPM is likely to contain also resuspended mineral grains, whereas higher in the water column or in muddy environments SPM occurs typically in the form of flocs, composed of aggregates of mainly clay minerals, organic matter and water. Mud and sand can be deposited as alternating layers when mud and sand settle, separately, from independent suspension or simultaneously. The latter implies segregation due to settling of sand grains through the non-consolidated mud layer (Van Ledden *et al.* 2004). Flocs vary in size on short-time scales (ebb-flood), as they are formed by collisions of smaller primary particles with cohesive properties in low-turbulence regimes, and are ruptured by shear in high-turbulence regimes (van Leeussen 1994; Winterwerp 1998). With increasing turbulent shear, floc sizes decrease and the probability of resuspension of gradually larger mineral increases. SPM is therefore likely to have a multi-modal particle size distribution (Mikkelsen *et al.* 2007; Mietta *et al.* 2010; Verney *et al.* 2010; Lee *et al.* 2011); this reflects the fast temporal changes in floc sizes due variation in turbulent shear, as well as the overlapping distributions of flocs and mineral grains in mixed sediment environments and strongly varying shear stresses.

It is clear that complexity of processes (temporally and spatially) in the shallow coastal zone is high. To enable distinguishing natural from anthropogenically-induced changes, both small- and large-scale investigations were needed.

Meanwhile, there is a change in attitude towards coastal protection and coastal management, generally due to the growing risk and uncertainty generated by climate change. In line with this, there is also growing awareness of environmental and socio-economic implications of coastal activities, in general, and coastal defence, in particular. Applied to the Dutch coast, Horstmann *et al.* (2009) favour large-scale solutions for long-term coastal management strategies and give arguments for soft engineering measures. These are nature-based and have a flexibility allowing design adaptation as insights increase. Horstmann *et al.* (2009) also emphasize the importance of continued investigation into future hydraulic conditions, due to climate change. Although uncertainty will remain, ranges need to be reduced. However, the manner in which the system would react to large engineering works is not known and few data exist on past changes.

To ensure more cost-effective operations at sea, to better gauge the human footprint, and to develop environmental policies aiming at a more sustainable ecosystem-based approach to management, dedicated research was needed.

2. METHODOLOGY

2.1 Introduction

Research strategies consisted of state-of-the-art observations/sampling (RV Belgica), experiments and advanced modelling, within the space, depth and time domain (4D). A multi-sensor tripod, a.o. measuring turbidity, currents and in-situ particle size is deployed on a quasi-permanent time-scale. Parameters are measured in function of model improvement, and observations are made on seabed nature and dynamics, often in a multidisciplinary context. Signifcant efforts were made on the reconstruction of a historical baseline and to analyse ecosystem changes on the medium- to long-term. A worldwide unique dataset of 1900 was at our disposal.

Modelling developments, although significant, are provided in the methodology section only. Their application is integrated in the Result section.

2.2 Natural variability of sediment processes

2.2.1 Sediments and sediment transport

a. Cohesive, non-cohesive and mixed sediments on the BPNS

Existing and newly collected bed samples have been used to reconstruct the cohesive and non-cohesive behaviour of the sediments in the nearshore zone. Further, multi-sensor tripod data (§2.2.1b) have been analyzed for mixed sediments in suspension. The aims are to: (1) Estimate the erosion characteristics of cohesive and mixed bed sediments, see §3.2.2 and Fettweis *et al.* (2010a) and former Q4D reports (Van Lancker *et al.* 2009). (2) Collect grain size characteristics and erosion characteristics of bed sediments in order to develop a bed-module for the sediment transport model, see §2.2.2 and former Q4D reports (Van Lancker *et al.* 2009). (3) Examine the influence of tides, wind and waves on the particle size distribution of SPM, composed by flocs and granular particles, see §3.2.1.

Erodibility measurements

Erosion characteristics have been determined from erodibility measurements on mud samples taken at different locations in the nearshore area. Boxcores were subsampled using cylindrical perspex tubes allowing retrieving relatively undisturbed mud samples of the first 40 cm of the sea bed. Using a gamma-ray densitometer, bulk density profiles of these samples were determined in a non-destructive way. The measurements were performed at the University of Stuttgart using the SETEG-flume (Kern *et al.* 1999; Witt and Westrich 2003). The top of the perspex tubes can be attached to a circular hole in the bottom of the flume, and by pushing the sediment upwards until its surface, its level with the bottom surface of the flume the erosion behaviour of the top layer of the sediment can be investigated. After erosion of the top layer, the sediment can be pushed further upwards and the underlying layers can be studied. The critical shear stress for erosion is determined by visual observation of the onset of erosion by a gradual increase of the discharge. Shear stresses are calculated from the measured discharge via the Darcy-Weisbach equation, using the Colebrook formula to determine the roughness coefficient (Streeter 1996). In addition, the flume is equipped with the so-called SEDCIA-system, enabling to measure the erosion rate. This system consists of a camera which observes the time-dependent shift of a series of parallel laser lines projected under a certain inclination angle on the sediment's surface, from which the sediment's volume change –and hence also the mass change, since the bulk density is known– can be calculated in function of time.

Hydro-meteo influence on particle size distributions (PSD) in a mixed sediment environment

PSD provide essential information on floc and particle dynamics as emphasized by Mikkelsen *et al.* (2006). With this scope in mind, in situ measurements of SPM concentration, PSD, as also of currents have been carried out in the Belgian coastal waters, using optical (OBS, LISST 100) and acoustical sensors (ADP, ADV). Statistical methods (entropy analysis, fitting of PSD with sum of log-normal functions) were applied and low-pass filter averaging to classify the PSDs and to establish the link between PSD and the underlying processes. Similar measuring approaches (e.g. Thorne and Hanes 2002; Fugate and Friedrichs 2002; Voulgaris and Meyers 2004; Hoitink and Hoekstra 2005), statistical methods (Jonasz and Fournier 1996; Mikkelsen *et al.* 2007) and averaging (Baeye *et al.* 2011 and §2.2.1b) have been successfully adopted in various marine environments.

Two methods for classification of the particle size spectra have been applied. The first one uses the flow data to separate the LISST records in different groups corresponding to different hydrodynamic forcing, see §2.2.1b. The second method for classification is entropy analysis; it is a method from information theory to evaluate the randomness of an event (such as a particle size distribution) and to assign the event to a group with similar characteristics or to place it in a new group. Applied to PSD entropy analysis allows grouping the size spectra without assumptions about the shape of the spectra and is therefore suited for analysis of uni-modal, bi-modal, as well as multi-modal distributions (Woolfe *et al.* 1998). Entropy analysis has been successfully applied to grain size distributions from sedimentary deposits (Forrest and Clarke 1989; Woolfe *et al.* 1998; Orpin and Kostylev 2006) and to LISST particle size distributions of suspended matter (Mikkelsen *et al.* 2007). Our analysis was carried out with the FORTRAN routine of Johnston and Semple (1983), extended with a module to calculate the optimal number of groups using Calinski-Harabasz pseudo F-statistic (Orpin and Kostylev 2006). The results are presented as an averaged and normalized PSD for every group.

b. SPM dynamics

A turbidity maximum characterises the Belgian nearshore zone between Nieuwpoort and the mouth of the Westerschelde. SPM concentration varies between minimum 20-70 mg l^{-1} and maximum 100- >1000 mg l^{-1} during calm meteorological conditions at 2 m above the sea bed; lower values (<10 mg l^{-1}) occur in the offshore area (Fettweis *et al.*, 2007a). SPM dynamics have been studied using in situ measurements obtained with a tripod and from a vessel, and remote sensing measurements from the MODIS satellite.

Research set-up and aims of measurements

1. Assessing the hydrodynamics, sediment dynamics and bed erosion processes during extreme meteorological events, in order to better understand the variability of SPM concentration and its relation to erosion, resuspension and transport of sediments, see §3.2.2; and Fettweis et al. (2010a).
2. Identification of the effects of forcings (tidal and wind-induced flows) on suspended sediment transport, see §3.2.1, §3.2.4; and Baeye *et al.* (2011).
3. Presentation of the impact of continuous disposal of fine-grained sediments on the SPM concentration and on fluid mud dynamics, see §3.3.4c; and Fettweis *et al.* (2010b).
4. Identification of the temporal SPM heterogeneity in the Belgian nearshore; determination of their statistical characterisation; examination of how they describe the nature of coastal systems; and evaluation of SPM as indicator for ecosystem changes, see §2.4.2, §3.4.1a; and Fettweis and Nechad (2010).

Instrumentation

The tripod was developed for collecting time-series (up to 50 days) of SPM concentration, particle size distribution, salinity, temperature, pressure and current velocity at fixed locations. The instrumentation suite consisted of a 5 MHz SonTek Acoustic Doppler Velocimeter (ADV Ocean-Hydra), a 3 MHz SonTek Acoustic Doppler Profiler (ADP), two D&A optical backscatter point sensors (OBS), a Sea-bird SBE37 CT and a Sequoia Scientific Laser In-Situ Scattering & Transmissometer 100-X (LISST-100X, Type-C). All data (except LISST) were stored in two SonTek Hydra data logging systems. The OBS's were mounted at 0.2 and 2 meters above the bed (hereafter referred to as mab). The ADV velocities were measured at 0.2 mab, while the ADP profiler was attached at 2.3 mab and down-looking, measuring current and acoustic intensity profiles with a bin resolution of 0.25 m. Mean values were obtained once every 10 min for the

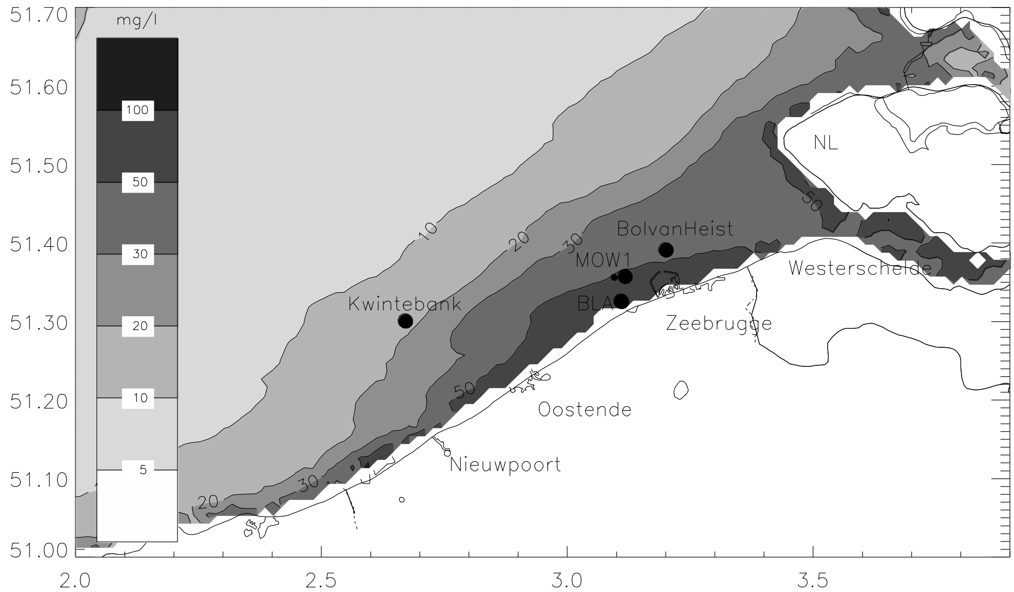


Figure 2.2-1: Map of the Belgian part of the North Sea with the in-situ measurement stations Blankenberge (BLA), MOW1 and Kwintebank and the wave measurement station Bol van Heist. The background consists of the yearly averaged surface SPM concentration (mg/l) from MODIS images (2003-2008). Coordinates are in latitude (°N) and longitude (°E).

OBS, LISST, and ADV, while the ADP was set to record a profile every 1 min; later on averaging was performed to a 10 min interval to match the sampling interval of the other sensors. The tripod was deployed at three locations during the period 2004-2009. A total of 240 days of data have been collected at Blankenberge, 138 days at MOW1 and 9 days at the Kwintebank (Figure 2.2-1). The long deployments have ensured accurate sampling of conditions that include complete periods of neap and spring tides, as well as the occurrence of a variety of meteorological events.

During the period 2001-2008, 16 tidal cycle measurements have been carried out at MOW1 and 8 on the Kwintebank (Figure 2.2-1). During the measurements, the ship remained anchored during one tidal cycle. The Sea-Bird SBE09 SCTD carousel sampling system, containing 12 10 l Niskin bottles and an OBS was kept at about 3 m above bottom (mab). Every 20 minutes a Niskin bottle was closed and every hour the carousel was taken on board of the vessel. Per retrieval of the carousel a vertical profile was measured. About 13 profiles per tidal cycle have thus been collected. In total 198 vertical profiles are available at MOW1 and 103 on the Kwintebank. The measured vertical profiles collected from the vessel during a tidal cycle cover the water column from 3 mab towards the surface. Therefore a linear regression (minimizing absolute deviation) between water depth and the logarithm of the SPM concentration, averaged over depths cells of 0.5 m, was calculated to construct the missing lower part of the profiles. The fitted profiles have been used to calculate ratios between SPM concentration at the surface and at different depths in order to extrapolate surface SPM concentration, measured by the satellite towards deeper water layers and/or near bed SPM concentration, measured by the tripod towards the surface (Fettweis and Nechad 2010).

MODIS data of level 1A (L1A), covering the period 2003-2008, have been downloaded from the NASA GSFC web site http://oceancolor.gsfc.nasa.gov. The L1A data contain the radiance at the top of the atmosphere, which were geometrically corrected using the SeaDAS software (available from the same NASA web site). The turbid waters atmospheric correction (Ruddick *et al.* 2000) implemented in SeaDAS was then applied to obtain the marine (water-leaving) reflectance. SPM concentrations were derived from water-leaving reflectance following an algorithm calibrated for turbid waters (Nechad *et al.* 2010). For Belgian waters about 60 (partially) cloud free images per year are available from each sensor, resulting in total in 460 samples at MOW1 and 502 at the Kwintebank location. 64% of satellite images are during spring and summer and only 36% during autumn and winter. The latter two seasons are characterised by higher SPM concentrations.

SPM concentration from acoustic and optical sensors

The backscattered signal from OBS and ADP were used to estimate SPM concentration. The voltage of the OBS was converted to SPM concentration by calibration against filtered water samples during several field campaigns (Fettweis and Nechad 2010). A linear regression between all OBS signals and SPM concentrations from filtration was assumed. The backscattered acoustic signal strength from ADP was, after conversion to decibels, corrected for geometric spreading and water attenuation. Further an iterative approach (Kim *et al.* 2004) was used to correct for sediment attenuation. The upper OBS-derived SPM concentration estimates were used to empirically calibrate the ADP's first bin. In general, the acoustic backscattering is affected by sediment type, size and composition. All are difficult to quantify by single frequency backscatter sensors (Hamilton *et al.* 1998). Limitations associated with optical and acoustic instruments have been addressed in literature (Thorne *et al.* 1991; Bunt *et al.* 1999; Fugate and Friedrichs 2002; Voulgaris and Meyers 2004; Downing 2006). Briefly, acoustic devices produce better estimates of mass concentration than optical for the coarser granular fraction. Besides time series of current velocities and acoustic amplitude, the ADV and ADP was configured to also measure and store the distance between sensor and boundary (i.e., sea bed). The altimetry of the ADV and ADP was used to detect variation in bed level, as also for the identification of deposition and resuspension of fine-grained sediments. For the study site, decreasing distance between probe and bed boundary can correspond to the presence of High Concentration Mud Suspensions (HCMS) acting as an acoustic reflector. However, the boundary detection may fail, due to attenuation of the signal (Velasco and Huhta, 2008).

Low-pass filtering of tripod time series

The effects of various hydrodynamic forcings (tidal and wind-induced flows) on suspended sediment transport have been analysed in terms of climatological parameters for the Blankenberge site. The collected current velocity (ADV and ADP) time series from tripod measurements were filtered for the tidal signal using a low-pass filter for periods less than 33 hours and decomposed in an along and cross-shore component (Baeye *et al.* 2011). The alongshore low-passed flow was used to characterize the tidal cycle in terms of wind-driven flow.

Three cases were identified, one corresponding to pure tidal flow (Case 0) and two to periods with significant influence of wind-driven flows with residual alongshore currents in excess of 0.05 m/s. Case SW corresponds with NE winds resulting in residual alongshore currents directed towards the SW and Case NE with SW winds and residual alongshore currents directed towards the NE. In addition to the above classification, each tidal cycle was classified as neap or spring, in terms of the tidal range of the particular cycle. The tidal cycles, from each category, were ensemble-averaged to create a "typical" representative tidal cycle for each case. Following the methodology described in Murphy and Voulgaris (2006), the time of data collection from each tidal cycle was converted from absolute time to tidal phase within the cycle, using the local high water slack time as a reference time. Then data (SPM concentration, currents, salinity, temperature, particle size distribution) from each case, falling within the same bin (width of 10 min) of the tidal phase, were averaged and a mean cycle and associated standard error were calculated and the tidal cycles, from each category, were ensemble-averaged to create an average tidal cycle for each case.

Wave- and current induced shear stress from ADV

High frequency ADV measurements (25 Hz) permit to decompose the velocity in terms of a mean and a fluctuating part. Several studies report on the possibility to estimate shear stress from second moment (turbulence) statistics (Pope *et al.* 2006; Verney *et al.* 2007; Andersen *et al.* 2007). The estimation is based on the calculation of the turbulent kinetic energy (TKE), which can be obtained from the variance of the velocity fluctuations. The shear stress has found to be proportional to the TKE through $\tau = C \times TKE$, where C=19 was adopted as proposed by Stapleton and Huntley (1995) and Thompson *et al.* (2003). This linear relationship will however fail in the presence of waves. The inertial-dissipation method uses the spectrum of velocity components and allows to apply a correction for the advection by waves (Trowbridge and Elgar 2001; Sherwood *et al.* 2006). In this case the vertical component was used, as it is least contaminated by waves. ADV data were discarded when the signal-to-noise ratio dropped below 15 dB and the correlation coefficient was lower than 0.8. Data were then transformed into a power density spectrum using a Fast Fourier Transform with a Hanning window and the spectral density, E_{ww}, was normalized such that the integral over the spectrum yielded the variance over the burst. Afterwards it was transformed to $E_{ww}\, \omega^{5/3}\, (2\pi)^{-1}$, with ω the radial frequency, as the turbulent dissipation, ε, scales with $E_{ww}\, \omega^{5/3}\, (2\pi)^{-1}$ in the inertial subrange, defined as the range between 1 and 2.5 Hz (Trowbridge and Elgar 2001). By calculating the mean over this range an estimate of $E_{ww}\, \omega^{5/3}\, (2\pi)^{-1}$ was obtained and ε calculated and a correction for the presence of waves implemented, see Trowbridge and Elgar (2001) and Sherwood *et al.* (2006). The shear stress at elevation z can then be obtained using $\tau = \Delta\, (\varepsilon\, \kappa\, z)^{2/3}$, where κ is the Von Kármán constant and Δ the water density.

c. *Clay mineralogical analysis*

The intriguing question why large deposits of muds are found in an energetic and otherwise sand dominated environment has inspired a large number of provenance studies. Until the reconnaissance studies of Fontaine (2004) and Grégoir (2005) the most important component of the muds, clay minerals, were never studied as provenance indicators. A new methodology was worked out to qualitatively and quantitatively characterize, with the highest possible resolution, BPNS muds, BPNS suspension samples and sediments from potential source areas to detect possible provenance relations. Existing (English Channel (e.g. McManus and Prandle 1997), Scheldt river (Gullentops *et al.* 1976) and local erosion (Fettweis *et al.* 2007b)), as well as new provenance hypotheses (Holocene salt marshes, Scheldt river upstream Bath, Eemian intertidal deposits, Atlantic Ocean, French coast West of Calais, Early Pleistocene and Late Pliocene deposits, Weichselian cover sands, Paleogene deposits on the BPNS) have been investigated.

d. *Substrate and habitat characterisation, and sand dynamics*

Erosion/deposition patterns are also studied in typical sandbank areas. Extensive new data have been collected north of the Vlakte van de Raan. This area includes the disposal ground B&W S1, one of the main sedimentation areas on the BPNS (see Result section). Side-scan sonar and multibeam echosounder data (MBES) were acquired for detailed substrate characterisation. Four areas with bedforms were identified and were followed in time (2006-2010). The areas include: (1) zone just north of the disposal ground (S1); (2) zone where dense aggregations of tube worms occur; (3) zone just north of these aggregations; and (4) intermediate zone between (1) and (2). Zone 1 is indicative of an area influenced by human activities. Sediment and macrobenthos samples were taken with a Van Veen grab.

Large-scale sedimentation patterns were investigated along a disposal ground of dredged material (B&W S1), based on chrono-sequential multibeam and single-beam echosounding data. These were confronted with disposal intensity data and sedimentation patterns of the shallow subsurface, revealed from vibrocores. Vibrocore analyses included density profiles, lithological descriptions, photographs and sediment subsampling. Extensive reporting on the vibrocore analysis can be found in Dezeure (2007) and Veys (2008). Bathymetric difference maps of chrono-sequential single-beam data from 1976 till 2006 were made.

To assess natural variability, the bathymetry data series are being correlated with hydro-meteorological forcings (based on data from the Flemish Hydrography). For an existing dataset, relationships were already established. Methodology included a principal component analysis, differentiating sediment budgets of the consecutive bathymetric soundings against the directionality and strength of the sand transporting agents: winds, waves and currents.

Results are reported under § 3.2.4; 3.2.5; and 3.3.4.

e. Substrate alteration – biological Influences

As mentioned in previous paragraph, areas with dense aggregations of macrobenthos were characterised, in high resolution, also. Their occurrence is being related to sediment dynamics, as well as to human influence. A hull-mounted Acoustic Doppler Current profiler (ADP) was used to characterise current flow over these areas.

f. Substrate alteration – beam trawling effects

Beam trawling on the seabed can be revealed from very-high resolution sonar imagery (Van Lancker *et al.*, 2007). However, to evaluate the spatial extent of impacts and to extrapolate some of the findings, data are needed over wide areas. Datasets from various sources (e.g. from UG-RCMG and FPS Economy, SME's and Energy) have been merged, and multibeam tracklines were sailed additionally to bridge some of the most important gaps. From the datasets, the spatial extent of fishing activities was estimated, hitherto never done before. The analyses required a careful processing of the data, as also advanced filtering techniques to remove noise and artefacts (i.e. spatial frequency filtering and spatial directional filtering). Analyses are extensively reported in Janssens (2009).

2.2.2 New model developments

To better estimate sand/mud balances along the BPNS, model improvements were needed, incorporating a better structure of the seabed and accounting for the occurrences of mixed sediments. Allowances were made for bed armouring, consolidation, and washing out of sediments. Improved modelling of flocculation (e.g. to estimate the fall velocity of the particles), and of turbulence was needed. New models can account for the transport of sand and mud at the same time. Another significant improvement of the sediment transport model is its 3D representation. Whereas at the moment, the sediment transport model only account for depth-averaged concentrations, also the vertical structure of the sediment distribution over the water column can have very important implications (e.g. related to the disposal of dredged material).

Major developments take place within the VLABEL[1] project (Flemish Authorities) and will become available to the scientific community in 2011.

a. *Refined hydrodynamic and sediment transport model*

Development of a better representation of the structure of the sea bottom

To account for erosion of old sediments (Holocene and outcropping Tertiary clays), a distinction between an active layer and a parent bed is needed. A critical erosion shear stress τ_{ce} of up to 4 Pa, was considered representative of recent sediment deposition. The active layer consists of different sub-layers allowing consolidation of mud, pore filling of sandy sediments by mud and segregation between sand and mud layers. Both the active bed layer and the parent bed layer are characterised by 15 variables, resulting in 30 variables on every sampling location. These variables include erosion characteristics, e.g. τ_{ce} at surface, τ_{ce} averaged over a depth interval, bulk density averaged over a depth interval, mass in a depth interval and critical erosion rate averaged over depth interval, and sediment characteristics, as grain sizes in 8 classes from gravel to clay. The definition of clay ($< 8\ \mu$m) is based on the difference between sortable silts and aggregated particles (Chang *et al.* 2007) and the discrimination between a cohesive and non-cohesive behaviour is based on van Ledden *et al.* (2004). Data were extracted from the SediCURVE@SEA database (Van Lancker, 2009); interpolation is done on a 250 m grid. Sedimentological maps with sand, silt and clay content are constructed, together with a spatial map of the van Ledden classes (Figure 2.2-2).

A sand/mud bottom model, based on the work of Waeles *et al.* (2007; 2008), Hayter (1983) and Sanford (2008), is being developed, also. The Waeles approach allows for the calculation of transport of cohesive and non-cohesive sediments in one single model. In the bottom, different layers are possible with changing composition. The model allows for consolidation and armouring of fine-sediments. The Waeles model was slightly adapted to also allow washing out of fine sediments from a sandy bottom structure.

[1] VLABEL is a project of the Department of Mobility and Public Works section Maritime Access of the Flemish Authorities; its aim is the development of a Flemish-Belgian instrument of numerical models for the North Sea harbours (call 16EF/2008/02). This numerical instrument has to be able to simulate flows and tidal propagation in seas, estuaries and rivers in 3D including sediment transport and morphological bottom changes due to flow or due to human intervention. The development builds further on previous collaboration between MUMM and Flanders Hydraulics, but now also involves universities and private companies into the model development.

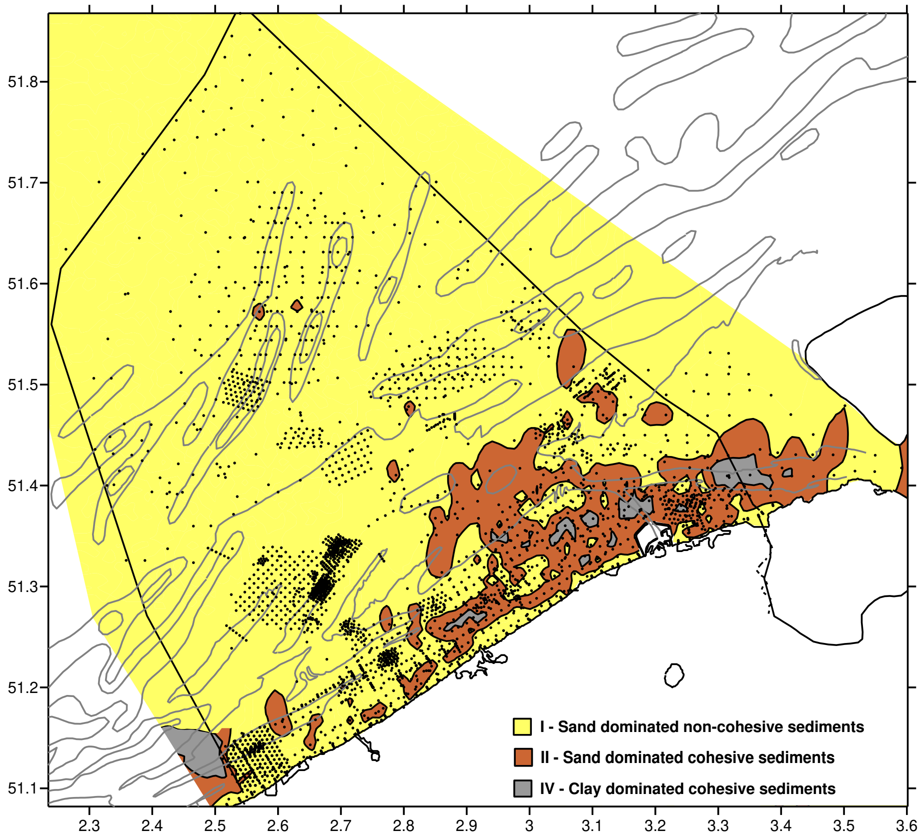


Figure 2.2-2: Spatial distribution of cohesive and non-cohesive sediments, based on van Ledden's criteria: sand dominated non-cohesive sediments in yellow, sand dominated cohesive sediments in brown and clay dominated cohesive sediments in grey.

Roels (2010) has developed a Sanford-type model, describing consolidation with relaxation method, extended with the property to describe fluidization by waves. The model has been tested with MUMM's tripod data, showing that a mud layer, once eroded by a storm does not form a consolidating bed. However, combined with a depth-averaged sediment transport model, it is impossible to simulate the likely formation of fluid mud layers during slack water, which are expected to reduce the actual bed friction on the hard bed surface, such that new bed formation would be expected to occur in reality. Therefore, it is concluded that full 3D modelling of sediment transport in the water column is absolutely necessary to allow the correct simulation of fluid mud behaviour and the correct interpretation of the tripod data, which only give time series at 2 distances from the bottom. Also the potential role of advection could not be determined. As stated above, the development of the 3D sediment transport model is being executed in the framework of the VLABEL project.

Regarding flocculation modelling, new modelling strategies using bimodal distributed cohesive sediment aggregate or a combination of physical and biological flocculation dynamics are being developed to calculate the representative settling velocity of cohesive sediment aggregates. LISST particle size data from the tripod measurements at MOW1 and Blankenberge have been used. In the first approach the population balance equations is solved for two floc populations (Lee *et al.*, 2011a). LISST particle size data have been analysed, using the commercially available DISTFIT software to determine the effective number of particle populations (Lee *et al.*, 2011b). Instead of discretizing the particle size distribution (PSD) in multiple classes, each population is modelled using a continuous distribution (Wang *et al.*, 2009). In order to minimize the number of variables, the PSDs are described by simple continuous analytical functions, following the work of Maerz & Wirtz (2009). The second approach is based on a flocculation model (Maggi 2009) that couples mineral and micro-organism dynamics to predict the median floc size. Natural SPM comprises many different substances with concentrations that are generally site specific and time varying. The model has been calibrated using a set of shipboard tidal cycle measurements and tripod data (see Chen *et al.* 2010a, 2010b).

Important progress is made in the development of an auto-adjusting low-Reynolds turbulence model for the simulation of high-concentrated near-bottom sediment transport. A break-through is made for the formulation and implementation of so-called four-way coupling particle-turbulence effects by adding a second turbulence generation mechanism, i.e., turbulence generated in the wakes of the particles, into the equations (Toorman, 2011 and articles in preparation). It is intended to implement and test this new turbulence model in the COHERENS v2 code (Luyten, 2011) in the framework of the VLABEL project (scheduled for 2011-2012).

b. Dynamic coupling of wave and current models

There is a growing tendency to couple different types of models (climate-ocean-waves-transport) (e.g. Bolaños *et al.* 2010). Coupling of models for coastal hydrodynamics and coastal waves is also pursued and is needed to better represent hydrodynamic processes in the shallow coastal zone. Both the computational logistics and the understanding of the interaction processes is a major challenge and an area of continued research. The COHERENS v2 model was used to simulate currents and was coupled to the wave model SWAN (SWAN, 2008). SWAN is the state-of-the art model for (spectral) wave propagation in coastal areas. It has a large active community, is still in active development and therefore incorporates new insights in wave modelling. The WAM-model (WAMDI Group, 1988) was used to provide boundary conditions for the coupled COHERENS-SWAN model. The coupling was done one way in which water levels and currents from the COHERENS model are transferred to the SWAN-model. This coupled model has been used to assess impacts of large scale sand extraction on the BPNS (see section 2.4). It has also been used in the Belspo BOREAS project, to hindcast a 10-year period (1999-2008) and to assess the wave energy potential on the BPNS (Fernandez *et al.* 2010). For a full dynamical coupling of COHERENS and SWAN, considerable work is still needed, but ongoing.

2.2.3 Setting-up a historic reference framework

a. The Gilson collection: period and sampling area.

The Gilson collection (RBINS) is a large set of biotic and abiotic samples and measurements acquired between 1898 and 1939 in the English, French, Dutch and Belgian parts of the southern North Sea and in the Eastern English Channel. Two compartments of the ecosystem were focused on: sediments (acquired with the 'ground collector') and macrobenthos (acquired with the benthic dredge, towed over a distance of 1,852 m). The bulk of data was acquired in the Belgian-Dutch zone between 1899 and 1908, within high definition sampling grids (Houziaux *et al.* in revision). More information on the collection can be found in previous technical reports (Houziaux *et al.* 2008; Van Lancker *et al.* 2009; 2010) and in Annex (Houziaux *et al.* in revision).

b. Reference map of sediment types

Gilson collected 2,979 sediment samples using an originally-designed cupped instrument (the 'ground collector'). This instrument enabled the preservation of sediment layers and was designed to avoid leaking of the finer sediments (see van Loen *et al.* 2002 and references therein). Only 690 sub-samples, created in 1956, of the collected sediments are still available in the repositories of the RBINS. Most samples (100-200 g) were kept dry, though a small part was stored with formalin. Not all available samples originate from accurately positioned stations, hence less material was available for direct long-term comparison purposes. Seafloor composition was recorded in field log-books in the form of visual descriptions of the fresh sample, as observed in the sampling gear. Gravel, pebbles and cobbles collected with the towed benthic dredge were kept as well and are still stored. A part of the collected cobbles was cleaned from epibenthic cover and was stored dry in the petrographic repository; their composition was studied by Verbeek (1954). The remainder was stored in alcohol in the invertebrate repositories, together with their attached epifauna. See Houziaux *et al*. (2007; 2008) for analyses and interpretation.

Geographic position of the samples was determined, as precisely, as weather conditions enabled using two angle measurements with a sextant, sometimes a compass, with reference to well-defined landmarks and/or seamarks (Gilson 1900; 1928). Prior to analysis, a detailed evaluation of geographic positioning accuracy was carried out to enable a strict quality-based selection of samples (see Annex; Houziaux *et al*. in revision). For the larger pebbles and cobbles, collected with towed gears, a similar verification was carried out on dredge samples. Data were mapped using the mean geographic position between the start and end point of tows (the dredge was towed on a standard distance of one nautical mile, or 1,852 meter). Data were mapped to check consistency with nautical charts of Stessels (1866) and Urbain (1911) and with the present-day bathymetry.

Processing of visual sediment descriptions

Visual sediment descriptions were provided in field log-books. The layered structure of the sediments was generally described, providing an exhaustive image of the surficial sediment composition, but the relative proportion of every major constituent (namely: mud, sand, shell debris and mineral gravel) was not systematically recorded. As a consequence, drawing a ternary diagram of mud, sand and gravel content can be achieved only at a very limited amount of stations. However, estimates still enable considering the spatial distribution of every feature, e.g. areas with low or high amounts of mud can be identified and mapped, independently from other constituents, enabling spatial analysis of the mud levels distribution. Therefore, estimated relative amounts of mud and shells debris, estimated grain-size of the sand fraction and occurrence of stones were processed separately.

Calibration of visual descriptions: grain-size analyses

To calibrate the accuracy of Gilson's visual estimates, grain-size analyses were carried out on selected archived samples. Details on methods, used to analyze the samples and calibrate the descriptions (mud content, median grain-size of the sand fraction), are given in Annex (Houziaux *et al*. in revision).

b. Reference map for macrobenthos

Data acquisition focused on Bivalvia, Amphipoda and Polychaeta, because they represent the bulk of Gilson's soft bottom macrobenthos. Polychaete data could not be acquired from the collections. For this group, species inventories (records of species per sampling number) were used instead, but their adequacy with the collection content needs further verification. They display an apparently much reduced abundance, compared to the present-day situation; this could bear ecological significance.

In total (including Gilson's and other benthos collectors), the merged raw data-set provided information on 870 taxa, of which 708 are determined at the Species level; 96 at the Genus level; and 35 at the Family level. With 24,475 'records', Gilson's historic data represents 87 % of the collection of regional marine invertebrates of the RBINS, confirming the importance of this data-set for marine biodiversity studies. The archive is dominated by molluscs (mainly bivalves and gastropods), arthropods (mainly crustaceans), annelids (polychaetes), bryozoans and cnidarians (mainly hydrozoans), as shown in Figure 2.2-3. From the bulk of invertebrate data, a selection was made for long-term analyses purposes. The benthic dredge, which was operated in the BPNS within a grid and sequentially with sediment sampling, represents more than 60% of the bulk data-set. Our initial expectation that soft-bottom macrobenthic invertebrates should be best represented in Gilson's sediment samples was wrong, since only few hundreds of 'records' were obtained. It seems that the plan of Gilson was to rely on dredge data, which probably led him to discard specimens collected with sediments. Hence we focus on the dredge data and on specimens collected alive. For dry samples (e.g. shells of gastropod and bivalve molluscs), the status of the animal at sampling is often unclear, *i.e.* we do not know whether the collected specimen was alive and subsequently dried or already represented by an empty shell. Therefore, the "specimen status" and the "freshness level" were determined when encoding in the database of RBINS collections and combined. This information is lacking for taxa, encoded prior to 2004; this results in about 10% of taxa flagged with 'unknown' states. These were excluded from the data-set for further analysis. Such is the case for most dry gastropod shells, a part of the bivalves and some tube-building polychaetes. Assuming that the transport of empty bivalve doublets by tidal currents must rapidly lead to a breaking of the ligaments that hold the valves together, "fresh" doublets are considered as indicative of either alive specimens stored dry or specimens which died shortly before sampling. For the bulk of bivalves, the states "collected alive", "fresh" and "doublet" (dry valves still attached one to another) states were therefore retained from the database to analyse the composition of 'living' benthos.

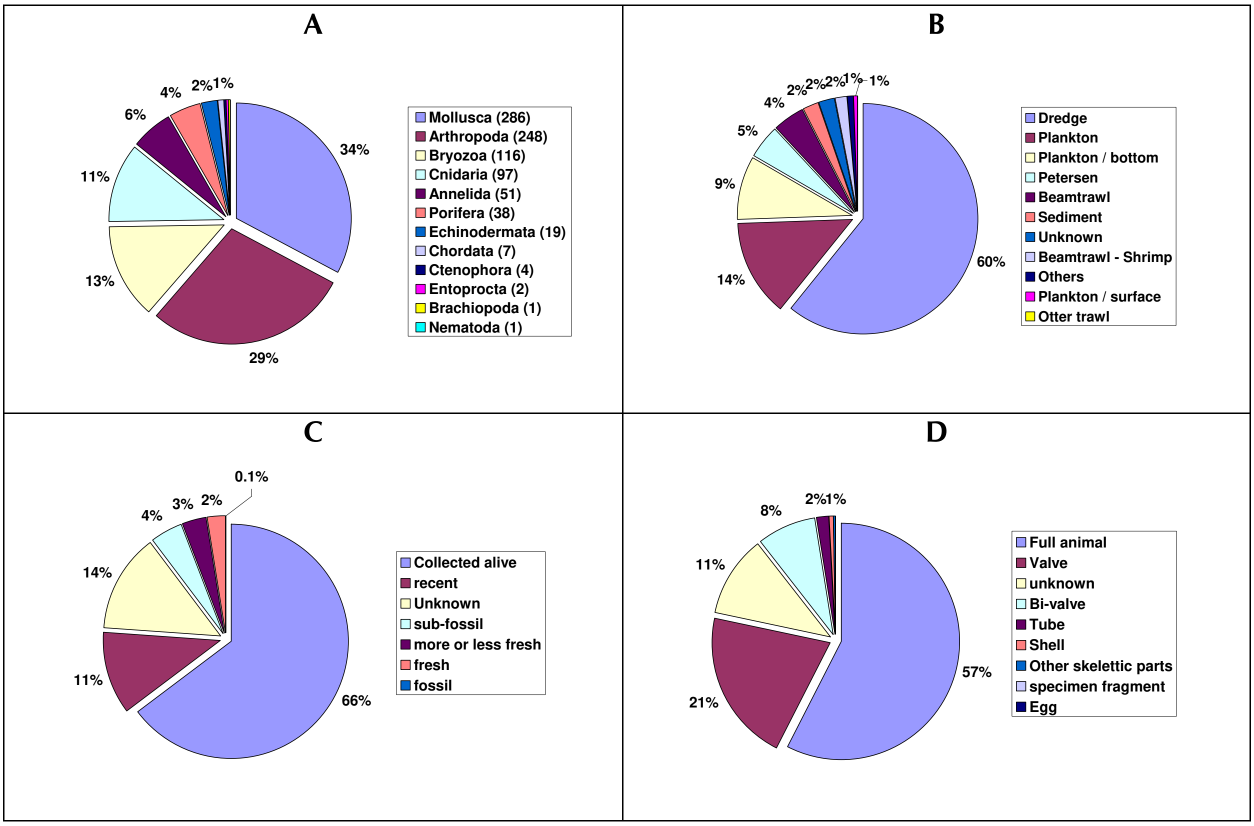


Figure 2.2-3. Overview figures from the bulk of the historic data on invertebrates (G. Gilson) (relative proportions of 'records' from the bulk data-set). A. Species richness of the represented phyla. B. Relative importance of sampling methods. C. Relative abundance of specimen "freshness" levels in the collections. D. Relative abundance of specimen stated in the collection.

Integrative maps were created for the 'baseline' distribution of species richness and overall specimen abundance. All species considered as 'collected alive' are taken into account, only at the accurately geo-referenced sampling stations. For colonial organisms (e.g. hydrozoans or bryozoans), abundances are replaced by presence/absence counts.

2.3 Ecosystem changes and trends

2.3.1 Quantification of decadal to centennial changes and trends

a. *Large-scale, long- to medium-term bathymetry changes*

Long-term bathymetry changes on the BPNS

Based on historical navigation charts (~150 years ago up till now), the morphological evolution of the BPNS is studied. A selection of charts spanning a large spatial (a large part of the BPNS) and time (last centuries) domain, is being digitized. Table 2.3-I presents the selected navigation charts that have been digitized (the most recent chart is a compilation of different datasets, already digitally available).

ArcGIS is used to interpolate the digitized charts to grids with a spatial resolution of 20 m x 20 m, making it possible to study the morphological evolution by visualisation of depth lines chart differencing and trend analysis. For the interpolation, a special methodology was used in order to create grids with smoothly varying depth values. In this methodology, a chart of a specific year is not only based on the interpolation of data points of that year, but also on the chart of 2007, which had a much higher data point density. By doing so, the derived charts not only are the result of an interpolation in space, but also in time, and it is implicitly assumed that the basic morphologic patterns (such as presence of sandbanks) on the BPNS are approximately stable, which is confirmed by earlier studies (Van Cauwenberghe, 1971). The application of this methodology results from the observation that straightforward interpolation of the chart data points into a grid using one of the algorithms provided by ArcGIS would result in the artificial creation of pits and peaks on the location of some data points, making it impossible to compare the different grids, since different charts have data points on different locations.

It must still be noted that, given the large uncertainties on the water depths of the data points, especially on the older charts, results of the analysis of the grids must be handled with great care (a quantitative uncertainty analysis was not carried out).

Using the ArcGIS bathymetry grids, long-term morphological evolution is studied by visualization of depth contours, chart differencing and trend analysis.

Table 2.3-I. Details of the digitized charts (Flemish Authorities, Division Hydrography)

date	title of chart	surveyed
1866	Carte Générale de Bancs de Flandres compris entre Gravelines et l'embouchure de l'Escaut	?
1908	Mer du Nord Dunquerque – Flessingue	1901 – 1908
1938	Noordzee – Vlaamsche Banken	?
1969	Noordzee – Vlaamse Banken	1959 – 1969
2007	(composed from different recent charts)	1997 – 2007

Medium-term morphological evolution of beach, inshore, near coastal offshore zone

Medium-term bathymetry and topography changes along the Belgian coastline are studied, based on the digitally available topography and bathymetry datasets. Various datasets have been gathered at the Coastal Division (MDK – Afdeling Kust) and include the yearly foreshore soundings and dune measurements, the inshore echo soundings and the offshore single beam measurements (from 1.5 to 10 km off the coast). Digital datasets are available roughly from 1995 till now, for beach and shoreface almost on a yearly basis, for the near coastal offshore zone time intervals between two successive datasets are typically 3 years. See Table 2.3-II for a list of the available data sets for each zone.

Datasets (mostly plain text files, containing XYZ data) were converted into more manageable bathymetry grids to be analyzed with ArcGIS software. This task was particularly elaborate because of different dataset formats, the use of different coordinate systems and bathymetry reference levels; sometimes clear metadata was lacking. Subsequently, medium-term evolution is analyzed through visualisation of depth contours and cross-sectional profiles, and trend analysis.

Table 2.3-II. Overview of data used for the morphological trend analysis

Year	BEACH	SHOREFACE	OFFSHORE
1997-1		✓	Westende-De Haan
1997-2		✓	Zuydcoote-Westende
1998-1		✓	Wielingen-Scheur
1998-2		✓	
1999-1	✓	✓	
1999-2	✓	✓	
2000-1	✓	✓	Wielingen-Scheur
2000-2	✓		Westende-De Haan
2001-1	✓		Wielingen-Scheur
2001-2	✓		
2002-1			Zuydcoote-Westende
2002-2	✓		
2003-1		✓	Zuydcoote-Westende
2003-2			
2004-1	✓ (summer)	✓	Wielingen-Scheur
2004-2			
2005-1	✓ (summer)		Westende-De Haan
2005-2			
2006-1	✓		Zuydcoote-Westende
2006-2			
2007-1	✓	✓	Wielingen-Scheur
2007-2			
2008-1	✓	✓	Westende-De Haan
2008-2			
2009-1		✓	Westende-De Haan
2009-2			Zuydcoote-Westende
2010-1	✓		

c. Long-term sediment changes

The baseline sediment type map was compared with a recent map of mud content. The latter is based on the SediCURVE@SEA database (Van Lancker *et al.*, 2009), containing cumulative distribution curves of > 5000 samples. More detailed analyses were performed where detailed and reliable information was available in the historic data-set. It must be stressed that historic data are derived from visual descriptions, while recent data provide the proportion of grains <63 μm. It is not unlikely that historical very high mud levels (> 75%) are overestimated, hence giving the impression that much less mud is nowadays found on the seafloor. Therefore, we analyse the differences, spatially, assuming that 95-100% in the historic situation corresponds roughly to the 75-95% class in the recent map. The areas with high mud contents ('mud fields') were focused on. In all cases, data were interpolated using Inverse Distance Weighing (resolution: 0.2 km; search radius: 2 km). For studying changes in the sand fraction, median grain-size, sorting and skewness were evaluated. See § 3.3.2.

Human-induced changes have been quantified also, based on the comparison between historic (100 years old) and recent sediment and bathymetric data. Long-term human-induced effects are assessed, based (1) on qualitative sediment descriptions of historic and recent samples, and (2) on morphological evolution and quantitative (grain-size analysis of archived samples) sediment data. The aims are:

1. Determining to what extent the distribution of cohesive sediments and the transport of SPM may have changed due to increasing anthropogenic activities during the last century, see §3.3.4b; and Fettweis *et al.* (2009).
2. Reconstructing the sub-tidal sedimentary environment of the BPNS in the first decade of the twentieth century, see §3.3.1; and Houziaux *et al.* (2011).
3. Enhancing our knowledge of the local sediment composition and dynamics in the long run, see §3.3; and Fettweis *et al.* (2009); Houziaux *et al.* (2011); and Du Four and Van Lancker (2008).

d. Long-term changes in shallow endobenthic bivalves

For the bulk of the historic data, problems remain for which specific work must be further carried out. For instance, the polychaete record is based on paper archive information rather than on the specimens, which could not yet be digitized, creating incertitude on their historic abundance. On the other hand, amphipods were surprisingly less represented in the samples, which might be due to their small size. However, bivalves are well represented and are a major component of the coastal macrobenthos. Long-term analysis was therefore focused on this group of organisms, using recent data compiled by UG-SMG and ILVO-Fisheries (Degraer *et al.* 2009). Specific analysis strategies were developed to tackle the issue of comparing data, acquired with very different methodologies.

In the historical collection (1899-1914), mollusc specimens were collected with the dredge and are stored either in alcohol or as dry shells. Among the latter, a large part was obviously devoid of the animal when collected, while others were collected as living animals and subsequently emptied for dry storing. Loose valves, as well as unclear records, were eliminated from the data-set, which was reduced to the accurately geo-positioned stations in the sampling grid. The recent data were gathered between 1994 and 2008 by ILVO-Visserij and UG-SMB laboratories with a Van Veen grab (0.1 square meter), with a project-dependent distribution of sampling stations throughout the BPNS. 2080 samples were collected in this period at 806 stations. Only living animals were determined and counted.

Sampling efficiency of Gilson's dredge was considered to be much lower for endobenthic species than for epibenthic species. However, some endobenthic bivalve species numerically dominated the overall data-set (Figure 2.3-1). Furthermore, the geographic spreading of abundance of the numerically dominant species shows a trend to specific spatial clustering, which is consistently differing from a species to another (see Annex). This likely results from an apparent, better than expected, efficiency of the 'rake', disposed in front of the dredge to collect endobenthic species (see Figure 2.3-1), combined to locally high densities. On the other hand, towed gears such as trawls and dredges are known to underestimate the density of benthic organisms (Reiss *et al.* 2006), and such is most likely the case with the Gilson's dredge, although contact with the seafloor was certainly increased by the frontal rake itself (see Houziaux *et al.* 2008). Nevertheless, supposing the Gilson's dredge to collect as little as 1 % of the endobenthic specimens really present on its path, we assume that the geographic distribution of relative abundances of a given species (abundance at the station / maximum observed abundance) should represent a good proxy for the distribution of high density patches. On the other hand, we assume that species of similar size and occupying similar position in the upper sediment display similar catch probabilities. The observation of opposite spatial or temporal trends for species with such similar catch probability is thus considered as an indication that results are not due to bias and point at a trend.

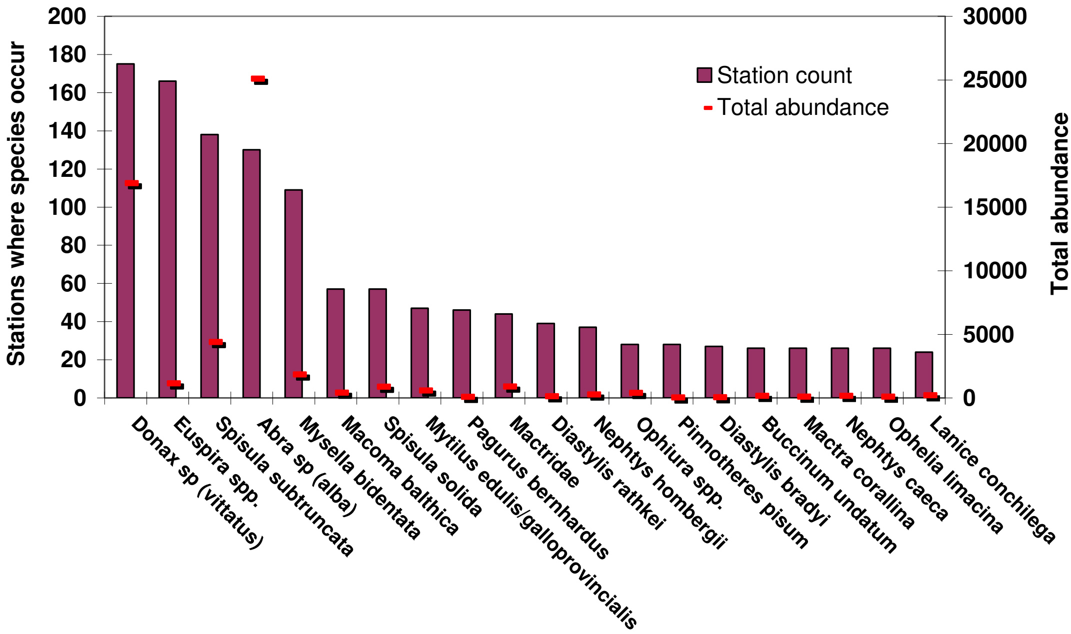


Figure 2.3-1: Most widespread (station occupancy) and abundant (total abundance) macrobenthic species within the historic data; period 1899-1911. Sampling gear: dredge.

In contrast, the Van Veen grab used in the recent surveys will catch all animals within the upper layer of soft sediments; the calculated density will likely be an accurate estimator of the real abundance in the surrounding square meter. A similar transformation of data to 'relative abundance' can thus be carried out to spatially compare the historic and recent distribution of high density patches.

In total, 50 bivalve species are represented in the two data-sets. Species typical of offshore gravel fields, as well as large epibenthic species such as oysters, queen scallops or common mussels, were removed from the data-sets because these are inaccurately collected with a Van Veen grab. Furthermore, the recent sampling effort is lower in the offshore, where these species were historically most abundant. Deep-burrowing and rare species were also discarded. The analysis finally focused on 14 species living in the upper layer of the sediment in coastal waters and numerically abundant in either of the data-sets. 2 of these species (*Tellimya ferruginosa; Ensis directus*) were found only in the recent survey data.

General patterns and distribution maps

The relative contribution of every considered species to their overall abundance in either data-set was calculated. Data were further reduced to presence/absence (P/A) at the stations to determine station occupancy (% stations where the species is present). Abundance data were standardized, at the sampling stations, to the maximum amount of specimen collected for each species in each data-set. For the historical stations, a problem appeared for *Donax vittatus* with one very high abundance of juveniles (over 13,000 specimens), which can be attributed to an exceptional recruitment event. Because this single value accounts for more than two third of all specimens collected, the second maximum abundance (400), more representative of usually observed values (from few to some tens of specimens), was used to standardize abundances for this species. These data were used to draw distribution maps of relative abundances in the form of spatial interpolations. Interpolation maps of relative abundances (max. value 1) were created for all species in the two situations (interpolation method: Inverse Distance weighing; search radius: 5 km; Annex).

Spatial analysis: grid approach

As large differences exist in the geographic spreading of sampling stations in both data-sets, hampering accurate spatial analysis of changes (Figure 2.3-2), a grid was created to pool and compare historical and contemporary data where they existed. The grid was designed to accurately encompass Gilson's historical sampling grid, respecting his sampling design based on minutes of latitude and longitude. The grid extends from 2°16'30" E - 51°04'00" N to 3°16'30" E - 51°40'00" N, with a 2 nautical mile step (grid cell dimension: latitude axis, 2.3 km; longitude axis, 3.7 km).

We considered one historic sample per grid cell as the minimum requirement, because the gear was towed over a large distance (one nautical mile). For Van Veen grabs, a minimum of 2 samples was considered to account for spatial variability, which is better captured with a towed dredge. Finally, 61 grid cells could be considered to analyze long-term changes in the distribution of bivalves (Figure 2.3-2).

To test whether long-term changes occurred in the distribution of relative abundances of the considered species, a Wilcoxon Rank Signed test was carried out on grid cell based abundance data. The evenness of their values across grid cells was further tested through a Mann-Whitney analysis of variance. The change in grid cell occupancy was mapped to track distributional trends and tested with a proportion test (z-test).

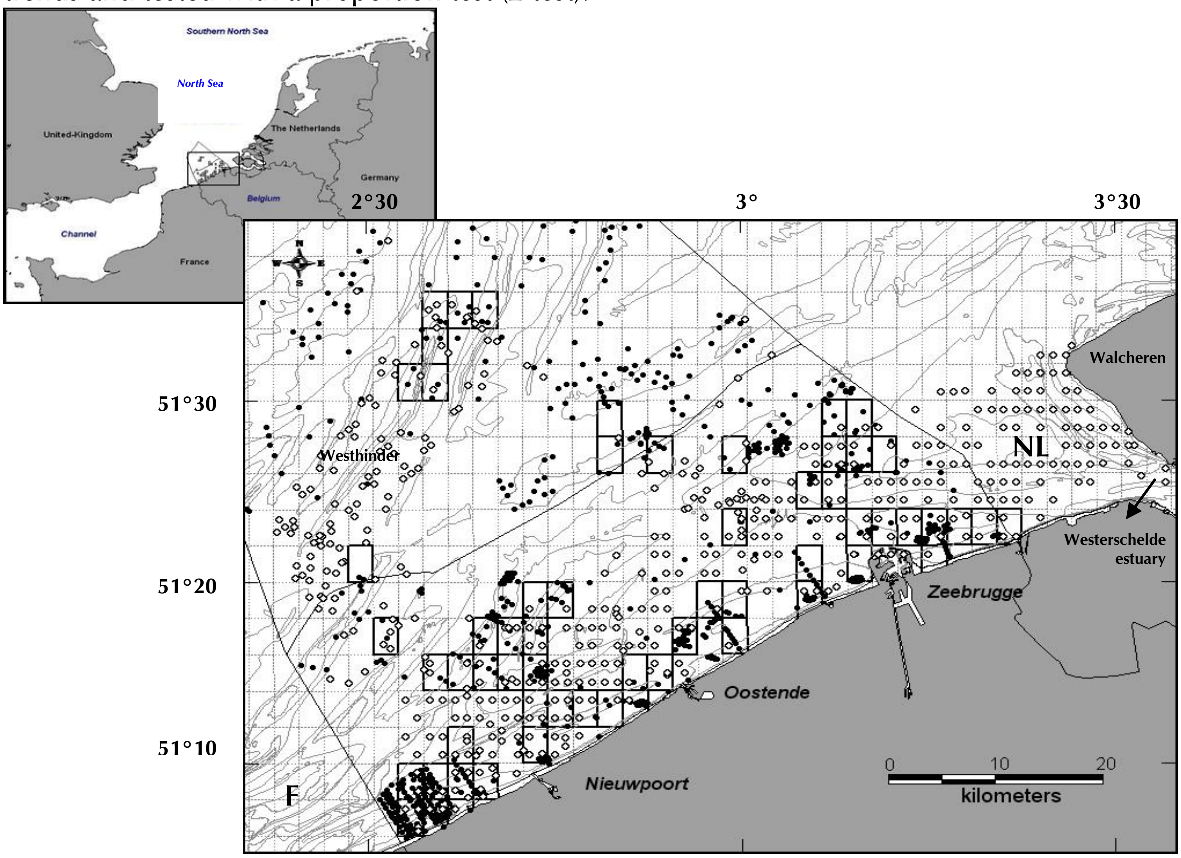


Figure 2.3-2. Distribution of sampling stations in historical (open dots; 1899-1914) and recent (plain dots; 1994-2008) data-sets along the coasts of Belgium and The Netherlands. Dashed lines represent the grid created for statistical analysis purposes. Grid cells where at least 1 dredge and 2 Van Veen grab samples were collected are shown as bold rectangles (n = 61). Geographic Datum: ED50. F: French waters; NL: Dutch waters.

2.3.2 Exogenic forcings: Climate Change and NAO

Climate Change

In Ullmann and Monbaliu (2010) it was shown that Wintertime (October-to-March period) 99th percentile of sea level (sea surges) at Ostend increased at a rate of +3 mm/year (+1 mm/year) from 1925 to 2000. To this end, relationships between daily sea surge at Ostend and five weather regimes Zonal (ZO), East Atlantic (EA), Greenland Above (GA), Blocking (BL), and Atlantic Ridge (AR) over the northeast Atlantic and Europe (40° W - 40° E, 30° N - 70° N) were analysed during the period of 1925-2000. More than 70% of sea surges >= 65 cm occurred during the AR weather regime, ahead of low pressure travelling on a northern track from Iceland to Scandinavia. The relationships between monthly/wintertime frequency of the AR weather regime and 99th percentile of sea surge at Ostend tend to strengthen during the twentieth century: for example, correlation between wintertime frequencies of AR and 99th percentile of sea surge increases from 0.21 in 1925-1950 to 0.74 in 1975-2000. This increase is associated with the pressure rise over the near Atlantic, between 30 ° W and 15° W and between 30° N and 50° N, leading to an increase in the frequency of strong surge-related pressure gradient during AR days.

In Ullmann *et al.* (submitted), a statistical downscaling method was used to set-up a model to relate Sea Level Pressure (SLP) to sea surge at Ostend. Linear regressions were designed to relate the daily surge height at Ostend with: (i) the daily SLP over the Baltic Sea; (ii) the daily value of the pressure gradient between the Baltic Sea and the Azores; and (iii) both of these atmospheric parameters. The multiple linear regression robustly reproduced the interannual to long-term variability of high surges at Ostend. This linear regression is then used with SLP time series simulated until 2100 by the ARPEGE climate model (Royer *et al.* 2000) using climate scenario A2 and B2 and with SLP time series from the ESSENCE project (Sterl *et al.* 2008), using climate scenario A1b. The ESSENCE data set consists of an ensemble of 17 runs using the same scenario, but with different initializations. It was concluded that high surges (at least up to the 99th percentile of the daily values) are expected to stay stationary during the 21st century, associated with no significant changes in SLP conditions over the Baltic Sea and over the Azores. This is illustrated in Figure 2.3-3 for the yearly 90th percentile.

In Ullmann *et al.* (2009) a multiple linear regression also reproduced interannual variability of high waves at a far offshore site very well. This is not surprising since high waves and high surges are well correlated for this circulation pattern. Note that in both Ullmann *et al.* (submitted) and Ullmann *et al.* (2009), a coefficient of inflation was used to make sure that standard deviations in the reference run have the same value as for the observed surges. This inflation was criticized by one of the reviewers, because it implicitly assumes that all variability in observed surge heights can be traced back to variability in the large scale field (here e.g. the pressure over the Baltic).

However, a similar result is shown in Ullmann *et al.* (2009), where a hydrodynamic model (WAQUA) was forced by the surface winds from the ESSENCE data set. Such a model integrates all possible effects over the domain and in time that leads to high surges and therefore does not assume that all variability is in the large scale field. The observed maximum water levels from the hydrodynamic model and from the reference run (1950-2000) compared well with observations. This is illustrated in Figure 2.3-4 where an extreme value distribution has been fitted to the observations and to the model data of the reference runs. In the same figure also an extreme value distribution has been fitted to the model data for the period 2050-2100. Extreme values are all very similar.

North Atlantic Oscillation

On a global scale, the North Atlantic Oscillation (NAO) is responsible for much of the observed weather and climate variability, especially during winter months (December through March)

(Hurrell, 1995; Hurrell and Deser, 2009). This wintertime NAO exhibits significant multi-decadal variability with positive values indicating anomalously strong westerly winds and wet conditions over northwestern Europe, whereas negative values exhibit weaker westerly flow and less precipitation (Hurrell, 1995; Chelliah and Bell, 2004).

The influence of the North Atlantic Oscillation (NAO) was first investigated against the Schelde streamflow. (Non-) linear regressions were used to investigated correlations between NAO index and the streamflow at various timescales (Levy et al., 2010).

NAO indices were also compared to spatial and temporal variability within SPM concentrations, as derived from satellite remote sensing (MODIS-Aqua) imagery (Baeye et al., submitted). SPM concentrations were grouped into classes, from which the extent of the turbidity maximum in the coastal zone could be derived. Variation in spatial extent was correlated with NAO index for winter periods (WI). The NAO Index Data were provided by the Climate Analysis Section, NCAR, Boulder, USA, Hurrell (1995).

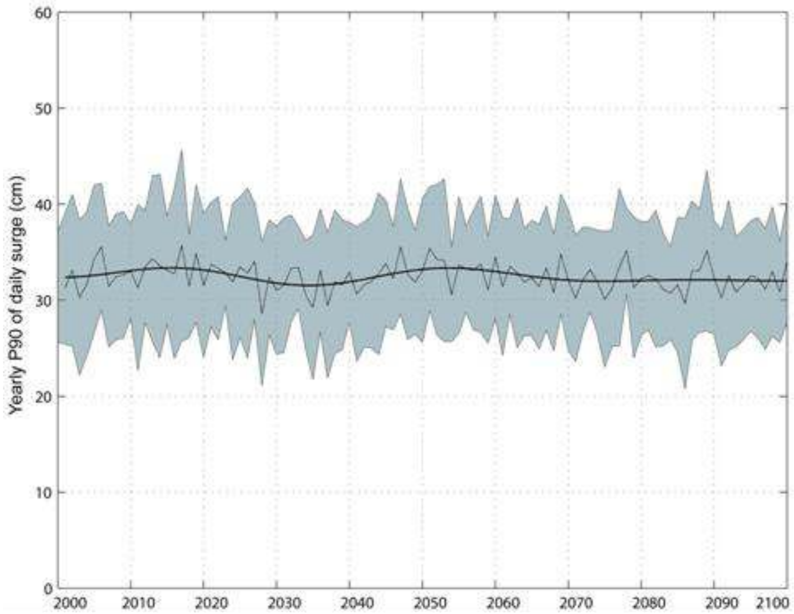


Figure 2.3-3. Thin line: average of the 17-ensembles time series of yearly 90th percentile of daily sea surge estimated with the linear multiple regression (2000-2100). Bold line: 30 year low-pass variations. The gray shading represents the variability within the 17-ensembles time series in each year (i.e. the yearly mean +/- σ^2).

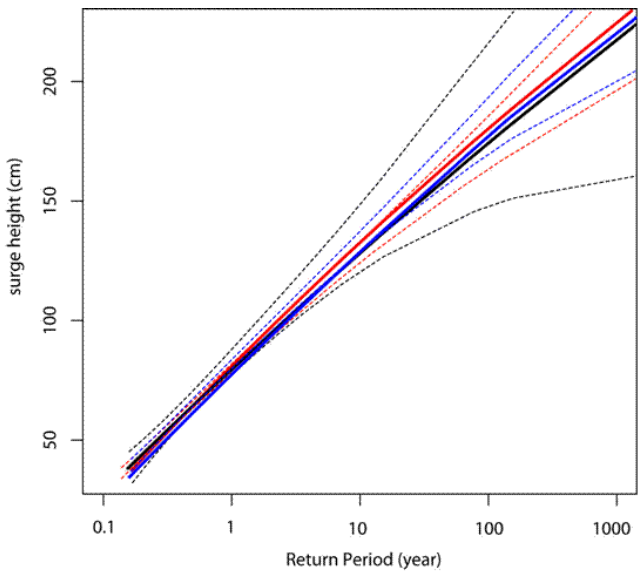


Figure 2.3-4. Return level plots and estimated 95% confidence intervals for annual maxima obtained with the GEV (Generalised Extreme Values) distribution at Ostend. For in situ observations for the period 1950-2000 (black lines). For WAQUA total set for the period 1950-2000 (red lines) and for WAQUA total set for the period 2050-2100 (blue lines).

The NAOWI (December through March) time-series exhibits two consecutive winters with opposite NAOWI index within the period of MODIS-Aqua data collection: winter 2005/6; -1.09 and winter 2006/7; 2.79.

2.4 Recommendations for more sustainable management of human activities

2.4.1 Development of indicators and monitoring practices

European Directives and international agreements require the monitoring of a range of marine biotic and abiotic parameters. Knowledge is needed on the condition of ecosystems and how they change. This knowledge is gathered by long-term systematic monitoring of species and habitats. A literature review was performed to highlight and summarize main issues when setting-up integrated monitoring programmes, particularly in the framework of the European Marine Strategy Framework Directive.

From Q4D results, increasing levels of SPM were regarded as a potential driver of benthos and habitat changes. Dedicated research was set-up to investigate if SPM concentration can be defined as indicator of environmental changes.

a. SPM concentration as indicator to detect changes in the marine environment

Since SPM dynamics is complex and is affected by external factors, such as hydrodynamics, waves, availability of SPM sources, biological processes, flocculation, deposition and resuspension, a SPM-related indicator is implicitly linked to the listed physical parameters acting in the water column. In order to assess this variability, we have defined SPM concentration as a statistical population. By doing so the measured SPM concentration time series can be considered as sub-samples that are characterised by statistical properties, such as median, geometrical mean, standard deviation and probability density distributions. Fettweis and Nechad (2010) have shown that SPM concentration has a log-normal distribution. The probability density distributions of the different sub-samples, consisting of the different time series or other sub-samples, were therefore fitted using log-normal distributions, and the χ^2 test probability calculated to assess how well the distribution fits a log-normal one. By doing so statistical properties can be calculated so that inferences or extrapolations from the sub-sample to the population can be made. E.g. if the data series collected during different periods have similar log-normal distributions, geometric means and standard deviations, then we could conclude that - within the range of natural variability and measuring uncertainties - these data series represent similar sub-samples of the whole SPM concentration population. Consequently, if a human activity, such as disposal of dredged material, has a significant impact on SPM concentration then this should be detectable in the differences between the statistical parameters of the sub-sample, collected during the dredging experiment and of the whole population. The statistical approach provides a tool to account for the complexities associated with natural dynamics and the need to evaluate human impact, quantitatively.

Objectives are:

1. Determining the statistical properties of the available SPM concentration data (tripod, tidal cycle and satellite) and of sub-samples (during a storm, calm weather) of the data, see §3.4.1 and Fettweis and Nechad (2010).
2. Application of the concept of statistical populations to evaluate the effects of disposal operations on SPM concentration in the Belgian nearshore area, see §3.3.4c and Fettweis *et al.* (2011).
3. Discussion of the sampling strategy and the representativeness of the different data sets (tripod, vessel and satellite) and formulation of optimised monitoring schemes, see §3.4.1 and Fettweis and Nechad (2010).

The use of SPM concentration as indicator for environmental changes assumes that the data collected are representative for the SPM concentration at this location. Therefore, a large set of SPM concentration data from MODIS satellite and from in situ measurements (tidal cycle, tripod) was used to evaluate temporal SPM heterogeneity in the Belgian nearshore. As match-ups (satellite picture at the same time as *in situ* measurements) are scarce, statistical methods were used to evaluate the differences and similarities in the data sets. This approach is new and allows comparing different data sets, not necessarily sampled at the same moment in time.

In order to assess storm effects, sub-samples of the SPM concentration data have been selected, based on bottom wave orbital velocities. The wave orbital velocity at the bottom was calculated from significant wave height measured at the station "Bol van Heist" (Figure 2.2-1), the measured water depth and the JONSWAP spectrum of waves (Soulsby 1997). Sub-sampling of the data series allows filtering out the effects of random storms from the harmonic SPM concentration variations caused by tides. The statistical properties of sub-samples representing good/stormy weather conditions can thus be calculated and the SPM concentrations can be correlated with sea state conditions.

b. SPM concentration as threshold for habitat and benthos changes

Q4D research has shown an increase of SPM concentration along the BPNS in the last century, accompanied by a shift in the distribution of benthic communities. This might be a response to exceeding thresholds in amount of food available, indicating possible limitations in their feeding strategies and habitat variations.

Suspended particulate matter (SPM) indeed carries a major part of the food resources for the macrobenthos, but might turn into an environmental stressor for the macrobenthos when the concentrations are high enough to interfere with the species' filtering and respiratory systems.

Main objectives are:

1. Investigating the structuring role of SPM on the macrobenthic community structure;
2. Test the hypothesis that macrobenthos thrives at intermediate SPM concentration levels.

Therefore, relationships between SPM and benthic communities have been investigated using a vast amount of spatially-explicit information on the macrobenthos (e.g. Degraer *et al.*, 2008), surface SPM (e.g. Nechad *et al.*, 2010) and sediment composition (e.g. Verfaillie *et al.*, 2006; Degraer *et al.*, 2008). Explanatory variables were multivariate SPM concentration probability distribution classes (further called SPM classes), and the univariate D_{90} SPM concentration, indicative for the possible excess of SPM in the water column. Response variables were macrobenthic species richness, density and detrital feeding mode allocation. To extract the variability explained by sediment type from our analyses, sediment characteristics (i.e. five median grain-size classes and one Folk[2] class) were used as co-variables throughout the study. For more information on data availability and data selection procedures (see Annex 6, Rodriguez Palma et al., this report).

2.4.2 More sustainable practices of human activities

a. Allocating efficient disposal grounds

Sediments dredged in the port of Zeebrugge and in the navigation channels are disposed on designated disposal grounds. The dredged matter consists mostly of fine-grained material that is easily resuspended after disposal. Recirculation of the disposed matter, towards the nearby dredging places (port of Zeebrugge and Pas van het Zand), is therefore expected and results in an increase of sedimentation; hence decrease of efficiency of dredging operations.

For the dispersal of the fine-grained sediments, simulations with numerical models have been carried out to:

1. Simulate the dispersion of disposed fine-grained matter, see §2.2.2 and Fettweis *et al.* (2010b), former Q4D reports (Van Lancker *et al.*, 2009); and Annex 3 (Van Lancker et al., this report);
2. Investigate the efficiency of existing disposal locations (B&W S1, B&W S2) and the fictive disposal site Zeebrugge West, as alternative for the disposal site B&W Zeebrugge Oost, see §3.4.2a and Fettweis *et al.* (2010b);

Currents and surface elevation have been modelled using an implementation of the COHERENS hydrodynamic model for the BPNS, termed hereafter OPTOS-BCS (Luyten *et al.* 1999). In this application, 3D results of current velocity and water elevation, together with the bottom shear stress have been used. The sediment transport model solves the 2D depth-averaged advection-diffusion equation for cohesive sediment transport on the same grid as the OPTOS-BCS model. The values of the different parameters in the simulations have been determined through calibration, after consultation of published values in literature (Fettweis and Van den Eynde 2003), and based on erodibilty measurements (§2.2.1a).

The importance of both suspended and bedload transport in assessing the efficiency of dredging operations is discussed in Annex 3 (Van Lancker et al., this report). The assessment is based on repetitive multibeam data, in combination with current profiling (ADCP) and bed and water sampling.

b. Beach nourishments

The integrated morphological evolution, as described in § 2.3.1.a has been used to formulate recommendations on more optimised beach nourishment schemes.

[2] The Folk classification (Folk, 1954) determines the seabed type based on the gravel percentage and the sand to mud ratio. Here, a modified Folk classification was used subdividing the BPNS into the sediment types mud to sandy mud; muddy sand to sand; and coarse-grained sediments.

c. *Large-scale aggregate extraction*

Already since the late 70's, marine aggregates are being extracted from the BPNS, mostly on sandbanks. It was long believed that natural dynamics could compensate the sediment losses. However, recent studies showed that resources are not renewable and that intense extraction (e.g. $>1000 m^3$ per cell of 50 x 50m and per year) leads to depressions in the seafloor (Van Lancker *et al,* 2010a,b, for an overview; Roche et al., 2011) that do not show physical recovery (e.g. renewed sedimentation) on a 10 yrs time. To date extraction amounts up to 2.10^6 m^3/yr, but in the near future the amount may raise up to $2.9.10^6$ m^3/3 months, likely using large vessels (up to 12.500 m^3). The concession area is 46 km^2 (Hinder Banken region, at more than 35 km from the coast), subdivided into 4 sectors (4.4 to 19.1 km^2 per sector). Such large-scale extraction, mainly for beach nourishments, is a new practice in the BPNS. Environmental impacts are yet to be determined. Seabed type is coarse to very coarse sands.

Q4D anticipates through:

(1) Assessing the effect of large-scale aggregate extraction in the far offshore area on wave conditions on the Belgian part of the North Sea, including the coast. As such, also improving the understanding of sandbanks in the overall protection of the coastal area.

The coupled wave-current model was used (§2.2.2), with water-levels and currents being obtained from the COHERENS v2 model, and transferred to the SWAN wave model. One particular storm event in November 2005 was modelled, with wind and waves from the north-west. Measured significant wave height at the offshore sandbank was about 4 m. Such wave conditions are strong, but not exceptional, i.e. one can expect several storms per year of this magnitude. Two datasets were used for the bathymetry: 1) the standard coarser resolution (800 x 800 m) bathymetry of the COHERENS model implementation for the BPNS and the high resolution (300 x 300 m) bathymetry (Van Lancker *et al*. 2007). Generally, results are similar, though the effects are somewhat more pronounced using higher spatial resolution; only the latter are reported here. See Liste Muñoz *et al*. (2011) for detailed methodology.

(2) Providing hindcast hydrodynamic and sediment transport data (currents, waves, bottom shear stresses, total load transport, bed evolution, together with hydro-meteo conditions) over the past decade (1999-2010) to calculate seabed mobility over the BPNS. As such, data are provided that support the evaluation of monitoring results on sediment volumes (e.g. from multibeam). Natural variability can be assessed and evaluated against human-induced changes (e.g. from Electronic Monitoring Systems, and monitoring results) (see Annex for more details and a case study). The current-wave modelling suite (methodology see § 2.2.2), coupled to sediment transport modelling modules (Van den Eynde et al., 2010) was used. The following figure shows the modelling workflow.

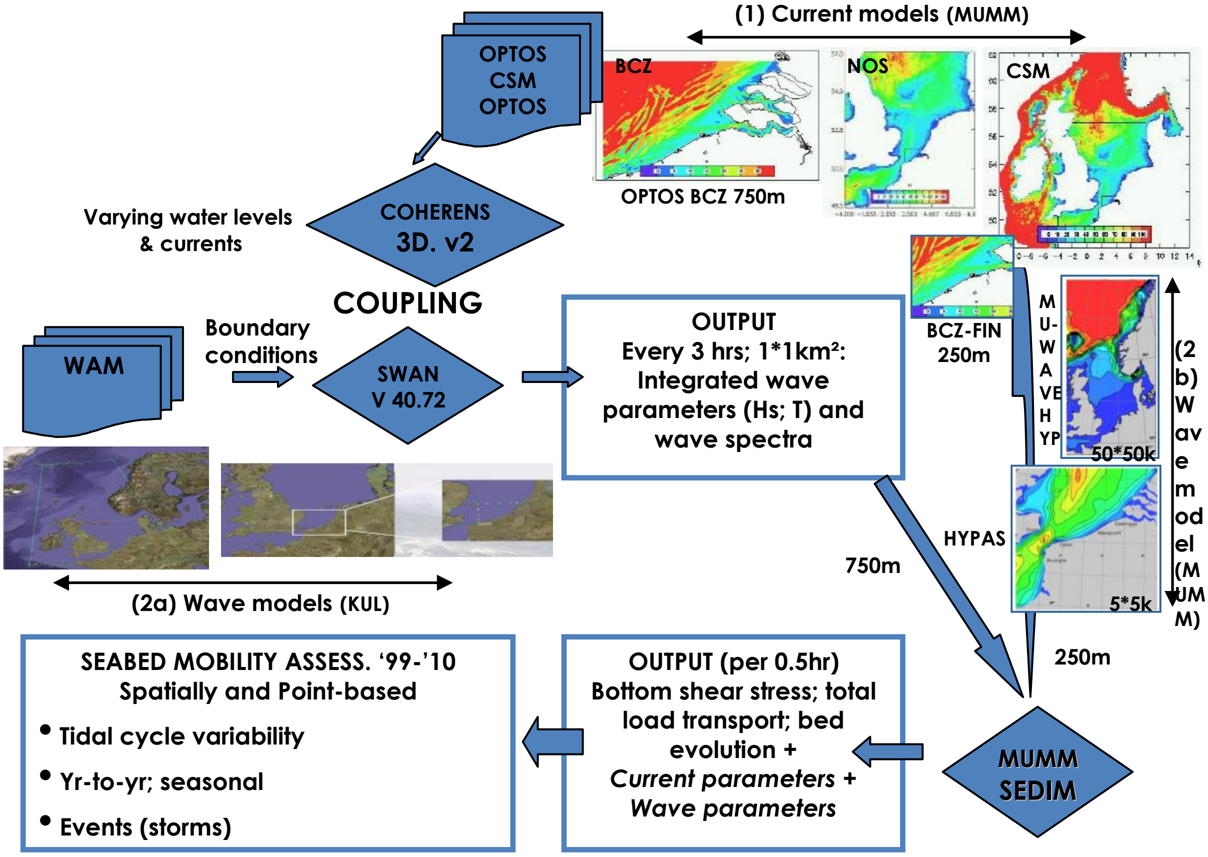


Figure 2.3-5. Modelling Workflow to assess seabed mobility, using the combination of current-wave and sediment transport models.

2.5 Data management

New and innovative approaches have been developed to manage the Q4D datasets. For the first time, the Belgian Marine Data Centre (BMDC) imported datasets with very high sampling rates that were derived from a multitude of sensors, mounted on benthic tripods and measuring over long time periods. In addition to fixed stations, data were also available that were measured during trajectories or vertical profiles, again from different sensors. These measurements were supported by data from operational models, also needing storage. Additionally, management was required of geological (e.g. vibrocores) and geophysical (e.g. side-scan sonar, multibeam and seismics) data. Internationally agreed guidelines and standards are being followed for all of these datasets, thanks to BMDC's involvement in large data infrastructure projects (FP7 I3), such as SeaDataNet (www.seadatanet.org/) and Geo-Seas (www.geo-seas.eu), respectively on the management of ocean and marine data, and on geological and geophysical data. Some of these European data transport routines are still in development, but after finalization, the Q4D datasets will be available through these European data portals. See Annex for more detailed information.

At present, the Q4D database (http://www.mumm.ac.be/datacentre/Databases/QUEST4D/) includes erosion rates at different excess shear stress values, bulk densities, grain size parameters, and the high resolution data series on temperature, salinity, optical backscatter, turbidity, currents and material in suspension, from LISST, ADV, OBS and CTD instrumentation mounted on a benthic tripod. Also, the historical Gilson datasets (~1900) on sediment and macrobenthos are processed for import. For importing the results of the operational OPTOS-BCS model (sea surface elevation, and salinity, current, temperature, turbulence kinetic energy and turbulence dissipation rate profiles; calculated twice a day, at stations relevant for the project) new routines have been developed. Due to the high amount of data (10'-previsions for 5 days), that would impose a lot of processing work for the user, and requiring high storage capacity with superfluous network traffic, only the best calculations, transposed into vertical profiles, were imported together with the necessary metadata. The resulting data structure is more flexible for changes in the model, f.e. calculation at more depth levels. Future perspectives are the development of an on-line query interface allowing user-defined queries. Meanwhile, requests can be executed on demand. For the benthic tripod data, differences in sensor heights were accounted for. Data were reorganized in files for every sensor, situated correctly in vertical space. A clear header was added, documenting parameters and units.

Guidelines were provided for clear and consistent file names, especially for files containing data cycles with a high sampling rate, maps and model results. Besides file names and meta information, file formats were defined for every type of data series. The user interface for the high resolution data series enables downloading series of measurements after the selection of the metadata. Queries or further processing (derived parameters, statistical summary parameters) on the contents of data series are performed and evaluated on demand.

Regarding the international data management guidelines and standards, the common data transport formats (e.g. ODV4 ASCII format), as well as the standard controlled vocabularies of SeaDataNet and Geo-Seas are followed. BMDC ensures that all information can be converted to the more generalized SeaDataNet ODV4 files in the case of profiles, time series and trajectories and to NetCDF for gridded data. The meta-information will be used to construct the Common Data Index (CDI) XML records as index to individual data sets in the Seadatanet and Geo-Seas portals.

3. RESULTS

3.1 Introduction

In the following sections, an overview of important findings is given. Some of them are formulated as hypotheses. They represent new insights in the driving forces of sediment transport, as well as benthos changes. A baseline of macrobenthos occurrences is provided also.

3.2 Natural variability of sediment processes

Hyp. 3.2.1: Cohesive and non-cohesive SPM dynamics occurs simultaneous

SPM concentration data from 2 m above the bottom (mab) as derived from ADP and OBS and the median particle size derived from LISST, from the tripod deployments at Blankenberge, have been analysed. The different entropy groups, as well as the low-passed filtered tidal PSD during tide-dominated conditions showed distinct multi-modal behaviour. Size class spectra are dominated by microflocs with rising tail in the lower size classes during maximum flood velocity, suggesting partially disruption of microflocs into primary particles (Baeye *et al.* 2011). It was therefore astounding to see that during SW storm conditions, when turbulence is even higher due to wave action, no primary particles were detected by the LISST. The PSD was log-normally distributed, uni-modal and remained almost constant (40 μm). The SW storm was characterized by lower SPM concentration (OBS) suggesting possibly that the flocs were transported away from the measuring location by wind-induced currents and replaced by sand, resuspended by wave action. The latter would also explain the absence of a rising tail in the LISST size spectra, as observed during flood. The ADP backscatter data confirm that sand was resuspended. The very low OBS signal during the storm is, however, probably significantly caused by the sensitivity of OBS to varying particle sizes, as the OBS was not calibrated for sand, but mud. Limitations associated with optical and acoustic instruments have been addressed in literature (Bunt *et al.* 1999; Fugate and Friedrichs 2002; Voulgaris and Meyers 2004; Hamilton *et al.* 1998; Thorne *et al.* 1991). Situations when changing suspended-sediment size can produce apparent variations in SPM concentration have been reported by Downing (2006), and include co-mingling of flows carrying different sediments.

Hyp. 3.2.2: Highly concentrated mud suspensions form under storm conditions

Between autumn 2005 and winter 2007, three storm periods have been selected with similar wave conditions from the MOW1 and Blankenberge tripod data (see §2.2.1b). The data show that during or after a storm, the SPM concentration increases significantly and that HCMS are formed. SPM concentration is clearly related to high waves and winds. An example of a storm period is presented in Figure 3.2-1; we refer to Fettweis *et al.* (2010a) for a detailed description of the results. The formation of HCMS in wave-dominated areas is well documented in the scientific literature (de Wit and Kranenburg 1997; Winterwerp 1999; Li and Mehta 2000). The occurrence of fluid mud or HCMS on many continental shelves is associated with wave or current-driven sediment gravity flows off high-load rivers (Wright and Friedrichs 2006). However, the origin of the suspended matter in the southern North Sea and in the Belgian-Dutch nearshore zone has been mainly ascribed to the inflow of fine-grained sediments through the Dover Strait (Gerritsen *et al.* 2000), as no high-load rivers exist in the area (Fettweis *et al.* 2007a). The fluctuation of SPM concentration with time is complex and it is not always straightforward to identify the origin of some of the variations. Wind direction and advection of water masses, previous history and availability of fine-grained sediments in fluffy layers, the very soft mud deposits around navigation channels, and the erosion of medium-consolidated mud of Holocene age influence the SPM signal. The data suggest that for the generation of very high

SPM concentrations near the bed, significant amounts of fine-grained sediments have to be resuspended and/or eroded (Fettweis *et al.* 2010a).

The effect of winds on SPM concentration is variable and depends also on the wind direction and the availability of muddy sediments. Our data show that high SPM concentrations are often more closely related to advection (Velegrakis *et al.* 1997; Blewett and Huntley 1998) rather than instantaneous bed shear stress (Stanev *et al.* 2009). This confirms the idea that the Belgian coastal area can be seen as congestion in the residual SPM transport of the southern North Sea, rather than an important source of sediments (Fettweis and Van den Eynde 2003).

The largest reservoir of fine-grained sediments in the nearshore area consists of the medium-consolidated Holocene mud (Fettweis *et al.* 2009). Erosion behaviour measurements (see §2.2.1a) confirm that consolidated cohesive bed layers are difficult to erode by only fluid-transmitted stress as the critical erosion shear stress is about 10 Pa. Near bed shear stresses derived from the ADV data amount up to 40 Pa (see §2.2.1b) during the measured storms (see Figure 3.2-1). These values indicate that erosion of Holocene mud by fluid-transmitted shear stress can occur and that SPM could have been released into the water column from the Holocene mud fields under storm conditions. Still, in literature, it is well documented that a cohesive mud bed may be eroded and fluidised by waves (Maa and Mehta 1987; De Wit and Kranenburg 1997; Li and Mehta 2000; Silva-Jacinto and Le Hir 2001). The stresses induced by waves modify the strength of the bed and thus also the erodibility of the sediments. Mud pebbles are an indication of this type of erosion; they have been observed regularly in the area of investigation (Fettweis *et al.* 2009). Other important erosion mechanisms are due to the mutual interaction of cohesive and non-cohesive sediments (Le Hir *et al.* 2007): one can distinguish between sand grains moving on a cohesive substrate and erosion of mixed sediments. Thin sand layers on top of Holocene mud layers and mixed sediments have often been observed in the turbidity maximum area and could therefore act as a reservoir for fine-grained material that is only resuspendable under more extreme meteorological conditions.

Numerical model results indicate that, under normal conditions, the bed shear stress in the navigation channels and at location MOW1 and Blankenberge are lower than 4 Pa. The critical erosion shear stresses of in-situ samples in the navigation channels are, below the fluffy surface layer, generally higher than 4 Pa. The deposits of fresh mud below the fluffy layer in these areas forms thus a reservoir of SPM that will only be resuspended during periods with high shear stresses, e.g. caused by storms. The data suggest that a major part of the HCMS, measured at both sites, could have been resuspended from the very soft mud deposits in the navigation channels and adjacent areas. **This result is important as it suggest that the deepening of the navigation channels has made available fine-grained matter that contributes significantly to the formation of high concentration mud suspensions.**

Hyp. 3.2.3: The coastal mud fields have a distinct clay mineralogical fingerprint, resulting from a mixture of sources

Within mud deposits there is no systematic difference between sediments of different age (recent, Holocene) or with a different consolidation state. SPM in the turbidity maximum area has the same clay mineral composition as the cohesive bed sediments. Clay mineralogy of bed sediments and SPM, outside the coastal mud fields, is more variable and confirms that the mud fields are a distinct unit on the BPNS. The French coast east of Calais, the Westerschelde, the Schelde upstream Bath, the Holocene salt marshes and the Eemian intertidal deposits have identical or very similar clay mineralogies. The French coast west of Calais, the English coast, SPM from the Atlantic Ocean and the English Channel, the Paleogene clays on the BPNS, the Weichselian cover sands, Early Pleistocene and Late Pliocene deposits have a different clay mineralogy. The latter can thus be excluded as potential major provenance sources.

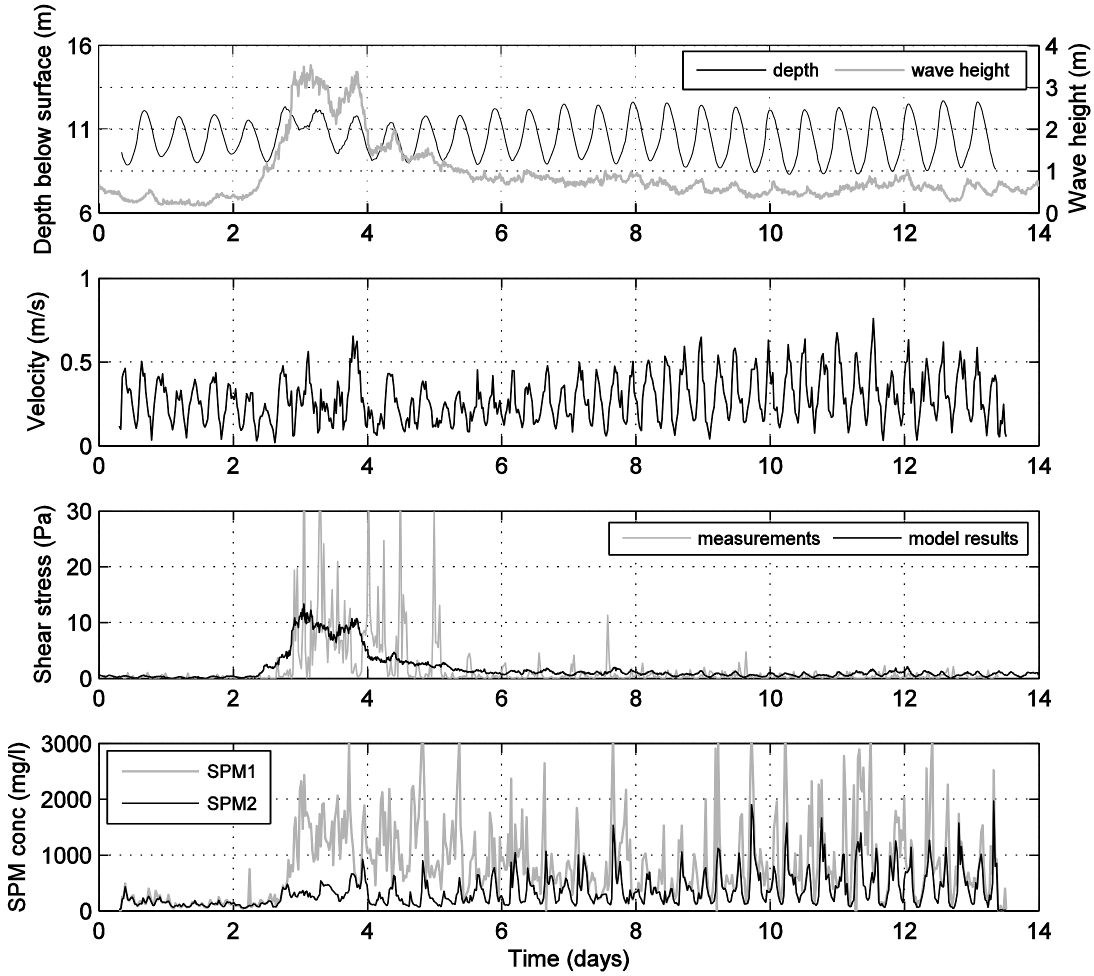


Figure 3.2-1. MOW1 site, tripod measurements of 22 November – 5 December 2005 (survey 2005/29). From up to down: depth below water surface (m) and significant wave heights; ADV current velocity (m/s); shear stress (Pa) derived from the ADV and from the hydrodynamic model and SPM concentration at 0.3 mab (SPM1) and 1.9 mab (SPM2).

Hyp. 3.2.4: Wind-induced advection affects sediment transport in distinct ways

<u>Cases for mud</u>

Tripod measurements show that near bed hydrodynamics and sediment dynamics, although dominated by tidal forcing, are significantly modified by wind-induced flows with different effects, depending on the wind direction, see Baeye *et al.* (2011).

SPM concentration measurements, under tidal forcing only, show concentration maxima occurring at the end of ebb and at the beginning of flood. Near bed hydrodynamics and SPM dynamics are predominantly dominated by tidal forcing. Generally, SPM concentration is significantly influenced by advection during ebb, whereas during flood local resuspension is more important.

SPM measurements, from OBS show that wind-driven alongshore advection has a significant influence on SPM concentration. A significant modification of the tidal forcing results from alongshore advection due to wind-induced flows and influences the position of the turbidity maximum; as such also the origin of SPM. <u>Winds persistently blowing from the NE will increase SPM concentration</u>, due to an increased SPM outflow from the Westerschelde estuary. <u>SW winds will decrease SPM concentrations</u>**.** The latter is related to the advection of less turbid

English Channel water to the measuring location, inducing a shift of the turbidity maximum towards the NE and the Westerschelde estuary. Under these conditions, marine mud will be imported and buffered in the estuary.

Altimetry data, derived from ADV, show bed level variations that can be explained by the formation of HCMS, see Figure 3.2-2. During low wind and SW wind conditions their occurrence is limited to slack water periods. SPM consists of a mixture of cohesive sediments (flocs) and locally eroded sand grains during high currents (see also §3.2.1). With prevailing NE winds, the increase in SPM concentration results in the formation of persistent HCMS. The damping of turbulence by HCMS layers is a major mechanism maintaining these layers during longer time periods (Sheremet *et al*. 2005; Reed *et al*. 2009). The results have indicated that these layers mostly remain present throughout the tidal cycle. Inverse armouring occurs, as the sandy bed is sheltered from erosion. SPM consists of cohesive sediments only. These winds are not very frequent and their wind speeds are rather reduced. However, we believe that this type of benthic sediment transport is very important and has implications for object burial and sediment recirculation in and around the port of Zeebrugge.

Cases for sand

For a case study of a near coastal sandbank Baland Bank, a principal component analysis allowed to differentiate sediment budgets of 8 consecutive bathymetric soundings against the directionality and strength of the sand transporting agents: winds, waves and currents. Generally, northeastern conditions are associated with the lowest sands volumes, whilst winds blowing from the southwest are clearly associated with a sand input (Figure 3.2-3). From the temporal observations, the consistency and hence duration of the prevailing hydro-meteorological conditions seems more important than the strength of the process. Due to the natural cyclicity in erosion/sedimentation, the area recovered fairly quickly from stormy periods. A publication of the results is underway.

For the area, north of the Vlakte van de Raan, time series of multibeam bathymetry over bedforms revealed for all observations, in the period 2006-2010 bedload transport in a SW direction, being opposite to the overall acknowledged NE directed water and SPM transport. This has major implications on dredging and disposal activities in these areas. Results are reported in Annex 3 (Van Lancker et al., this report.)Bedload transport rates still need to be determined, as also the relation with hydro-meteorological forcing.

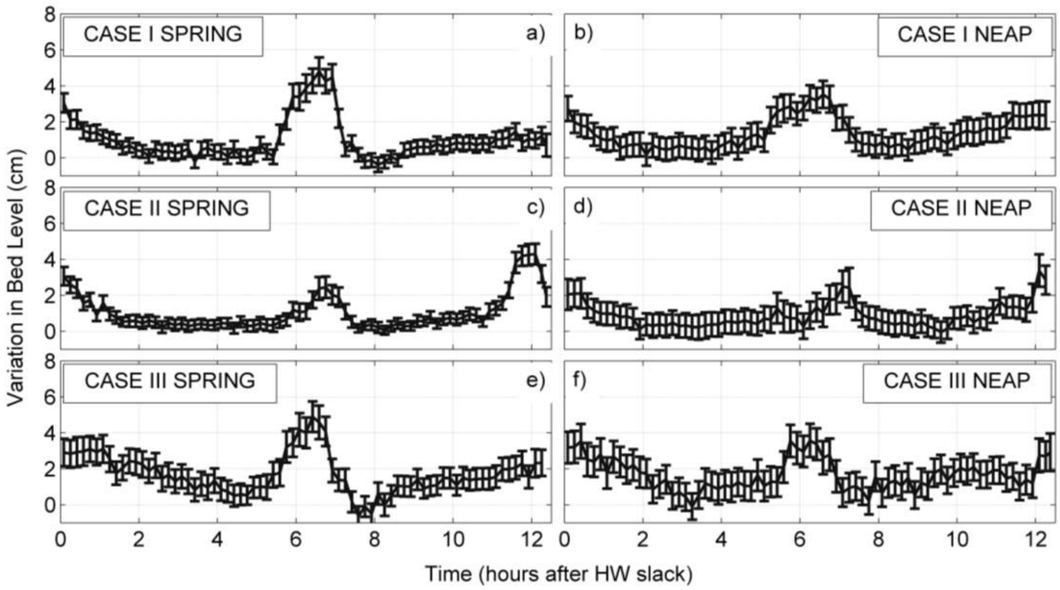


Figure 3.2-2. Average sea bed level change, derived from ADV, with standard errors bars. Case I corresponds with no (low) wind activity, case II with NE wind condition and case III with SW wind conditions.

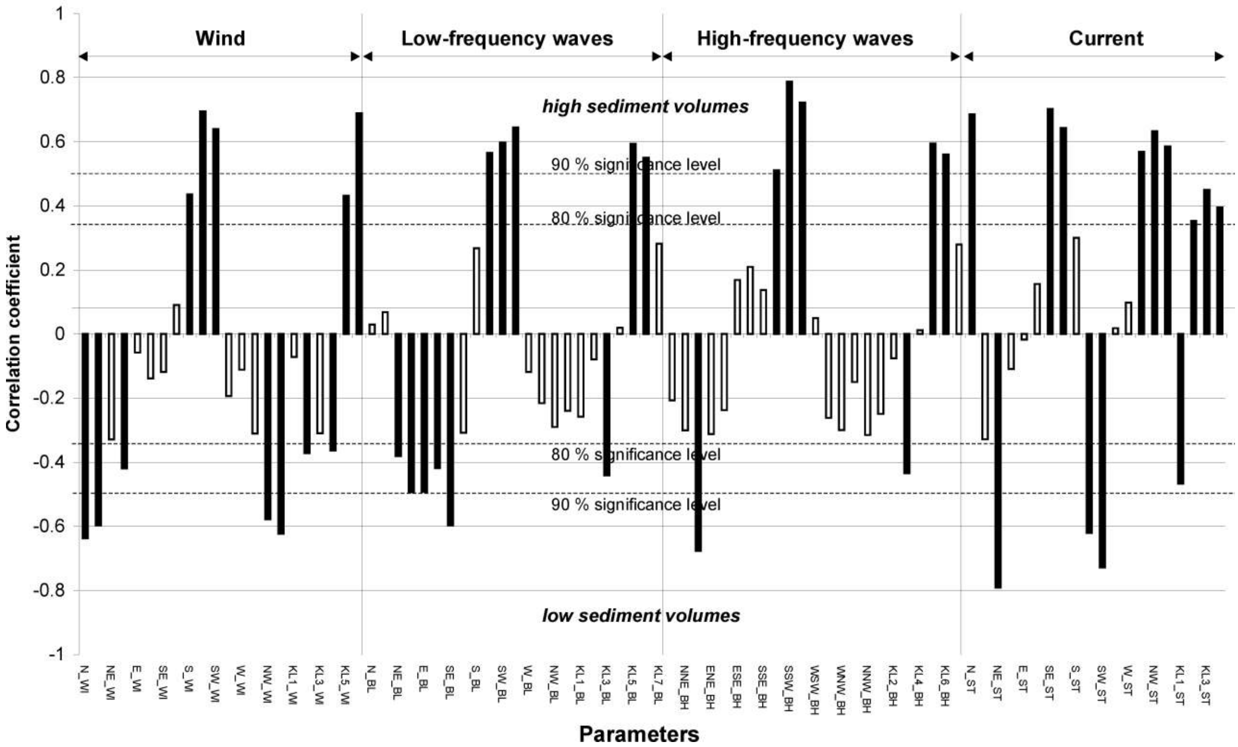


Figure 3.2-3. Correlation coefficient matrix obtained after an analysis of all hydro-meteorological data against sand budgets. The darkest colour represents a significance level of 90 %, the lighter colour a significance level of 80 %. The white columns represent values that tend to be insignificant. Sediment volumes are calculated from bathymetric chart differencing. WI refers to wind classes; BL and BH respectively to low and high frequency wave classes; ST refers to currents. KL1 to KL7 relates to increasing strengths of the agents.

Hyp. 3.2.5: Macrobenthos thrives where fine-grained material naturally deposits

Near the Belgian-Dutch border extensive small-scale sedimentation patches were revealed on high resolution multibeam imagery (Figure 3.2-3, for an overview of seabed features). From sampling, these could be related to dense aggregations (up to 6000 tubes per m²) of the tube-building polychaet *O. fusiformis* (Figure 3.2-4). They occupy areas of up to 12 km². The patches occur in-between large to very large dunes, which form sheltered conditions to the tubeworms. Multibeam time series show that the patches are stable, regardless extensive fishing activities in the area. Results were submitted for publication (Rabaut *et al.* in revision). From the intensive seabed mapping, in combination with current and turbidity measurements, and hydrodynamic modelling, it was shown that the occurrences of dense aggregations correspond to areas where fine-grained material naturally deposits: **(1) near bedload convergence zones, where sediment fluxes are higher and where settling may occur during slack water; (2) along the upper slope, where fines from the shallow part of the Vlakte van de Raan, whether or not also originating from disposal activities, are transported downwards the slope during the ebbing phase of the tide. The counteraction of flood-dominancy in the gully and along the foot of the slope with the ebb-dominancy along the upper slope will further enhance trapping and sedimentation of fine-grained material.** See Annex 3 (this report) for detailed information.

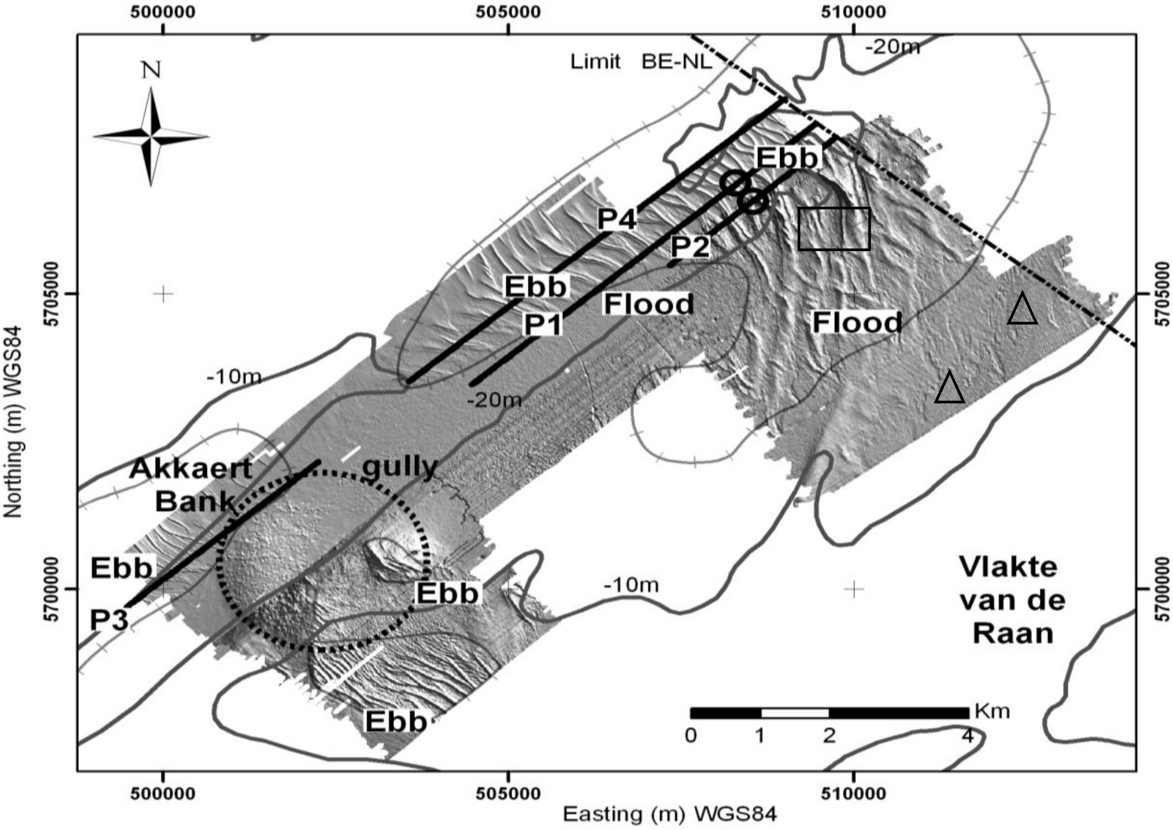
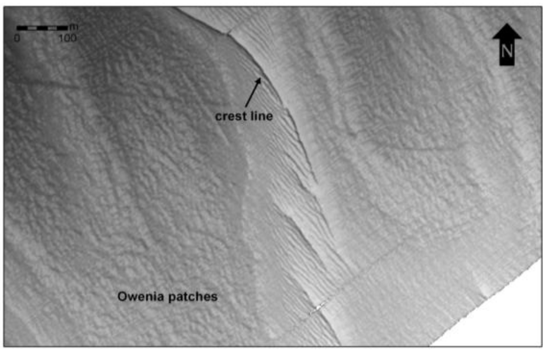


Figure 3.2-3. Detailed seabed morphology, as derived from multibeam seabed mapping. Areas with large dunes are observed south and north of the present disposal ground of dredged material (dashed circle). At the northeast extremity of the gully, a series of large complex dunes (up to 4m) are present. In the axis of the gully and towards the slope their asymmetry is clearly flood-dominated; this gully is a flood-dominated channel. However, in the prolongation of the Akkaert Bank, dunes show an ebb-dominancy. The broad end of the flood channel is a bedload convergence zone, where flood- and ebb-dominated sediment transport meets. Here, dense aggregations of the tube worm *O. fusiformis* occurs in the troughs of the dunes (rectangle, see Figure 3.2-4 for a detailed view), as also large quantities of *E. directus* juveniles, American razor blade and most important invasive species in the BPNS. Higher up the slope high densities of *O. fusiformis* and *E. directus* adults occur (triangle). Four profiles (P1 to P4) are indicated along which bedform evolution was followed (see Figure 3.2-5 and Annex 3). The circles on profile P1 and P2 indicate where flood- and ebb-dominated dunes converge. The intersected line represents the maximum extent of the bedform area, as derived from broad-scale DTM's.



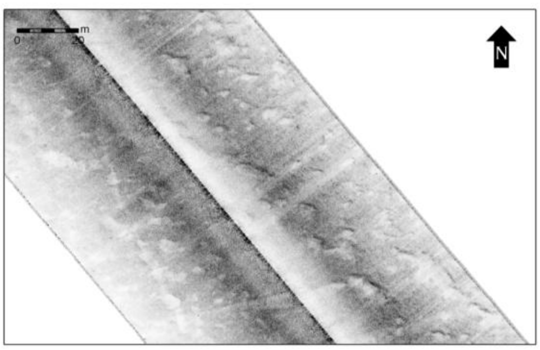


Figure 3.2-4. (left) Detailed shaded relief map of an area with very large dunes; in the troughs extensive fields of *O. fusiformis* are present (rectangle on Fig. 3.2-3); and (right) detailed side-scan sonar mosaic, showing individual *Owenia* patches.

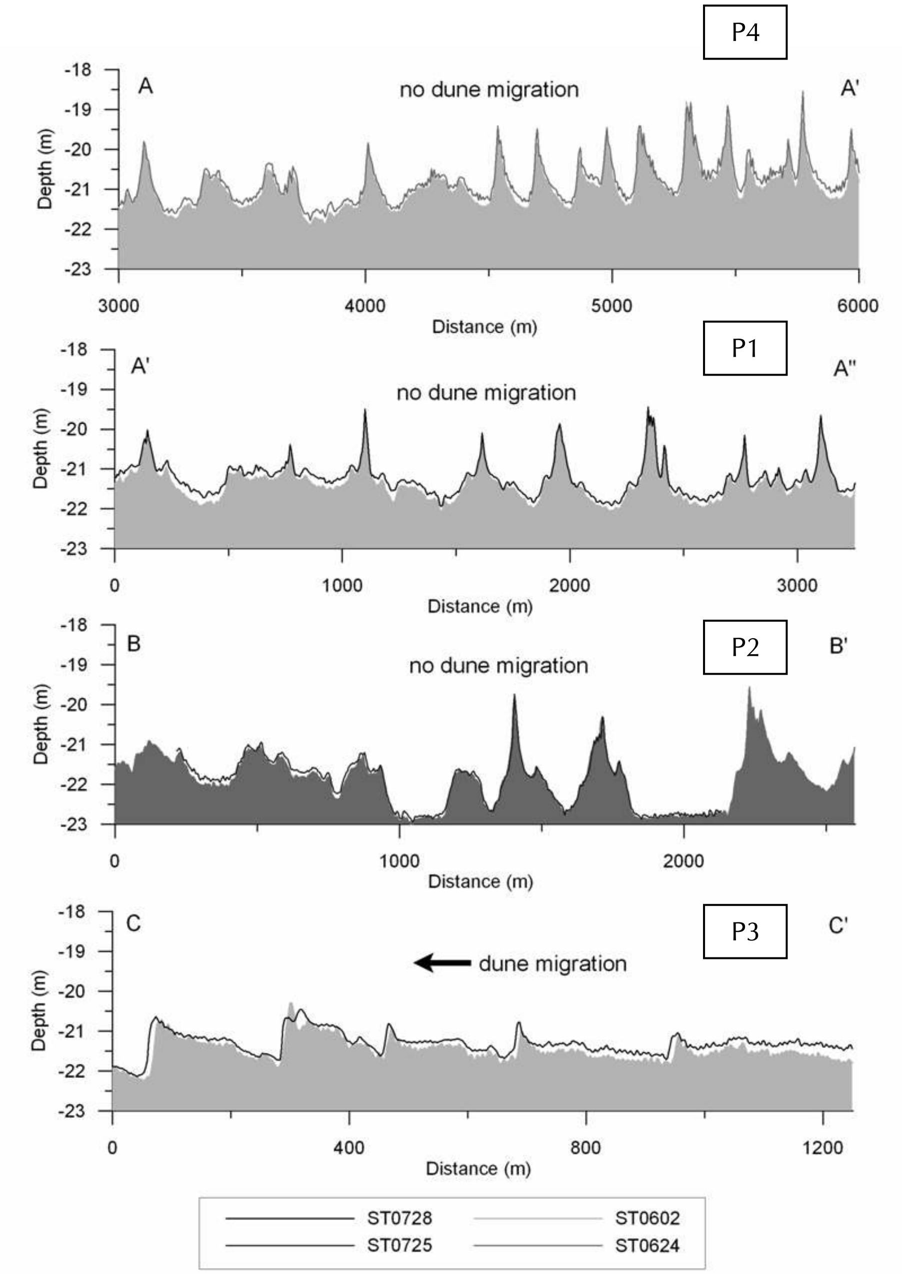


Figure 3.2-5. Cross-sections based on the DTMs of successive bathymetric surveys aligned transversally to the dunes (2006-2007). Only dune migration is observed north of the disposal ground S1 (up to 20m in SW direction). Vertical scale x30 exaggeration. For location, see Figure 3.2-3. The evolution in the period 2008-2010 is given in Annex 3, this report.

3.3 Quantification of ecosystem changes during the last century

Results are given from a large- to small-scale. More detailed evolution of sedimentary characteristics is discussed in case studies; results are provided on a short-, medium- and long-term. Hypotheses are formulated, highlighting most important findings.

3.3.1 Establishment of a historic reference (early 20th century) for sediment and soft substratum macrobenthos in the BPNS

From the calibrated visual descriptions of sediment samples, an integrated map of sediment types (Figure 3.3-1) was produced. This map represents a considerable improvement, compared to the previous reference sediment map of Van Mierlo (1899), being very difficult to interpret, because of a lack of calibrated visual descriptions and the limited amount of sampling stations (n = 300). Even though important constraints result from the historic nature of the data (e.g. qualitative nature of the processed information, sand grain-size being limited to two broad categories, separation between biogenic and mineral components), the map provides very accurate information on the historic distribution of various sediment types, which are discussed in more detail in Houziaux *et al.* (under revision). For instance, the 'mud fields', *i.e.* areas with very high contents of grains smaller than 63 μm, clearly appear as a major (and natural) characteristic of this part of the southern North Sea.

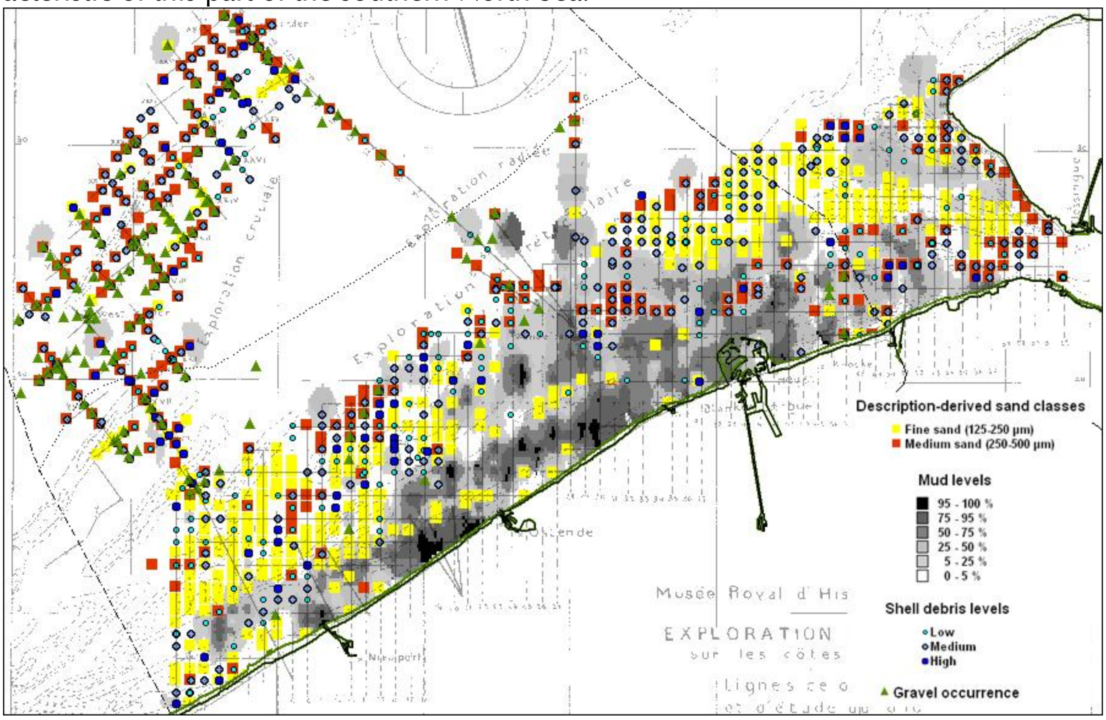


Figure 3.3-1. Integrated map of historic seafloor composition, as inferred from the calibrated visual descriptions of sediment samples. Data are mapped onto the original map of Gilson (1914). The modern coastline is superimposed in green. The limits of the BPNS, as well as the 12 nm line are shown as dotted black lines.

Offshore, gravel fields and coarse neritic sands are evidenced, as already mentioned in Houziaux *et al.* (2008). In coastal waters, large patches of fine sands are observed more at the Western and Eastern sides of the sampling grid, while coarser sand patches are smaller and more scattered; they mostly coincide with large amounts of shell debris.

In the same area, overall abundance and species richness of macrobenthic species (endobenthos and epibenthos) could be mapped at the dredge stations (Figure 3.3-2). It must be stressed that some work remains to be carried out on species for which limited information was gathered (mainly polychaetes). An integrated sediment – macrobenthos analysis could thus far not be carried out due to technical issues yet to be solved (e.g. combining multiple point sediment data with benthos information, acquired with a towed dredge). However, superimposing the sediment and macrobenthos maps do provide some insight into the former structure of benthic biodiversity and seabed habitats.

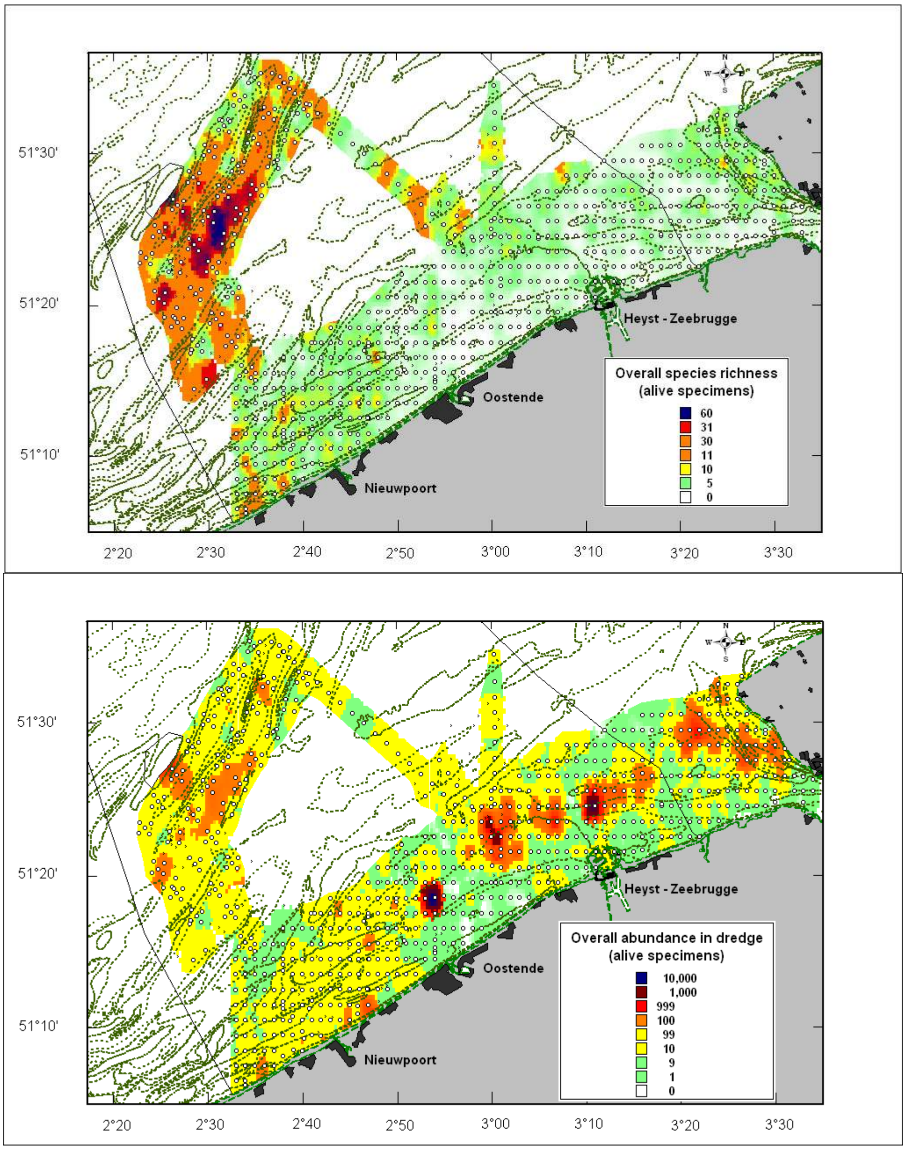


Figure 3.3-2. Interpolation maps (Inverse Distance Weighting, Search radius = 2 km, cell size 0.5 km) of total species richness (above) and total specimen abundance (below) at accurately geo-positioned dredge stations, mostly for the period 1899-1911. Historic data were mapped onto the present-day bathymetry and coastline.

As shown previously (Houziaux *et al.* 2008), the offshore gravel grounds sheltered the highest levels of species richness, much contrasting with the species content of the surrounding sandy sediments. The coastal – offshore gradient of species richness as suggested by Govaere (1980) and Cattrijsse and Vincx (2001) is again confirmed for the historic situation. In the coastal waters, a gradient of increased macrobenthic species richness is observed from the Dutch to the French border, similarly in agreement with recent observations (see Cattrijsse and Vincx 2001). However, the cross-border distribution of total abundances reveals that highest overall densities of macrobenthic organisms were encountered at some distance off the Eastern coast, in coarse sand patches characterized by high levels of turbidity (Fettweis and Van den Eynde 2003), and in a large patch of moderately muddy sediments along the Dutch coast of Walcheren; here high macrobenthic densities are clearly restricted (see Annex 4, Houziaux, this report). In Belgian coastal waters, species richness is very low, and overall abundances are dominated by very few bivalve species. In Dutch waters, slightly more species contribute to the observed overall densities. The area of maximum densities off Zeebrugge largely coincides with the present-day position of artificially deepened navigation channels. Unfortunately, only few macrobenthos samples are available for recent times; this hampers direct long-term comparisons (see §3.3.5). Noteworthy, the coastal areas with high mud contents ('mud fields') (see Figure 3.3-1) were almost devoid of macrobenthic species in the historic situation. Highly concentrated suspensions at the sediment surface probably create harsh conditions for benthic organisms to thrive. These suspensions may occur due to permanent erosion of consolidated (ancient) mud or to permanent depositional trends. According to Fettweis *et al.* (2009) mud deposition likely occurred in this area prior to 1900, resulting in a shallowing of the Grote Rede trough in the period 1866-1911. Thus, the data point at absence of benthos due to deposition of muddy sediment in this area.

The historical data provide useful 'baseline' maps and more specific investigations can now be carried out to better understand long-term ecosystem changes. Unfortunately, these maps can hardly be directly compared to the recent situation, mostly because of: different spatial spreading of samples (which were very much project-oriented in the recent situation); different sampling strategies (in the recent surveys; separation of endobenthos and epibenthos, through more specific sampling gears); and different outputs (e.g. recent sediment data all originate from quantitative analysis of grain-size distributions; macrobenthic data obtained with contemporary sampling gears are more 'quantitative'). Nevertheless, it is remarkable that the historical data provides patterns of distribution for maximum species richness (in the limitedly studied offshore gravel fields) and abundance (in the maximum turbidity area) which were largely unexpected based on the recent information available (e.g. see Degraer *et al.* 2006). The unique combination of endo- and epibenthic species may reveal ecological patterns in the composition of benthic communities (e.g. prey-predator relationships) once some pending questions – e.g. on polychaete data).

The importance of these historic data to better understand how human activities alter marine ecosystem functioning in the long run is discussed below (see Hyp 3.3.5). It builds further on the results of Houziaux *et al.* (2008), focusing specifically on gravel grounds. Present results on the soft substratum of the coastal area provide a unique view on the sedimentological and ecological continuum existing across the Belgian-Dutch border, more specifically in the Westerschelde River mouth area; this will likely constitute an important basis for future cross-border investigations.

3.3.2 Natural seabed changes vs anthropogenic influence?

a. *Enrichment of fine sands*

For the period 1900-2009, sediment changes in the sand fraction were studied based on cumulative grain-size distribution curves (SediCURVE@SEA, Van Lancker *et al.* 2009). For the median grain-size (d50), no major or consistent changes were found over large areas. However, striking differences were found when evaluating the sorting and skewness of the sediments. Figure 3.3-3 shows the sorting of all sediments of the Gilson collection: except for some locations where gravel or shell hash prevails (e.g. offshore sandbanks or areas with bedforms), all sediments are well-sorted. This is not the case for the recent sediment samples, now showing an overall worsening in sorting over vast areas. For clarity, Figure 3.3-3b shows only the distribution of the moderate to poorly sorted sediments. Noteworthy is the observation that this trend only occurs in the coastal zone; though also along the area with newly implanted windmills, offshore. To explain the cause of the wide-spread worsening of sorting, the skewness was evaluated for these locations. Figure 3.3-3c shows that the poorer sorting seems solely due to an enrichment of (very) fine sands. Although, more consistent patterns occur around harbours, near disposal grounds and aggregate extraction sites, the trend is widespread and also occurs in so-called 'natural systems', such as the Westdiep-Broersbank system.

b. Long-term morphological evolution BPNS: erosion of sandbank troughs, migration of sandbanks

The erosion-sedimentation map of Figure 3.3-4 is the result of trend analysis on the historical navigation charts and spans a period from ~150 years ago up till now. Only trends with $R^2 > 0.5$ are shown, and the scale is chosen to distinguish only 4 different types of trends (erosion-sedimentation, magnitude lower/higher than 2 cm/year). A finer scale would give a false impression of accuracy, which is not guaranteed by the historical navigation charts.

Many significant morphological changes are the result of human activity: deepening due to dredging of the navigation channels towards the harbour of Antwerp (Scheur) and Zeebrugge (Pas van het Zand) and towards Ostend, where the navigation channel cuts through the Stroombank; accretion due to dredge disposal on the locations S1, ZBO (near Paardenmarkt shoal), and OOS (near Ostend, on the southwestern tip of the Wenduinebank). A clear sedimentation trend can also be observed in the shelter of the breakwaters of the outer harbour of Zeebrugge.

Results (based on the trend analysis, but also on visualization of depth contours, not shown here) also indicate that there is no significant movement of the sandbanks during the last 150 years, though some banks (especially the Coastal Banks: Small bank, Nieuwpoort Bank, Ostend Bank and Wenduine Bank) seem to be prone to erosion at the seaward side and to sedimentation at the coastal side; this could indicate minor movement towards the coast. However, taking into account the relatively large uncertainties on both position and depth values of the original data points, this movement cannot be considered significant, though it must be noted that none of the banks showed the opposite effect (seawards movement).

Nevertheless, the Coastal Banks are the most naturally dynamic zones: significant sedimentation trends are observed for the Nieuwpoort Bank, the Wenduine Bank and the Stroom Bank, while erosion occurred in the troughs between the banks: between the Stroombank and the coast (Kleine Rede), at the seaward side of the Stroombank (Grote Rede), and north of the Small bank and of the Kwinte bank.

It is interesting to note that the long-term trends observed here seem to be confirmed by the medium-term analysis of the coastal offshore zone. This is illustrated by Figure 3.3-5, which shows the erosion-sedimentation trend of the past 15 years of the seafloor in front of Ostend and De Haan. The map shows a sedimentation trend on the landward side of both the Wenduine Bank and the Stroombank, while erosion occurs on the seaward side of both banks. The Grote Rede trough also seems mostly prone to erosion. Further analysis of the medium-term evolution is needed to support the hypothesized morphological evolution.

In front of Koksijde, an apparent accretion trend is found at the beach, shoreface and beyond (see Figure 3.3-6) which can be associated with the presence of two large groins (length:

~400 m). However, the sedimentation trend extends further than what could be expected from a local effect; hence the investigation of the accumulation of sediment in this area cannot be done without taken into account the influence of the shoreface-attached sandbank system (Broers bank and Trapegeer bank and the Potje trough). These naturally dynamic features exert a morphological control on the flow pattern, influencing the inflow of sediment in the area.

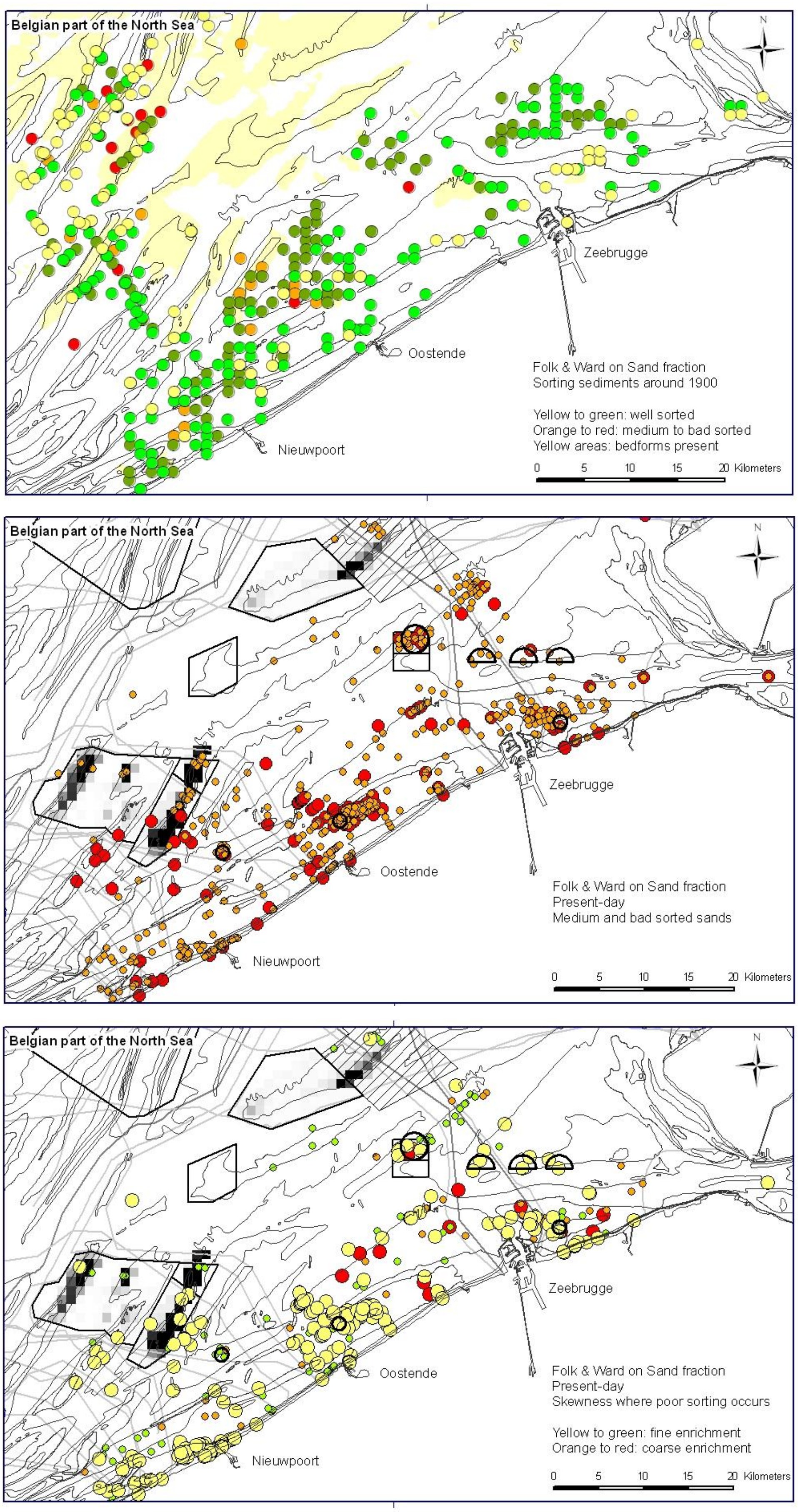


Figure 3.3-3. (a) Sorting of all re-analysed Gilson samples; (b) spatial distribution of recent sand samples having a moderate to poorly sorting; and (c) skewness of the nowadays moderate to poorly sorting sands. Analysis based on SediCURVE v.1 database.

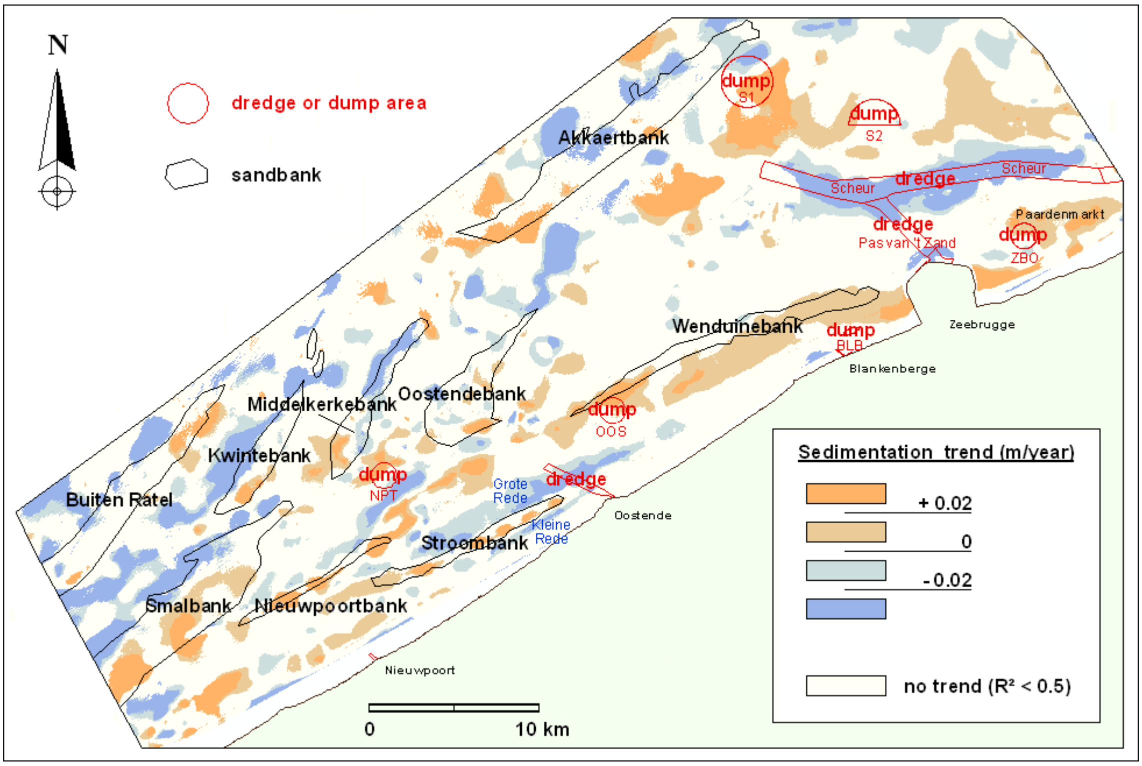


Figure 3.3-4. Erosion-sedimentation trend along the southwestern part of the BPNS, based on the bathymetric chart differences in the period 1866-2007.

In addition, it is argued that along the Belgian coast natural processes are able to drive large bathymetric changes: the part of the seafloor in front of De Panne and Koksijde has the least influence of human actions. The magnitude of the morphological evolution observed in the area surrounding the shoreface-attached sandbank system (trend in bathymetric change up to 15 cm/year) is comparable to that observed in the Zeebrugge area, where evolution is mainly driven by anthropogenic factors (presence of breakwaters, dredging and disposal activities). The morphological evolution of the shoreface-attached sandbank system is illustrated in Figure 3.3-7; it shows the bathymetric profiles on different dates along cross section A-B (see top figure in Figure 3.3-6 for the location of cross section A-B), together with a profile of the erosion trend.

3.3.3 Quantifying littoral drift

Based on the medium-term trend analysis of beach and foreshore in the area west of Zeebrugge, an estimation of the littoral drift can be made. The western breakwater of Zeebrugge harbour blocks the longshore transport of sediments along beach and foreshore, which is oriented from southwest to northeast along the Belgian coast. By quantification of the accumulation of sediments in the beach and foreshore area between Blankenberge and Zeebrugge, the magnitude of this littoral drift is estimated.

Figure 3.3-8 shows the result of the morphological trend analysis. Beach and foreshore between Blankenberge and Zeebrugge is divided in different zones, depending on the observed trend and origin of the trend (see caption figure for more detailes).

The total estimate of the net littoral drift from southwest to northeast along the Belgian coast –based on the measured volumetric trends and assuming no sediment is brought into the system from offshore areas– is calculated as 395 x 10^3 m^3/year.

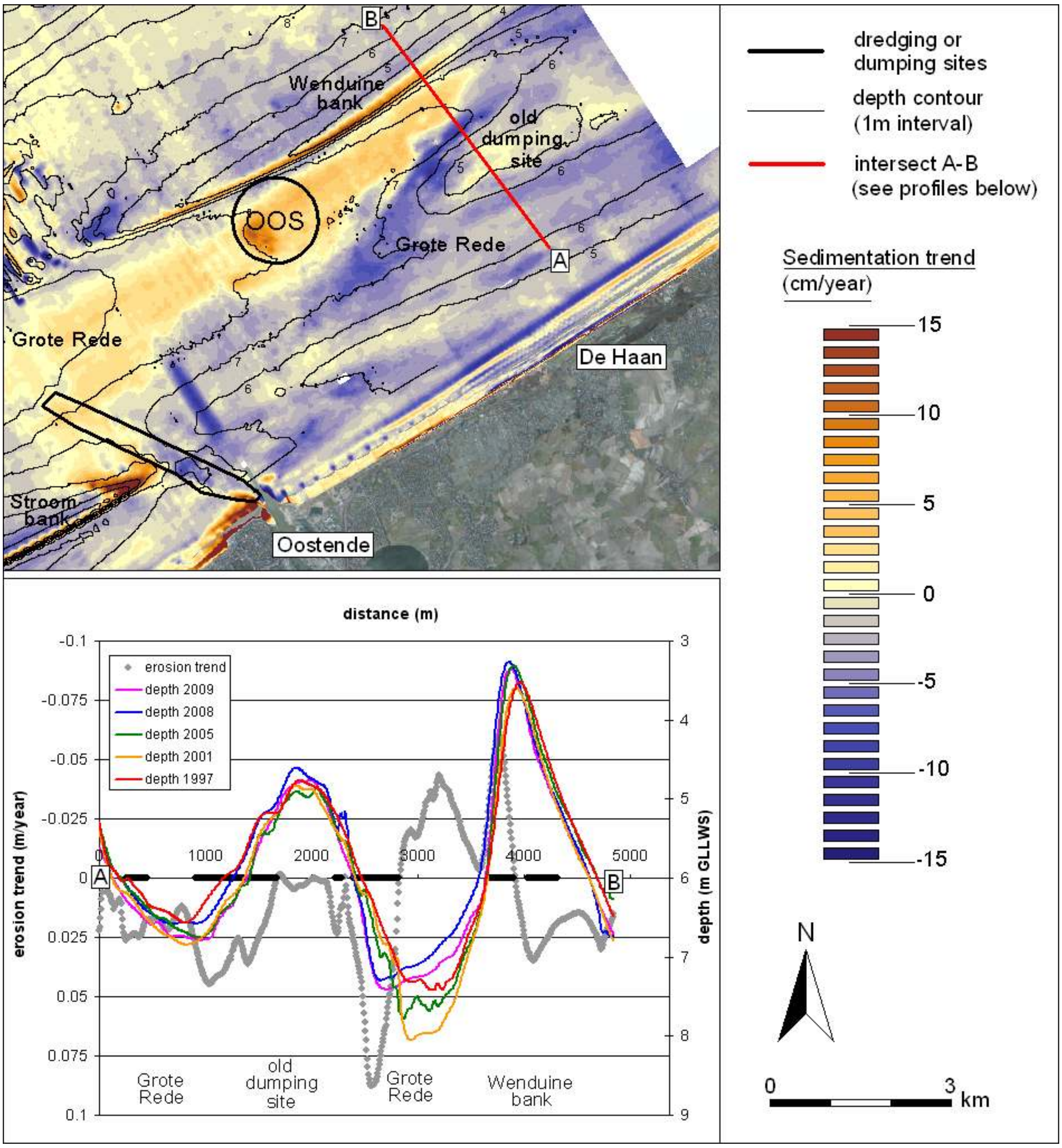


Figure 3.3-5. Top figure: erosion-sedimentation trend for beach, foreshore and the nearshore between Ostende and De Haan. Bottom figure: depth profiles (solid lines, right vertical axis) and erosion trend profile (dotted line, left vertical axis) along cross section A-B.

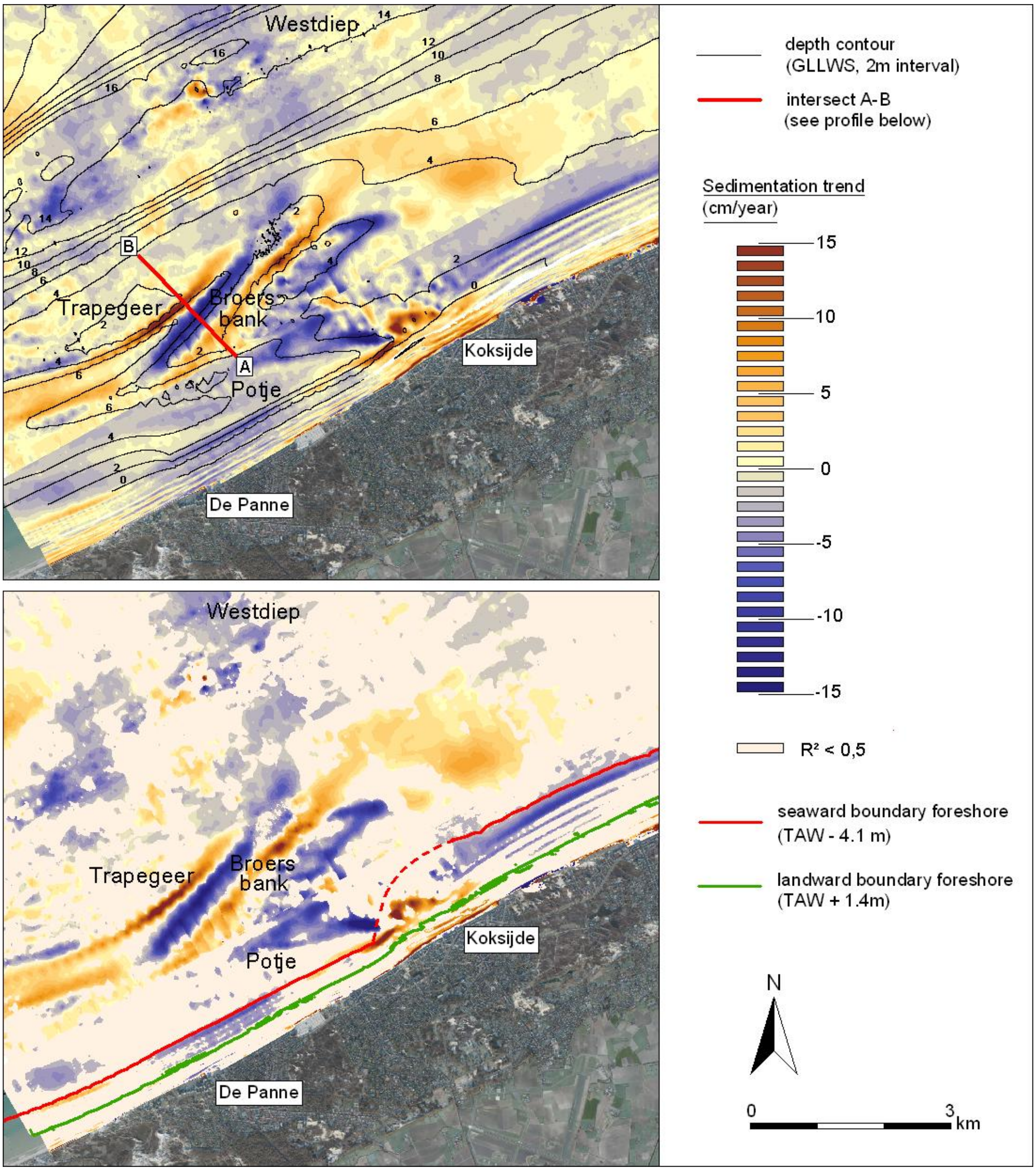


Figure 3.3-6. Erosion- sedimentation trend of beach, shoreface and nearshore in front of the Westhoek (area between De Panne and Koksijde). The top figure shows all trends; the lower figure only trends with $R^2 > 0.5$.

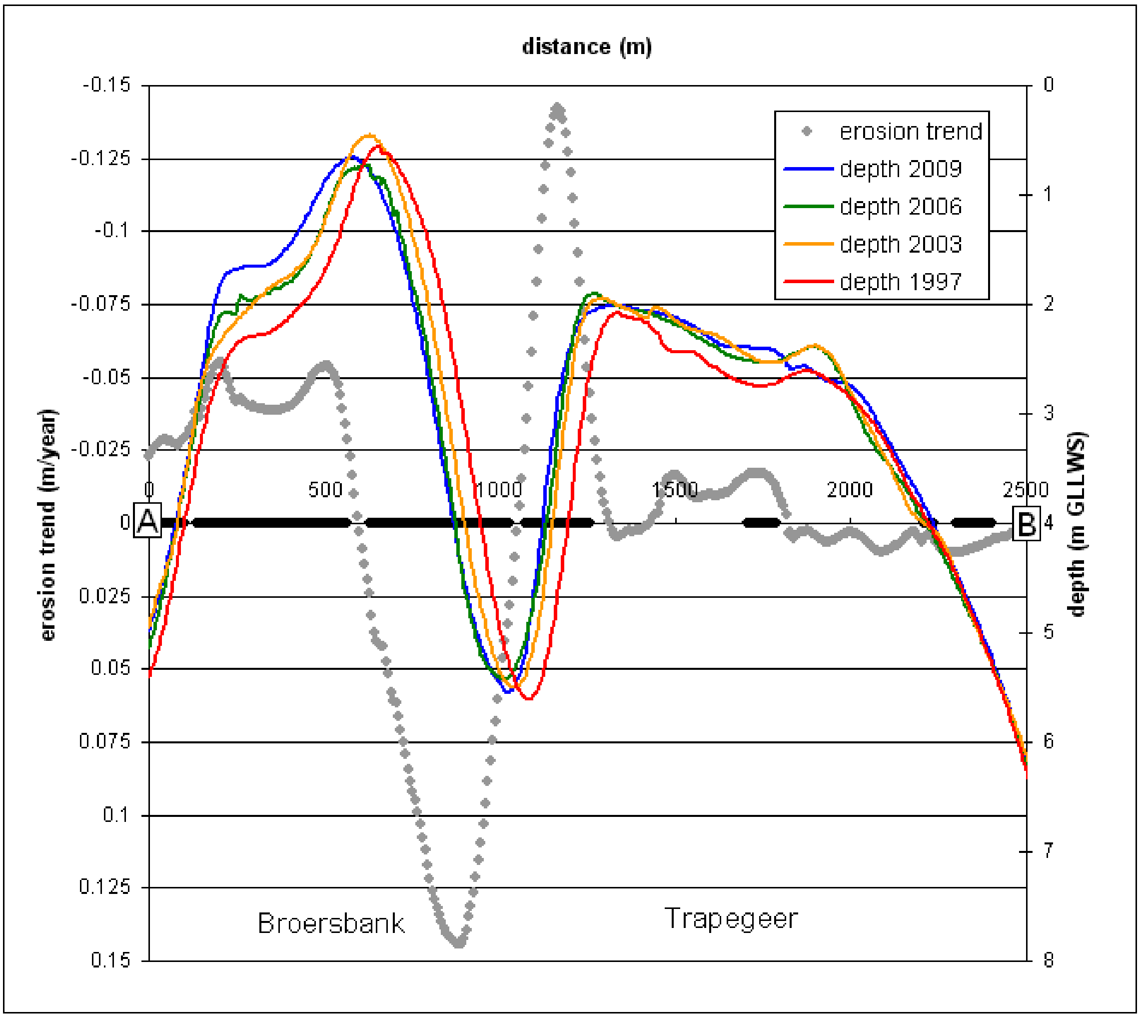


Figure 3.3-7. Depth profiles (solid lines, right vertical axis) and erosion trend (dotted line, left vertical axis) along cross section A-B. Bold parts on the horizontal axis indicate locations with significant trends ($R^2 > 0.5$).

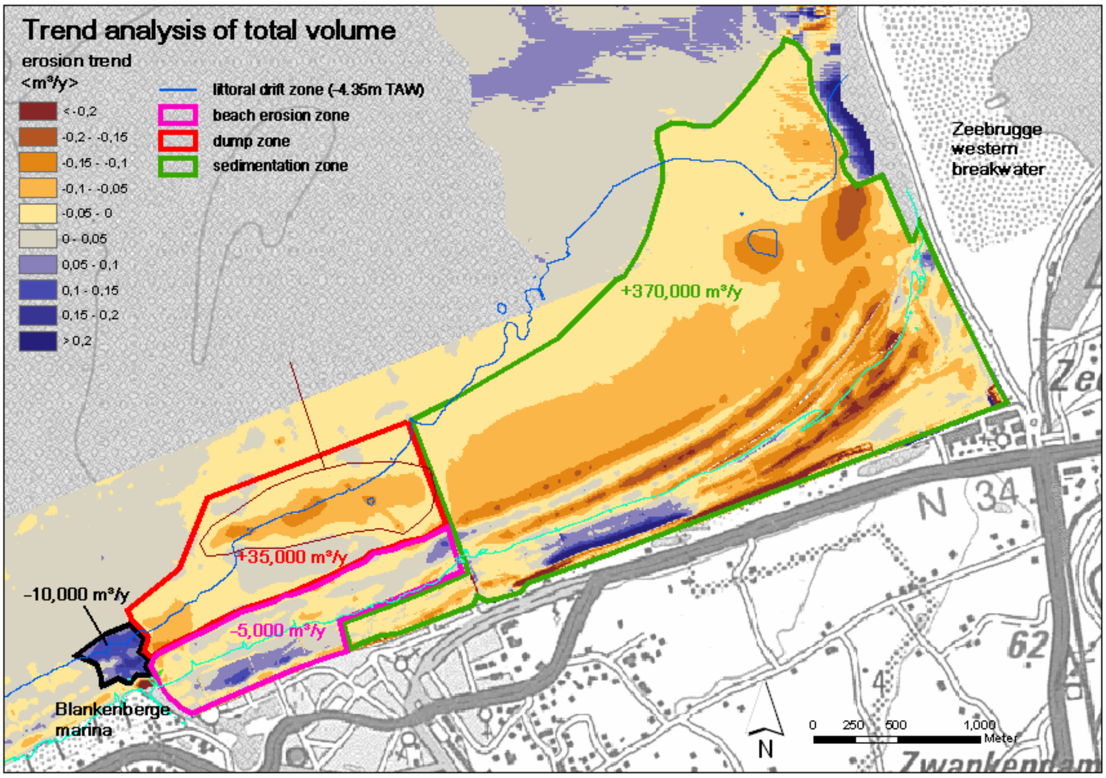


Figure 3.3-8. Result of the morphological trend analysis to delineate the accumulation area west of the western Zeebrugge breakwater, caused by blockage of the littoral drift. Green polygon: sedimentation due to blocking of the littoral drift. In the bottom left of this zone is a small area with a strong erosive character, which is due to the nourishment of the beach at the "Duinse Polders". This nourishment was carried out shortly before the period over which the trend analysis was performed. The limited erosive area thus represents the return of the beach system to a more stable morphology, in the period following the nourishment. Pink polygon: downstream erosion, due to the response of the system to the presence of Blankenberge harbour. Red polygon: accumulation, mainly due to the presence of the Blankenberge disposal site. Black polygon: deepening, due to dredging of the navigation channel towards the Blankenberge marina.

Hyp. 3.3.4 Long-term and far field effects of human activities are underestimated.

a. *Variations in long-term erosion/deposition rates reveal far field effects of human activities*

One of the most outstanding features in the Belgian coastal zone is the Harbour of Zeebrugge. The area surrounding the harbour shows strong erosion-sedimentation trends; these can be linked to mainly anthropogenic influence (Figure 3.3-9).

Based on this information different zones are delineated, where results of the morphological evolution show very significant trends. In Figure 3.3-9b, areas in green indicate accretion-dominated zones; areas in red, erosion-dominated zones.

Areas 1, 2, 3 and 7 show trends that are likely within the influence area of the harbour of Zeebrugge and the dredging and disposal activities in the navigation channels (Pas van het Zand and Scheur) and on the disposal site S2, respectively. Trends for areas 4 (ebb-dominated trough, in the extension zone of the Westerschelde), 5 (Paardenmarkt shoal) and 6 cannot be directly linked to anthropogenic intervention.

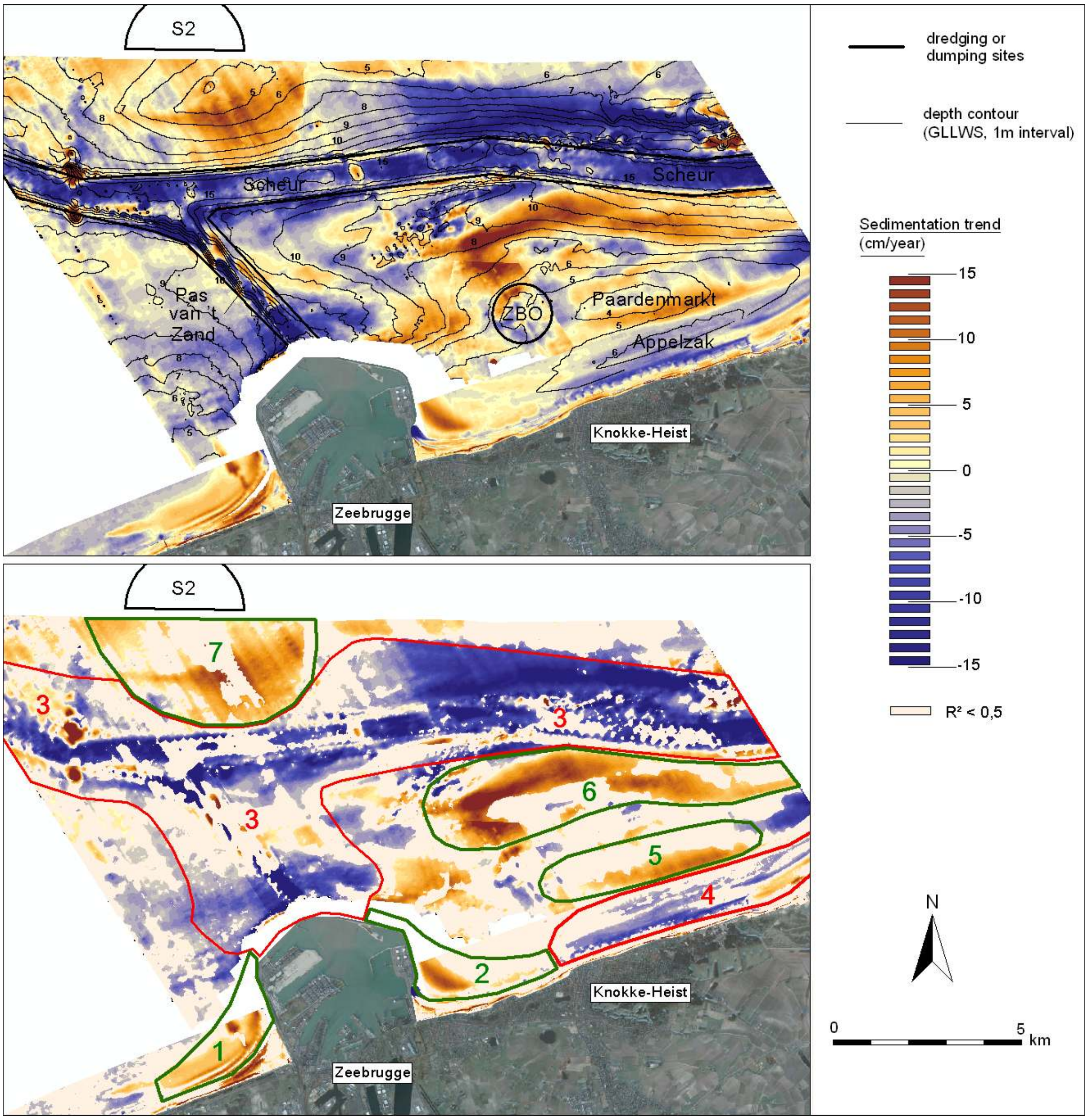


Figure 3.3-9. Erosion-sedimentation trend in the area around Zeebrugge harbour and the navigation channels. The top figure shows all trends; the lower figure only trends with $R^2 > 0.5$. Areas 1, 2, 3 and 7 show trends that are likely within the influence area of the harbour of Zeebrugge and the dredging and disposal activities in the navigation channels (Pas van het Zand and Scheur) and on the disposal site S2, respectively. Trends for areas 4 (ebb-dominated trough, in the extension zone of the Westerschelde), 5 (Paardenmarkt shoal) and 6 cannot be directly linked to anthropogenic intervention.

Table 3.3-I. Classification of the different zones with significant morphological evolution in the vicinity of Zeebrugge harbour.

	Dominant influence	Cause	Effect
Zone 1	Anthropogenic	Presence of a large breakwater downstream	Blocking of longshore transport
Zone 2	Anthropogenic	Presence of a large breakwater upstream	Accretion
Zone 3	Anthropogenic	Dredging of navigation channels + increased tidal flow, caused by the presence of the large breakwaters	Deepening of the bathymetry
Zone 4	Natural	Influence area of the Westerschelde?	Erosion of an ebb-dominated trough
Zone 5	Natural? Anthropogenic?	Needs further research	Accretion of bank crest that could be interpreted as migration
Zone 6	Natural? Anthropogenic?	Needs further research	Accretion
Zone 7	Anthropogenic	Disposal activities at S2	Accretion

Zone 1: This zone extends between Blankenberge and Zeebrugge harbour. The western breakwater of the harbour constitutes a physical obstacle blocking longshore sand transport (which is oriented from southwest to northeast along the Belgian coast). As a consequence, accumulation of sand at high rates is observed upstream the harbour. Zone 2: This zone concerns the "Baai van Heist" area, east of Zeebrugge harbour. Downstream the harbour, accretion occurs due to (1) blocking of the E-W directed littoral drift during ebb and waves coming from the north; and (2) deceleration of the tidal flow, after being accelerated in the vicinity of the harbour entrance, during flood. Zone 3: This zone includes the main navigation channel towards the Westerschelde (Scheur) and the channel towards Zeebrugge harbour (Pas van het Zand). It is hypothesised that continuous dredging activities in the navigation channels have an influence on the surrounding seafloor (e.g. strong erosion trend, directly north of Scheur). Where this zone nears the harbour entrance, the influence of the breakwater structures on the flow pattern (contraction of stream lines) is perceived; this is associated with erosion in front of the harbour entrance. Zone 7: Located beyond the Pas van het Zand; it is likely caused by disposal of dredged material at disposal site S2.

b. An overall increase of turbidity of Belgian waters is perceived in the long-term

The construction and extension of the port of Zeebrugge and its connections to the open sea, the disposal of dredge spoil, and the morphological evolution (e.g. Du Four and Van Lancker 2008) induced by these operations have had, and still are having, a substantial influence on the distribution of fine-grained sediment in the study area. Results are based on the combined analyses of recent and historic (100 years ago) sediment sample information and bathymetric maps. Data processing was based mainly on field descriptions of the samples (consolidation, thickness) and on bathymetric maps of 1866–1911. Generally, the historic relative mud content corresponds well to the modern quantitative mud content (Fettweis et al. 2009), as also their spatial distribution (Figure 3.3-3). The pattern likely corresponds to the position of the Holocene mud fields (e.g. Fettweis et al. 2009; and Mathys 2009). The layers of fresh to softly consolidated mud (>30 cm) reconstructed for the beginning of the 20th century were the result of natural morphological processes. Today, layers of fresh mud are concentrated in areas with high human impact and are not found in the remainder of the nearshore area. The data indicate that more Holocene mud probably outcrops today than at the beginning of the 20th century and that, as a consequence, erosion of these layers is more prominent today. This would explain the relative higher abundance of clay pebbles today, than 100 years ago. The Zeebrugge port extension and associated works have thus in all likelihood increased the amount of fine-grained sediment released into the North Sea, a process ongoing today. The latter is also confirmed by the tripod data at MOW1 and Blankenberge (see §3.2.2 and Fettweis *et al*. 2011). These data suggest that a major part of the high concentrated mud suspensions (HCMS), measured at both sites, could have been resuspended from the very soft mud deposits in the navigation channels and adjacent areas. This result indicate that the deepening of the navigation channels has made available fine-grained matter that contributes significantly to the formation of HCMS and suggests that these were probably less frequent in the past, when anthropogenic activities were limited.

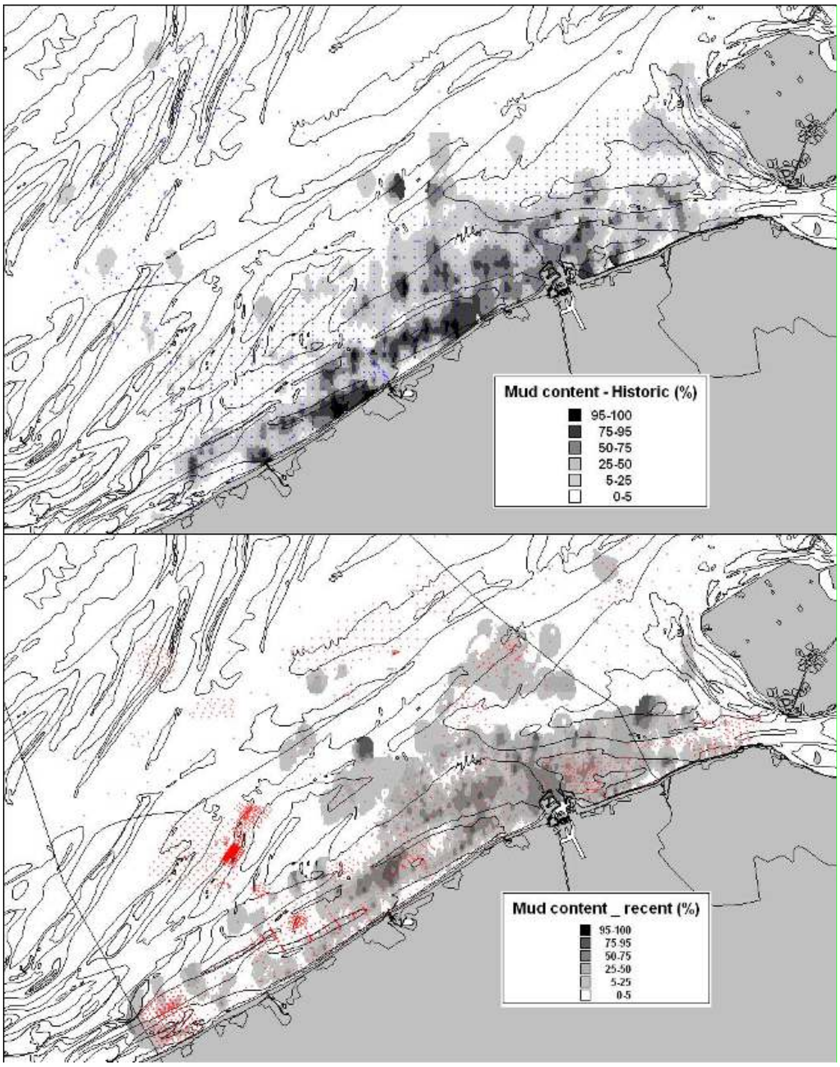
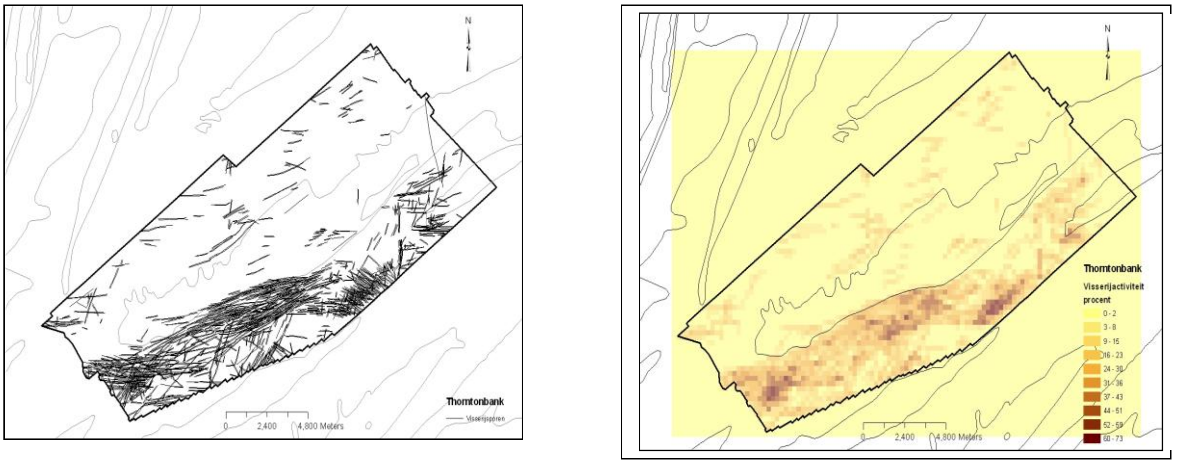


Figure 3.3-10. Historic (above) and recent (below) distribution of mud contents in the surface sediment. Sampling stations are represented as blue (historic, Gilson) and red (recent, SediCURVE@SEA database) dots. Mud levels are classified according to Flemming (2000): 0-5%: 'sand'; 5-25 %: slightly muddy sands; 25-50 %: muddy sands; 50-75 % sandy mud; 75-95 %: slightly sandy mud; 95-100%: mud.

Effect of beam trawling

Generally, fishing activities are concentrated in the troughs between sandbanks, with highest disturbance towards the slopes of the sandbanks. Based on multibeam backscatter images, trawling intensity has been estimated up to 73% of an area, with a minimum around 30%. Locally, completely fragmented seafloors are observed. A methodology is now in place to evaluate fisheries activities on a large-scale, whenever new high-resolution and good quality multibeam data are available. These data are crucial in the evaluation of long-term changes in soft-substrata habitats. Indeed, through mechanical disturbance, trawl fisheries are known to alter fine-grained sediment dynamics at the sediment-water interface. Given the fact that present-day beam trawls are much heavier than 100 years ago and are towed by a larger amount of powerful motorized vessels, this effect is intensified and more widespread than historically.



a b

Figure 3.3-11. (a) Identification of beam trawling marks, on the basis of very-high resolution multibeam backscatter data (2 m data resolution within the delineated area); (b) quantification of the marks on a 250 m grid. A maximum of 73% disturbance of a grid cell was calculated.

c. *Continuous disposal of dredged material significantly alters sediment characteristics and processes, also in the far field*

Effect on near-bed SPM concentration (Blankenberge case)

The impact of continuous disposal of fine-grained sediments from maintenance dredging works on the suspended particulate matter concentration in the Belgian nearshore area was investigated during a dredging experiment at Zeebrugge (Fettweis *et al.* 2010b). Before, during and after the experiment, monitoring of SPM concentration using OBS and ADV altimetry was carried out at the Blankenberge location, situated about 5 km west of the disposal site. A statistical analysis, based on the concept of populations and sub-sampling, was applied to evaluate the effect. The method provides a tool to account for the complexities associated with natural dynamics and the need to evaluate quantitatively human impact.

Tripod measurements showed the very high natural variability of SPM concentration (min-max: 10 - 3300 mg l^{-1}). SPM concentration near the bed (0.2 mab) were exceptionally high (median was more than 2 times higher) during the dredging experiment. Waves were not identified as being responsible for the high SPM concentrations. During the dredging experiment, a generally higher SPM concentration near the bed during ebb and at 2 mab during flood was observed, suggesting that the disposed material was mainly transported in the benthic layer. The time lag between high wave heights and high SPM concentration suggests further that SPM has been advected towards the measuring location rather than eroded locally. We can conclude that the disposal results in a long-term increase of SPM concentration near the bed at the measuring location, see Figure 3.3-12. This, together with ADV altimetry data, suggest that fluid mud layers have been formed during the whole of the disposal experiment, rather than being limited to neap tidal or storm conditions, as observed during the non-disposal periods.

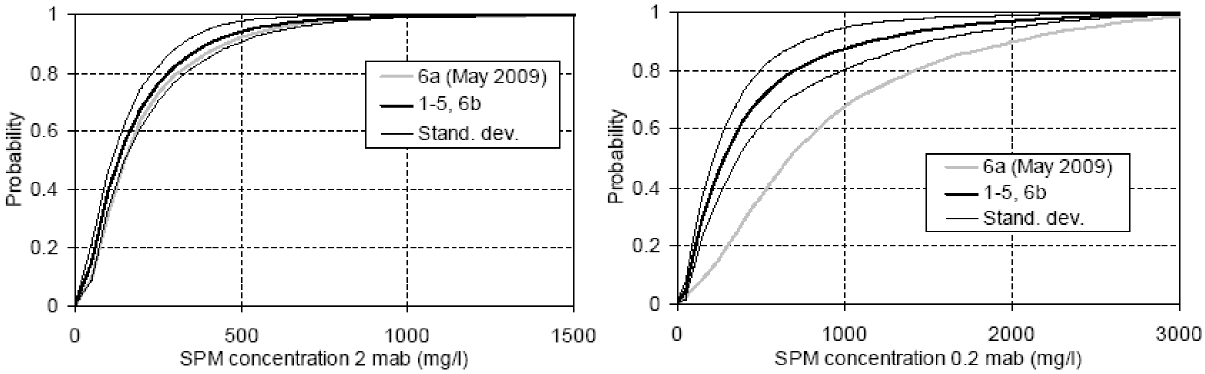


Figure 3.3-12. Cumulative probability distribution of SPM concentration measured at 2 mab and 0.2 mab. The black line (1 to 5, 6b) shows the data during the non-disposal periods ± one standard deviation (thin black lines); the grey line shows the distributions during the dredging experiment (6a). This shows that continuous disposal results in a long-term increase of SPM concentration near the bed.

Effect of disposing dredged material on sedimentation processes, near- and far field

Difference maps of chrono-sequential single-beam data from 1976 till 2006 demonstrate that the disposal of dredged material has strongly altered the former morphology of the area. Sediments have not only accumulated on the disposal site B&W S1, but also far outside, mainly towards the navigation channels, more specific to the SW (Figure 3.3-13). This SW-directed bedload transport is further confirmed by the consistent ebb-dominated asymmetry of the very large dunes and their SW migration. These findings contrast the overall flood dominated water and SPM transport direction. The disposal efficiency has been estimated as 30-40%, based on a comparison between the actual disposed amount of dredge spoil and the sediment volume changes (Du Four and Van Lancker, 2008). Vibrocore analyses, and their integration with depth evolution and disposal intensity data, allowed differentiating natural from anthropogenically-induced sedimentation. The latter is particularly demonstrated along the old and new disposal sites. Still, each site has a different sedimentation pattern, because of the difference in morphological setting (Figure 3.3-14). On the old disposal site, mainly sandy sediments are found, whilst on the new one, the mud fraction is important. As the old disposal site is located on a sandy shoal, fine sediments are winnowed and reworked more by waves than in a sandbank trough. However, if hard clay from Tertiary or Holocene origin, originating from deepening works, is disposed, it remains in-situ, both on the new disposal site, as well as on the old one. To assess natural sedimentation, difference maps, showing an alternation of erosion and accretion were compared over 30-yrs. From this, the dynamical character of the region was demonstrated, both at present and in the past. The latter emerged from a rather complex subsurface deposition, comprising Holocene sands, silty tidal flat deposits and Tertiary clays.

Annex 3 (Van Lancker et al., this report) discusses the effect of long-term disposal on the hydrographic conditions and combines these findings with habitat characteristics.

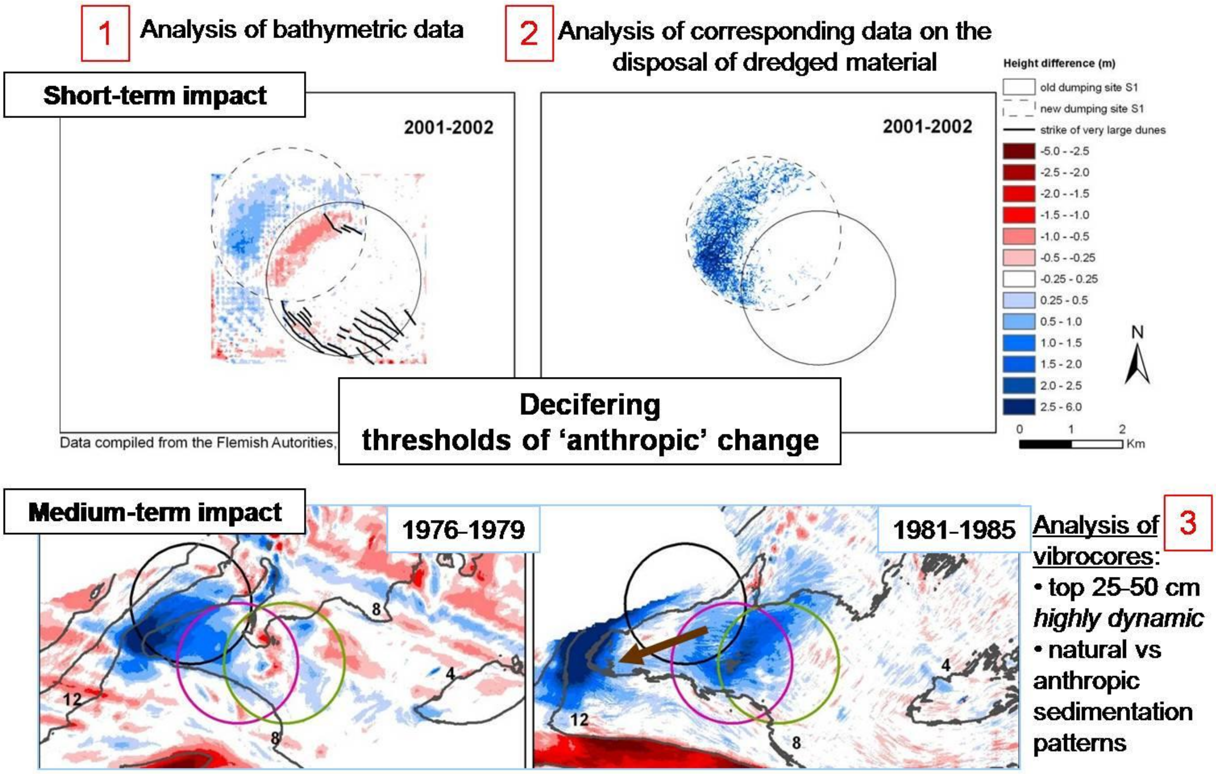


Figure 3.3-13. Analysis of natural vs anthropogenically-induced sediment dynamics along the B&W S1 disposal ground (North of Vlakte van de Raan). For the depth difference maps: Blue sedimentation; Red erosion. Circles show the consecutive positions of the disposal ground B&W S1. See also Annex 3 (Van Lancker et al., this report)

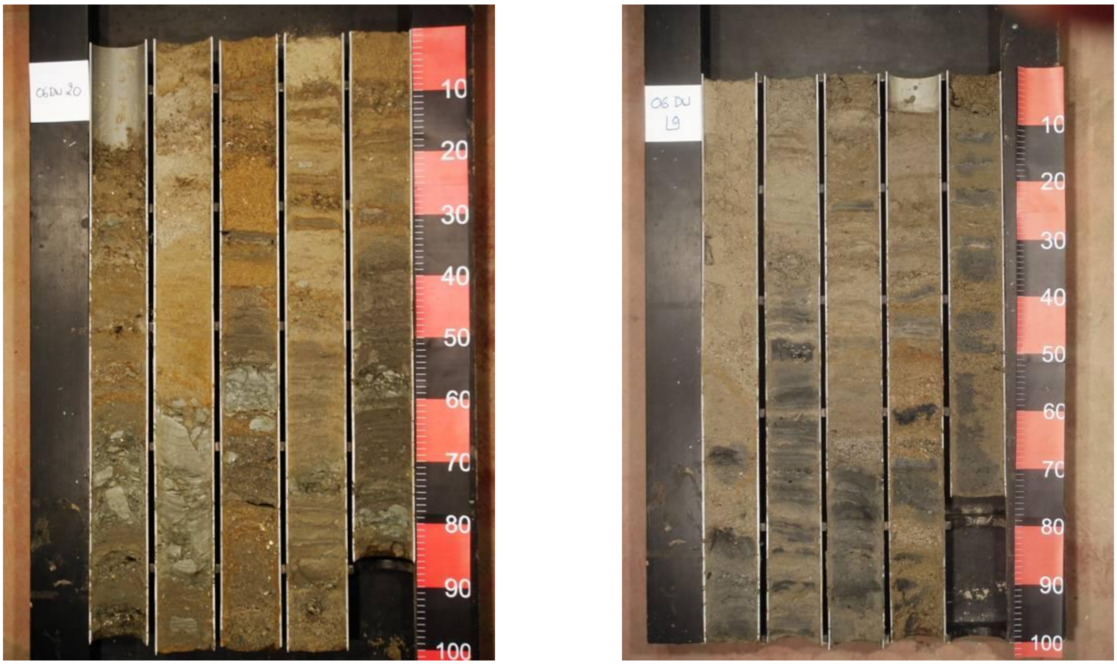


Figure 3.3-14. Photograph of 2 vibrocores taken on: a) the present disposal site (most NW site on Figure 3.3-13 (black)); and b) the old disposal site (cyan circle on Figure 3.3-13).

3.3.5 Long-term changes in the distribution and relative abundance of macrobenthic species

For the analysis of long-term changes in macrobenthos, we focused on 14 numerically abundant species, 2 of which were found in the recent data-set only. As a first step, the relative contribution of every species to the total abundance (sum of all specimens for these species) and their overall station occupancy rates were calculated for the two data-sets (Figure 3.3-15).

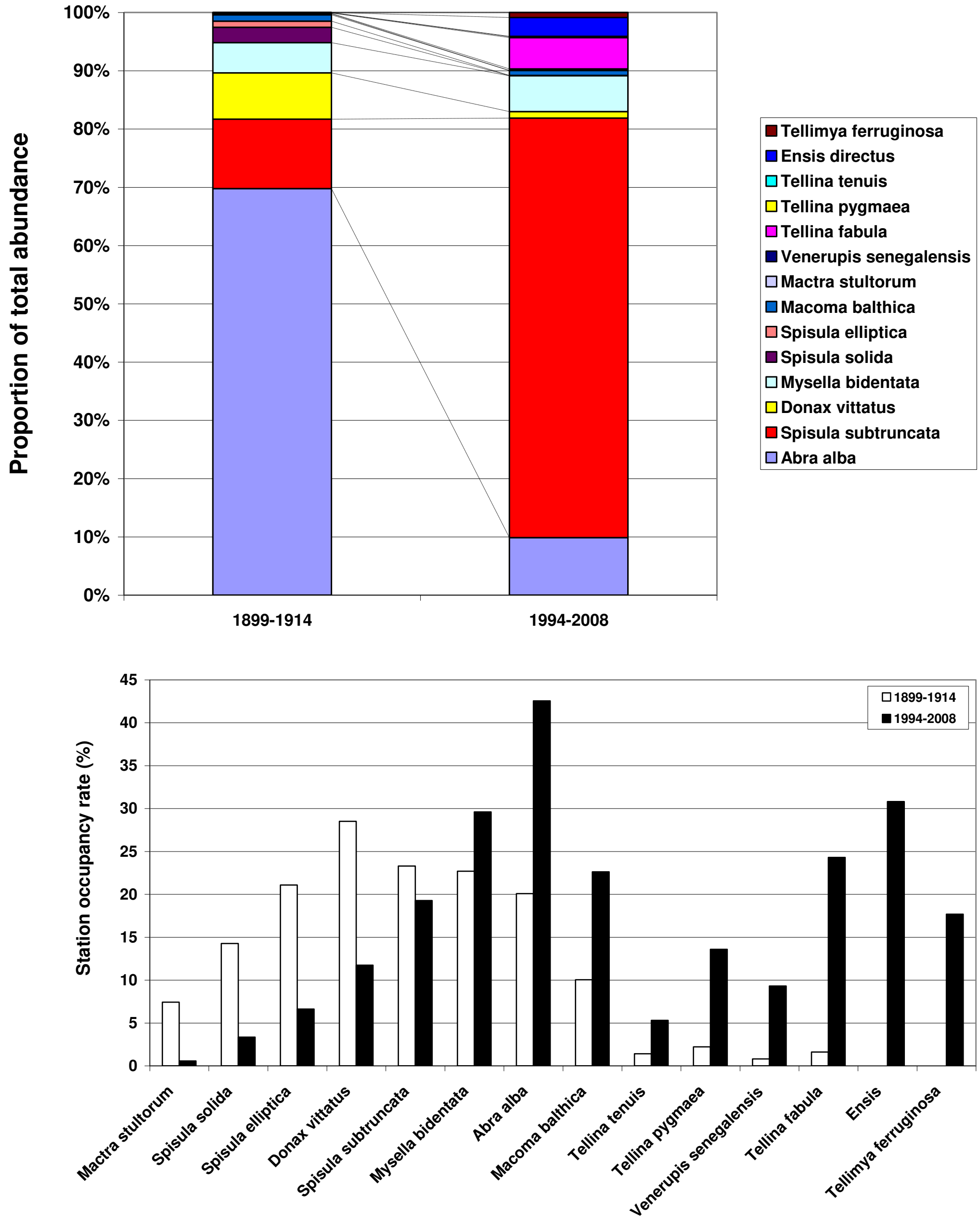


Figure 3.3-15. Overall figures calculated for the historical and recent data-sets for (above) contribution of species to total abundances and (below) station occupancy rates (proportion of stations where the species is present). In the first, the maximum observed abundance of D. vittatus was reduced from 14,000 to 400 (second maximum value) to avoid bias induced by one very strong recruitment event.

In both data-sets, four species (*Abra alba, Spisula subtruncata, Donax vittatus* and *Mysella bidentata*) represent the bulk of collected specimens (respectively 95 and 89 %). In the recent data-set, a significant contribution is further observed for *Tellina fabula* and the recently introduced *Ensis directus*. In terms of relative abundance, a clear 'switch' is observed between *A. alba* and *S. subtruncata*, with the latter most abundant since very recently. For *A. alba*, however, the historic data display a much lower station occupancy than in the present-day. This finding suggests that the species is nowadays more widespread, while it used to occur more abundantly at some stations in the historical situation. For *S. subtruncata*, similar station occupancies are obtained. *D. vittatus* was widespread historically, but in low abundances, and shows a dramatic regression in the present-day situation. The same observation can be done, to a lesser extent, for *S. solida* and *M. stultorum*. Interestingly, these three species are typical of clean fine sands. The changes in *S. elliptica* and *T. pygmaea* can hardly be discussed, because these less frequent species occur more offshore, where recent sampling effort is insufficient. *T. fabula* displays a spectacular increase in both contribution to total abundance and station occupancy; this indicates that this species, formerly rare, has become a prominent part of the macrobenthos of the area during the twentieth century. In the less abundant species, *M. balthica*, *V. senegalensis* and *T. ferruginosa* show a similar increased representation in the late twentieth century. For the latter species, an effect of species size could be invoked to explain the different patterns, but the historic abundance of the similarly small species *M. bidentata* contradicts this suggestion. *E. directus* represent the bulk of the 'Ensis' records in the present-day. It is an invasive species originating from the N-W Atlantic coasts; it established a permanent population in the area in the mid-1980. It is nowadays a prominent component of the local macrobenthos.

A spatial analysis of the long-term changes in the geographic distribution of these species is hampered by the structure of the recent data-set (owing to patchy project-based sample distribution). Interpolation maps of relative abundances at the sampling stations were drawn and are provided in Annex. The historical maps are particularly interesting since they show that the most abundant species were mainly found across the Belgian – Dutch border. Even though the distribution of sampling stations may lead to erroneous interpretations on long-term changes, the distribution of relative abundances provide interesting observations on former and current distributional patterns of high density patches. To overcome the problem associated to spatial distribution of samples, an analysis has been carried out at grid cells where sufficient information existed in both data-sets (n=61; Figure 3.3-16). Results of statistical analysis are presented in Table 3.3-II.

Altogether, the results obtained on the overall data-set analysis and on the station and grid cell distribution maps indicate important shifts in the distribution and relative abundance of these species, which are not randomly distributed among them: species which spatially expanded all show affinity for muddy sediments, while all species that regressed or seem to have regressed are typical of clean fine sands. The expanded species are also more evenly distributed in the coastal area than in the more patchy historic situation, with increased number of species represented in the grid cells. When considering the historic species distribution maps at the stations (Annex), such a higher contribution of species to species richness was restricted to Dutch waters, where most mud tolerant species were abundant, at the exception of *T. fabula* and *V. senegalensis*. These two species, together with *T. ferruginosa* and the recent alien species *E. directus*, can be considered as being part of the common macrobenthic species, in the course of the twentieth century. Thus, findings suggest that conditions defining benthic bivalve composition formerly restricted to the Westerschelde River mouth area, probably extended throughout the BPNS; this indicates that organic enrichment, typical of estuarine areas, is probably involved. As shown in the figure, the highest densities of species, historically, coincided with a large patch of moderate mud content in Dutch waters, which may reflect trend to deposition of SPM and food for these species. Unfortunately, we do not dispose of recent data from this area, yet, to compare with the historic situation.

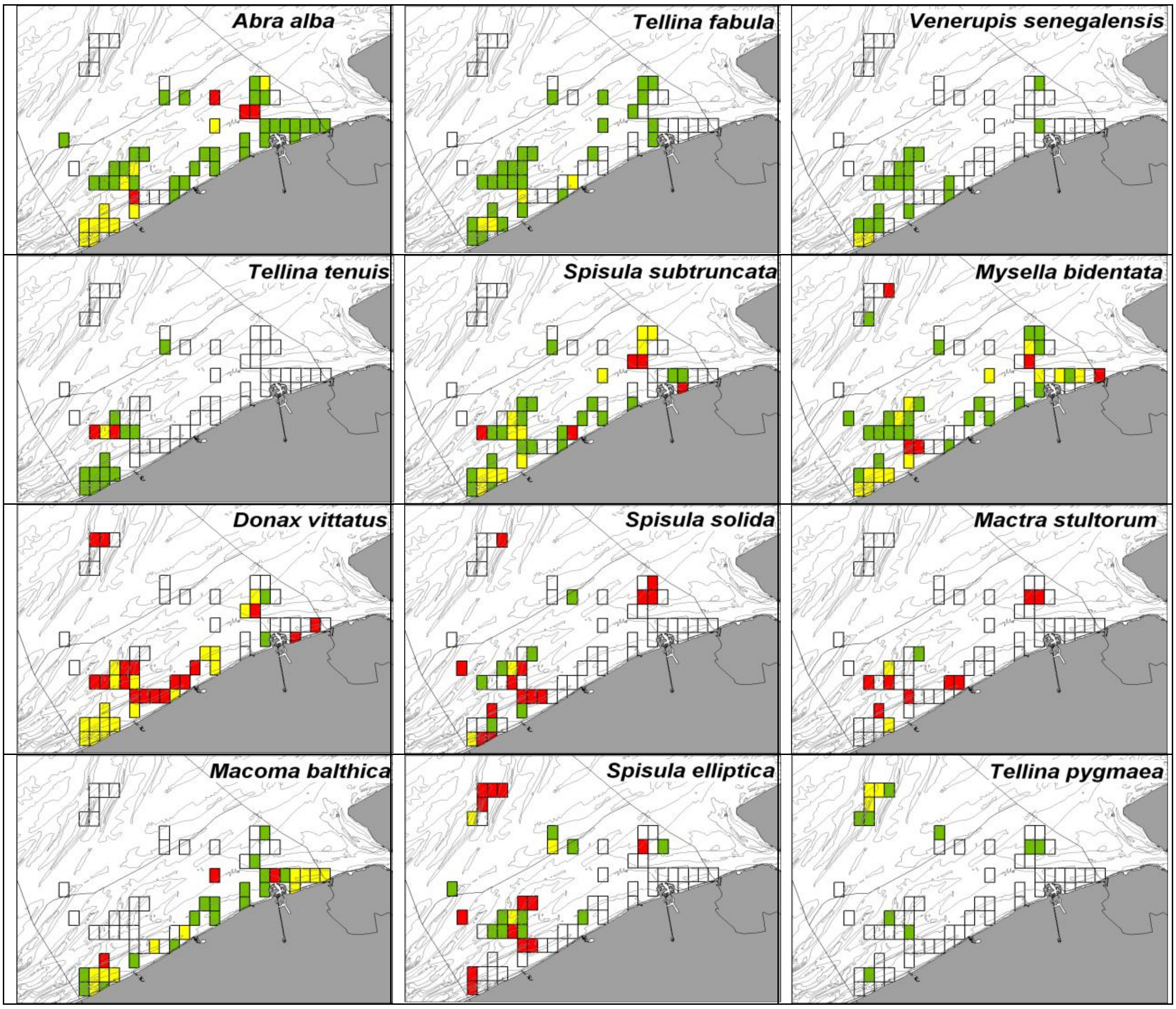


Figure 3.3-16. Difference maps for grid cell occupancy between the historical (1899-1914) and recent (1994-2008) situations. White: absent from both data-sets; yellow: present in both data-sets; red: present in the historic data-set only; green: present in recent data-set only. Four species display a statistically significant trend to geographic expansion and increased evenness in the distribution of relative abundances (*A. alba, T. fabula, V. senegalensis, M. balthica*). *D. vittatus* exhibits an opposite pattern. 4 other species display a statistically significant change in the grid cell occupancy only, with a trend to expansion. For *M. bidentata*, the pattern of change is less clear, but stays consistent with observations on *A. alba*, to which it is generally associated. *M. stultorum* and *S. solida* display a non-significant trend to contraction.

The case of *M. balthica* is interesting, as this species was historically clearly bound to the Westerschelde River mouth (Annex), outside the muddiest areas (see figure). Nowadays it is considered as typical of high mud contents (Degraer *et al.* 2007) and is widespread in the BPNS. The historically muddiest areas were almost devoid of any benthic species (except a cumacean, *Diastilys*; Houziaux, unpublished data), pointing at too harsh conditions for macrobenthos, likely due to highly concentrated near bottom mud suspensions. A glance at the distribution maps of this species in the period 1970-1984 (Degraer *et al.* 2006) tends to indicate that the observed trends were already present, although less marked. From this perspective, it would seem that the alien American Jack-Knife clam *E. directus*, now a prominent part of the macrobenthic communities, may have benefited from existing altered environmental conditions to thrive and is probably not directly responsible for the observed trends

Table 3.3-II. Statistical significance of observed trends for the 12 species represented in both data-sets (threshold p = 0.05 (in bold)).

Species	Distribution trend	z-test on grid cell occupancy	SIGNED-test on relative abundance	Mann-Whitney Rank Sum Test on relative abundance evenness
Abra alba	**Expansion**	**P < 0.001**	**p < 0.001**	**P < 0.001**
Tellina fabula	**Expansion**	**P < 0.001**	**P < 0.001**	**P < 0.001**
Venerupis senegalensis	**Expansion**	**P < 0.001**	**P = 0.016**	**P = 0.010**
Macoma balthica	**Expansion**	**P = 0.021**	**P = 0.002**	**P = 0.015**
Mysella bidentata	**Expansion**	**P = 0.002**	P = 0.170	**P = 0.017**
Tellina pygmaea	**Expansion**	**P = 0.027**	P = 0.519	P = 0.187
Tellina tenuis	**Expansion**	**P = 0.016**	P = 0.330	P = 0.143
Spisula subtruncata	**Expansion**	**P = 0.010**	P = 0.916	P = 0.135
Donax vittatus	**Contraction**	**P = 0.011**	**P = 0.009**	**P = 0.007**
Mactra stultorum	Contraction	P = 0.078	P = 0.084	P = 0.295
Spisula solida	Contraction	P = 0.165	P = 0.465	P = 0.337
Spisula elliptica	Unclear	P = 0.671	P = 0.121	P = 0.485

The shifts in macrobenthos can tentatively be related to observed changes in the distribution of mud contents in the sediment over the twentieth century (see above).

On the one hand, highly muddy areas, historically devoid of benthic species (Grote Rede and Kleine Rede troughs), display an apparent decrease in the mud content of the sediment, which might explain a recent colonization by mud tolerant species (*M. balthica, A. alba*) formerly unable to survive the highly concentrated near-bed suspensions. Thus, a reduction of mud content in the sediment might explain the recent expansion of some species in the very coastal waters.

On the other hand, the hypothesis of Fettweis *et al.* (2009; 2010a) of increased 'disponibility' of fine sediment to deposition/resuspension processes, as being due to anthropogenic disturbance, is in-line with the general pattern of expansion of mud-tolerant species. Indeed, if the dredging of deep navigation channels created hydrodynamic traps for suspended matter during calm weather conditions, their resuspension during storm events in the channels and at the disposal sites will lead to higher levels of turbidity and, subsequently, to redeposition of larger amounts of suspended matter over a large area. A possible second driver to altered fine-grained sediment dynamics is bottom trawling fisheries, which favour resuspension processes. It is worth mentioning here that although bottom trawling was already carried out in 1900, it concerned light wooden beam trawls, towed by sailing vessels, thus gears that penetrate far less in the surface sediment. Hence, we believe that resuspension by trawls was much reduced in 1900, compared to the recent situation (heavy beam trawls have been reintroduced since the 1960s in the Belgian fleet). However, the relative importance of trawling-induced resuspension to overall turbidity is unclear.

From these findings, it can be concluded that observed changes in soft-substratum macrobenthos are likely linked to: (1) yet, unclear changes in the dynamics of muddy sediments, favouring mud tolerant species; and (2) an organic enrichment, resulting from eutrophication, favouring an increase of species richness in the sediment.

3.4 Recommendations for more sustainable management of human activities

3.4.1 Effect of climate change on habitat changes

Results from statistical downscaling of climate scenarios did not show a future impact on extreme storm surges at Ostend, but the results were criticised by external reviewers and should therefore be used with great care. However, extreme surges estimated from a hydrodynamic model, forced by wind and pressure fields from a climate model (A1b scenario only), confirmed to some extent that a likely climate change scenario will not have a large impact on surge levels. However, extreme surges (and in fact also extreme waves) are although not entirely to a large extent linked to one particular circulation pattern. In fact, the conclusion from the statistical downscaling is based on the fact that there will not be appreciable changes for this particular weather regime. This does not say anything about possible other changes, e.g. stronger west or south-westerly winds. It is therefore recommended to continue investigating the effect of climate change on surges and waves. Particularly, it would be useful to investigate possible changes in (wind and) wave climate. A change in wave climate can only be studied with output from (spectral) wave models, driven by wind fields.

Trend analyses of wind directions did show an increase of southwesterly winds (Van den Eynde et al., 2011; Siegismund and Schrum, 2001) over the last decades. To investigate a potential impact on sediment transport, Baeye et al. (submitted) correlated various wind directions with SPM concentrations, as derived from satellite remote sensing data (MODIS-Aqua).

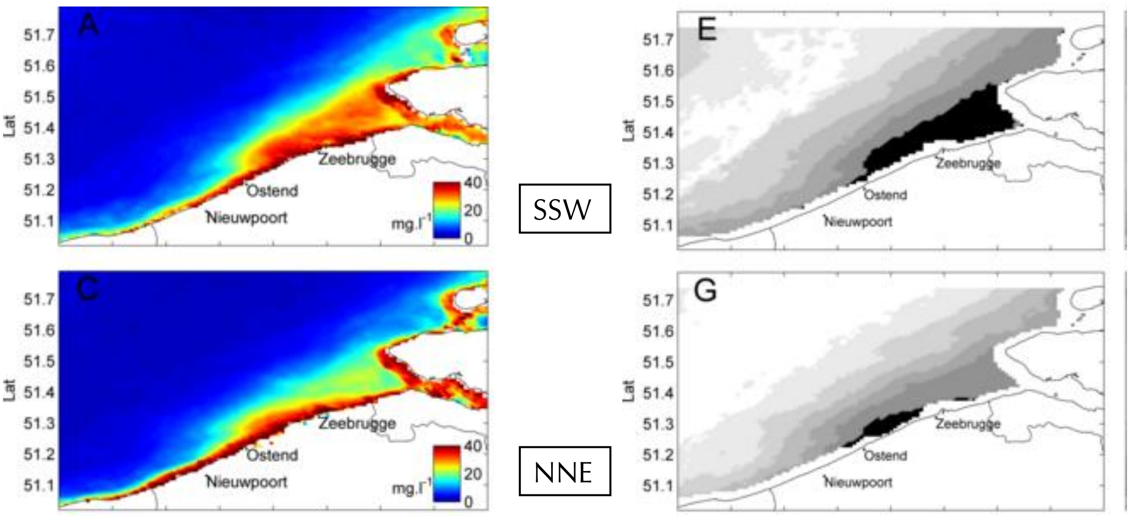


Figure 3.4-1. Representative surface suspended particulate matter concentration maps for two contrasting wind cases, as obtained from grouping-averaging MODIS-Aqua data images: SSW (A) and NNE (C), together with entropy grouping maps for those wind cases SSW (E) and NNE (G). (Extract from Baeye et al., submitted). Note that the black area in E and G only represent the highest SPM class, but do not represent the same concentration range.

Two contrasting cases could be derived: Southwesterly winds (SSW) typically corresponded to the largest extent of the coastal turbidity maximum, whereas northeasterly winds (NNE) tend to reduce it (Figure 3.4-1). Similar analyses were also done for contrasting NAO conditions during two winters. Results showed that a positive NAO winter exhibits more (stronger)-than-average southwesterly winds, compared to a negative NAO winter with more northeasterly winds (Figure 3.4-2). $NAOWI^{+}$ conditions, hence with more southwesterly winds, typically correspond to the largest extent of the coastal turbidity maximum, however with generally somewhat lower SPM concentrations, whereas $NAOWI^{-}$ conditions, associated with more northeasterly winds showed a reduced spatial extent, though with higher SPM concentrations. During a positive NAO winter, the turbidity maximum is shifted more towards Dutch waters (Baeye et al., submitted). Hence, with the climate-induced increase in southwesterly winds the turbidity maximum has shifted more towards the mouth of the Westerschelde estuary as before.

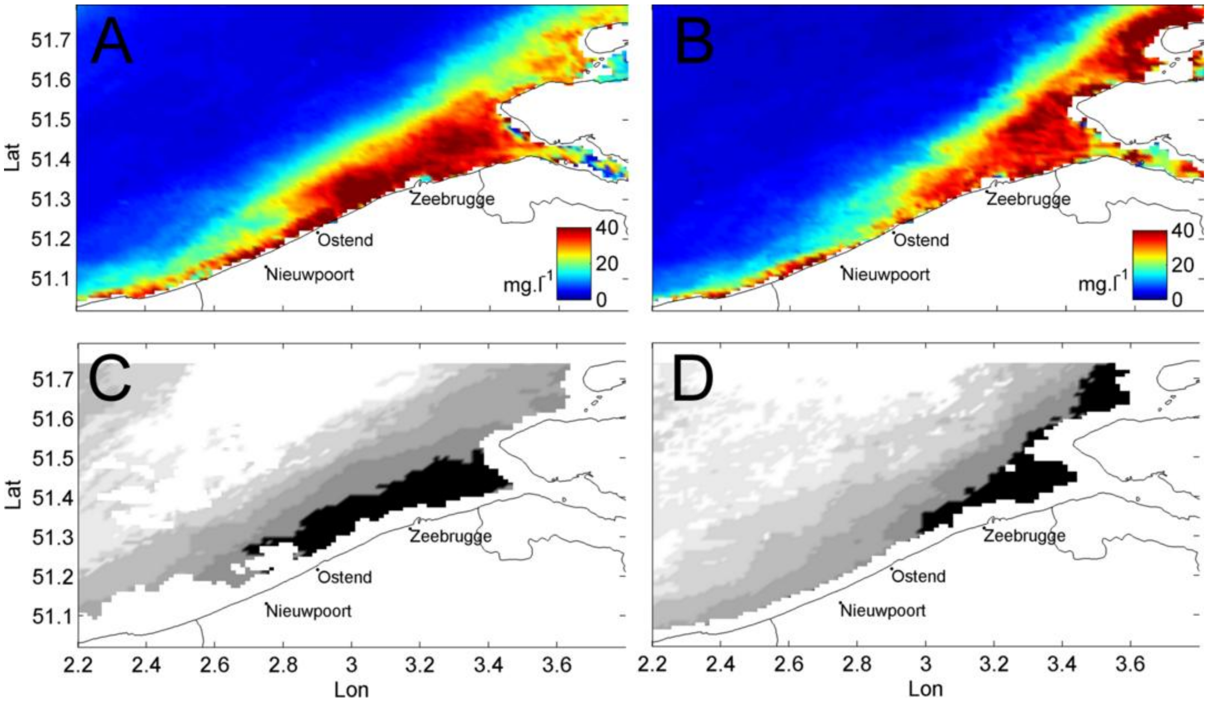


Figure 3.4-2. Representative surface suspended particulate matter concentration maps for two contrasting winters: NAOWI- (2005/6) (A) and NAOWI+ (2006/7) (B) and the corresponding entropy grouping maps (C) and (D), respectively. The winter of 2006/7 (NAOWI+) (B/D) corresponded with significant winds blowing from the SW sector, whereas the winter of 2005/6 (NAOWI-) (A/C) was characterized by abundant NE winds. The coastal turbidity maximum during positive NAO winter conditions (B/D) has shifted significantly towards the NE and is absent in front of Ostend. A negative NAO winter (A/C) coincides with a coastal turbidity maximum extending over nearly all the Belgian coast, up to the mouth of the Westerschelde. Median SPM concentration during NAOWI- (A/C) are higher (43 mg l-1) than during NAOWI+ (B/D) (35 mg l-1) (Baeye et al., submitted).

No significant linear relationships could be established between NAO and the Schelde's streamflow, neither seasonally, monthly or over a ten-days period. A non-linear relation, using the Spearman's correlation coefficient, hardly revealed any different yearly NAO-streamflow relation (with a R^2 not exceeding 15 %). Further analyses are needed, preferentially subdividing the streamflow into stormflow and baseflow, and investigating the shortest timescales, given the watershed's time of concentration (Levy et al., 2010). Still, from the figures above, there is only limited correlation between SPM concentrations in the Westerschelde and in the coastal zone. Merely, autonomous trends are perceived, decoupled from the estuary (Baeye et al., submitted).

Further research is needed to correlate the findings with the observed changes in macrobenthos over the past 100 years (see § 3.3.5). It was hypothesized that the expansion of mud-tolerant species was due to an increase in anthropogenic disturbance. Intensification of human activities can indeed have led to an increased 'disponibility' of fine sediment to deposition/resuspension processes, which together with an increase in southwesterly winds could have pushed this material more towards the offshore and further to Dutch waters. As long as SPM levels remain intermediate (average 4 mg/l, as derived from satellite remote sensing), this may be beneficial for species richness and densities (§ 3.4.2 and Annex), though higher levels may have deleterious effects. This should be considered in impact studies of any future large-scale infrastructure work.

3.4.2 Indicators and monitoring practices for the development of integrated management tools

EU Directives and Monitoring

A literature review and reflection on setting-up integrated monitoring programmes *w.r.t.* EU Directives is presented in Annex. Requirements related to the European Marine Strategy Framework Directive are highlighted particularly; ways forward are suggested, in view of ensuring marine sustainability. Figure 3.4-3 summarizes key findings.

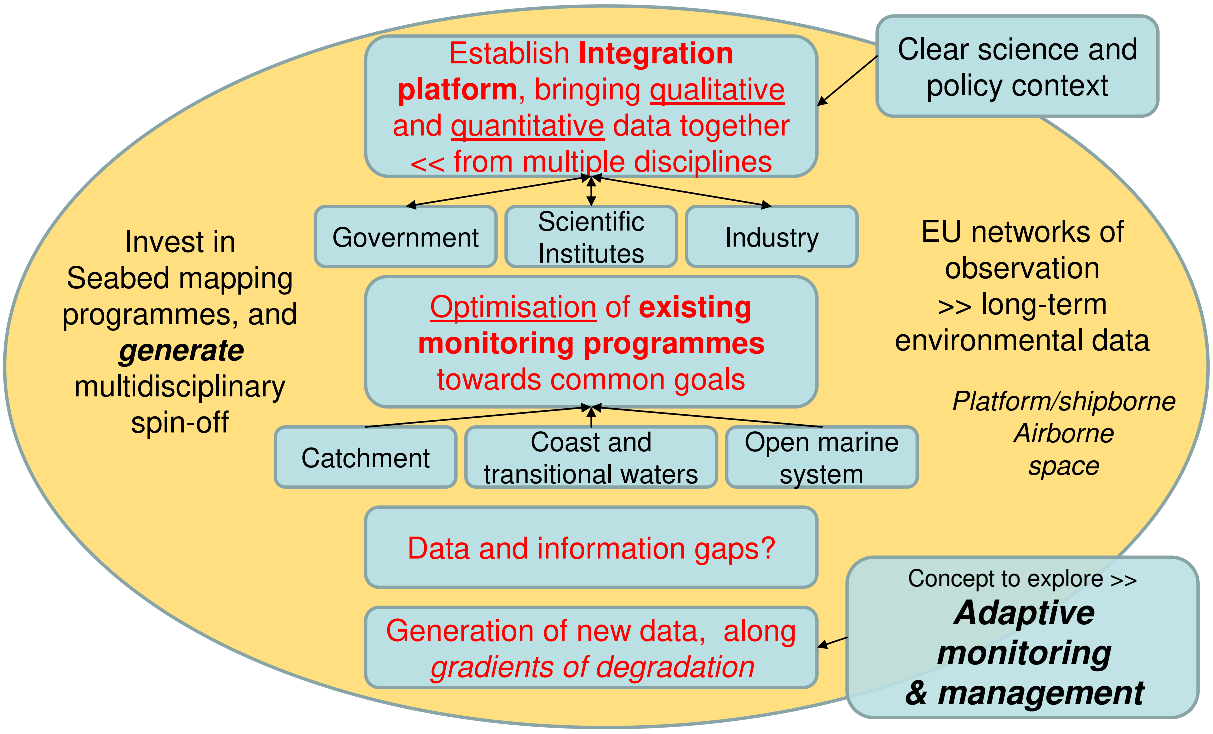


Figure 3.4-3. Summary of key findings regarding future monitoring programmes. See Annex.

SPM concentration as indicator to detect changes in the marine environment

In order to evaluate SPM as indicator of detecting changes in the marine environment, a large set of SPM concentration data from MODIS and from in situ measurements (tidal cycle, tripod) was used to evaluate temporal SPM heterogeneity in the Belgian nearshore. The heterogeneity has been statistically assessed by comparing the SPM concentration frequency distributions. Based on the median and the standard deviation, a representative population of SPM concentration was constructed under different conditions. The probability distributions of the SPM concentration data correspond well with a log-normal distribution (Figure 3.4-4). The median (x^*) and multiplicative standard deviation (s^*) of these distributions are calculated and can be used as a statistically representative background SPM concentration. In general, values of s^* vary between 1.5 and 2.9; hence they are included in the most frequently occurring range of approximately 1.4 to 3, observed in various branches of natural sciences (Limpert *et al.* 2001).

Results show that the tidal cycle, tripod and MODIS data sets at MOW1 and the Kwintebank have different distributions and that they represent a different sub-population of the whole SPM concentrations population (see Fettweis and Nechad 2010).

In order to compare near-bed SPM concentrations from tripod with surface concentration from satellite, correction factors have been constructed based on vertical SPM concentration profiles measured during tidal cycles. The differences between the data sets are related to the different meteorological conditions during measurements; to near bed SPM concentration dynamics, which are partially uncoupled from processes higher up in the water column; to the sampling methods or schemes used to collect the data; to the method of surface correction assuming a logarithmic profiles near the bed and to measuring uncertainties.

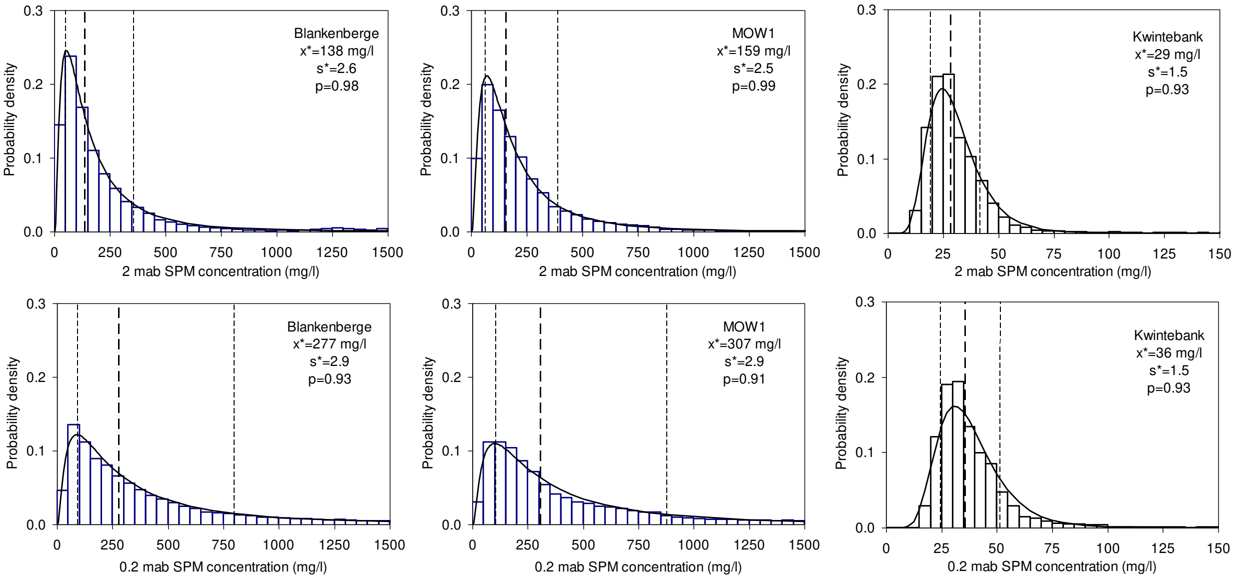


Figure 3.4-4. Probability density distribution of long-term SPM concentration data at 2 mab and 0.2 mab for the Blankenberge, MOW1 and Kwintebank sites and the corresponding log-normal probability density functions. The data fit the log-normal distribution with a χ^2 test probability of $p>0.9$. The dashed lines correspond to the median x* times/over the multiplicative standard deviation s*.

Main conclusions, with relevance to monitoring, are:

1. SPM concentration can be used as an indicator of environmental changes, if sufficiently long time series are available that are representative of the natural variability. Due to the time and spatial variability of SPM concentration in high turbidity coastal areas, greater sampling efforts are necessary, as compared to offshore systems with low SPM concentration.
2. Satellite, tidal cycle and tripod SPM concentrations are very similar at the Kwinte Bank (20 m depth, situated 20 km offshore at the edge of the coastal high turbidity area), with respect to uncertainties of SPM concentration measurements in low turbidity areas.
3. Satellites or low-frequent tidal cycle measurements cannot replace long-term continuous measurements in high turbidity areas, which include all sea state conditions. The former datasets consist of a sub-set of the population biased towards good weather condition or spring-summer seasons (satellite). Sediment transport based on these data will thus always underestimate reality.
4. The data demonstrate that, due to spatial turbidity variations, the use of a control site to detect changes is not suggested. We would recommend extending the duration of the measurements in order to have sufficient data for meaningful statistical analysis. Long time series at one location have the advantage that the natural variability can be assessed and that impact of construction works can be identified with higher probability. Such an approach was successfully used during the disposal experiment at Zeebrugge (see Fettweis *et al.* 2011).

5. Regarding instrumentation, it is shown that SPM estimates from OBS are only reliable when SPM consists of cohesive sediments only; with mixtures of cohesive and non-cohesive sediments, a combination of optical (OBS) and acoustic sensors (ADP, ADV) are needed to get an accurate estimate of the total SPM concentration (Baeye *et al.* 2011).

SPM as driver of habitat and benthos changes

Statistically significant differences in macrobenthic species richness and densities between five SPM classes (very low, average of 1.7 mg/l; low, average of 2.3 mg/l; intermediate, average of 4 mg/l; high, average of 7.3 mg/l; very high, average of 17.8 mg/l) were detected for the grain-size classes 200-250 μm, 250-300 μm and 300-350 μm (Figure 3.4-5),

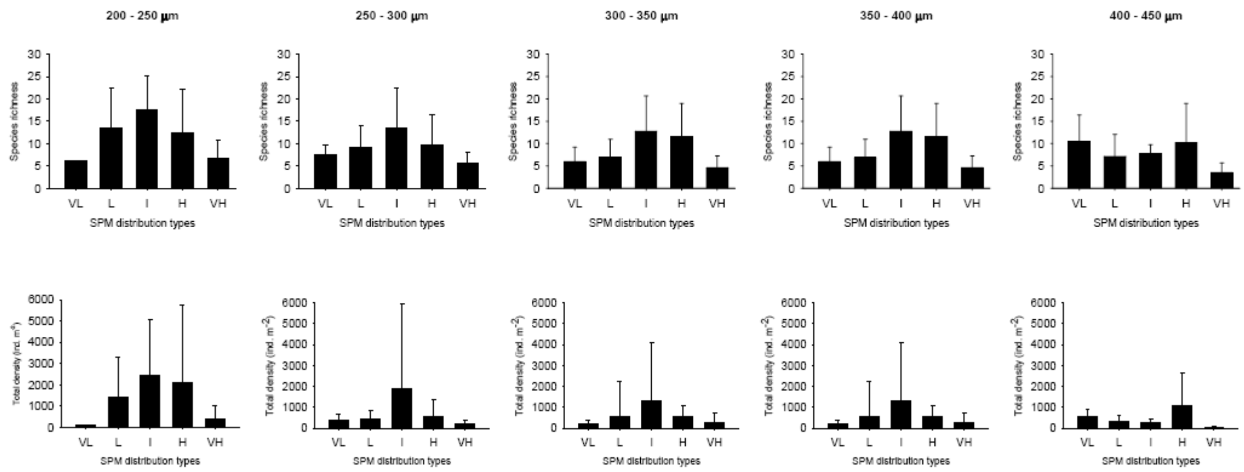


Figure 3.4-5. Macrobenthic response to SPM classes (VL, very low SPM concentration; L, low; I, intermediate; H, high; VH, very high) within the five selected median grain-size classes. Species richness, ind. 0.1 m^{-2}; total density, ind. m^{-2}. Whiskers, standard deviation.

Main conclusions are:

1. Within the grain-size classes 200-250 μm, 250-300 μm and 300-350 μm, a generally higher species richness and macrobenthic density was found in the intermediate SPM class (average 4 mg/l), compared to both lower and higher SPM concentration classes;
2. This pattern tended to weaken in the fine-grained and coarser-grained sediment classes, possibly indicating the higher relative weight of SPM in structuring the macrobenthos where favourable hydrodynamical conditions prevail.
3. Although the expected unimodal relationship between suspension feeding organisms and SPM concentration could not be found from the datasets, a generally increasing dominance of subsurface deposit feeders and grazers (SSDF.Gr) at the expense of interface, facultative suspension and surface deposit feeders (IF.FSF.SDF) from lower to higher SPM concentrations was demonstrated. SSDF.Gr organisms might benefit from higher SPM concentrations through the burial of the excess of particulate matter, which is more efficiently taken up in highly permeable, coarse sediments.
4. Further research is needed to derive thresholds for benthos changes, caused by SPM.

See Annex for more detailed results.

3.4.2 Towards more sustainable practices of human activities

a. Dredging works can be reduced, when disposal grounds are chosen in relation to natural sediment dynamics

Reducing recirculation of fine-grained matter

It is common knowledge that recirculation of disposed fine-grained matter to the dredging places is thought to significantly reduce efficiency of dredging operations at Zeebrugge (e.g. Malherbe 1991; Du Four and Van Lancker 2008). Based on tracer experiments Malherbe (1991) argued that SPM was confined in the turbidity maximum area. Further analysis of these data, in combination with in situ measurements and model results indicated that the turbidity maximum area is rather an open system (Fettweis and Van den Eynde 2003; Van den Eynde 2004). This has important consequences for the management of disposal operations. The way to reduce the amount of mud and SPM in a closed system and thus to reduce dredging works would be to dispose the dredged matter outside the turbidity maximum and thus far away from the dredging places. In an open system the efficient disposal of dredged matter, inside the turbidity maximum, depends on the sediment dynamics. The siltation rate, S, of a harbour dock can be calculated from $S=pQC$ with p the trapping efficiency of the basin, Q the water exchange between the harbour and the sea and C the SPM concentration outside the harbour (PIANC 2008). Deposition of fine-grained material can be reduced by reducing one of these parameters. If recirculation is reduced then C will decrease. The decrease in recirculation for the port of Zeebrugge due to the use of another disposal site than B&W Zeebrugge Oost has been calculated using numerical model results and in situ data. The results suggest a reduction of the dredging volumes of about 10% in case of using a more efficient alternative disposal site (Fettweis *et al.* 2010b). A field experiment is currently planned during which the disposal site B&W Zeebrugge Oost will be replaced by a more efficient one. The results will allow validating the numerical results, will make use of SPM concentration as indicator of changes, and will, in case of positive evaluation, help to reduce dredging and disposal operations.

b. Integrated morphological evolution of beach, shoreface and nearshore allows optimising beach nourishments schemes

When planning beach nourishments in the framework of soft coastal defence measures, it is crucial to evaluate their morphological stability in order to minimize the need for maintenance of such nourished beaches. However, it is important not only to examine the morphology of the beach, but also to take into account the morphological interaction between the beach and the shoreface and the adjacent seafloor. Moreover, in order to fully understand the processes that drive beach evolution, an integrated approach is recommended: topographic and bathymetric analysis should be supported by numerical modelling, together with in-situ measurements of the most important processes (e.g. sand transport rates).

c. The effects of large-scale aggregate extraction are difficult to predict; morphological changes are slow

The effect of large-scale marine aggregate extraction is studied by lowering the bathymetry of a far offshore sandbank area to a minimum depth of 15 m, 20 m and 25 m, respectively. Since wave energy dissipation (surf breaking and bottom friction dissipation) is an important parameter in sediment transport processes, its magnitude is compared with reference conditions keeping all other conditions similar. The differences in water depth are given in the Figure below.

Differences in significant wave height are shown in Figure 3.4-6 with reference to the storm (November 25, 2005 at 0h). There is a clear wave height increase in the area where the banks are lowered. At the control point CP, the wave height has increased with about 0.45 m, 0.55 m and 0.70 m, respectively (compared to a wave height of 3.8 m). Also changes in the wave propagation direction of up to 7° are noted, due to changes in the wave refraction process. Changes in wave propagation direction explain the slight decrease of wave height in certain areas.

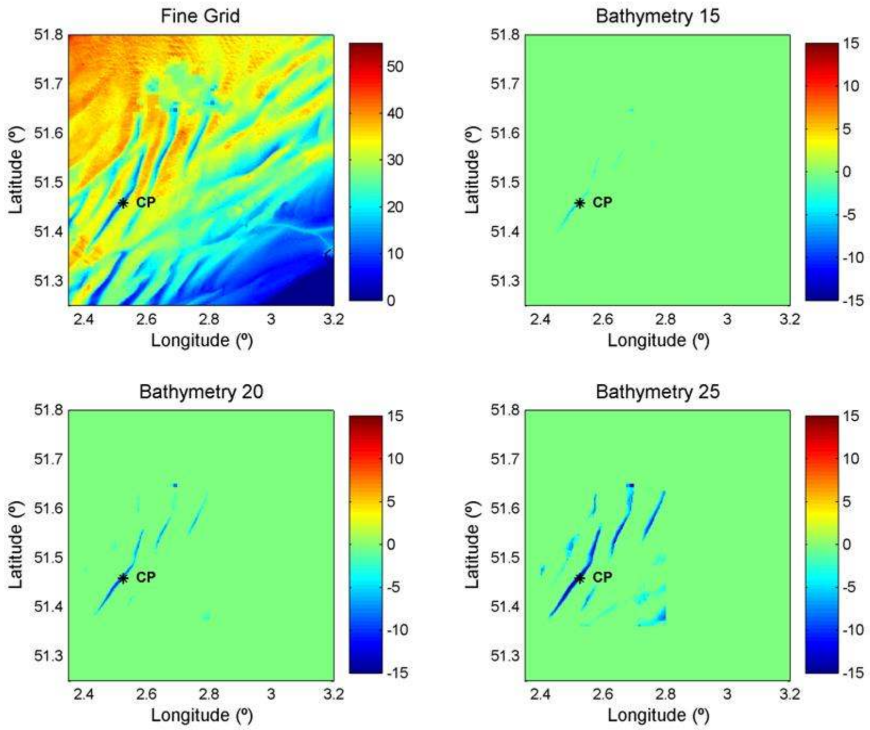


Figure 3.4-6. Zoom of the differences between the fine-scale bathymetry grid and the adapted bathymetries (lower to 15, 20 and 25 meters depth). CP is a control point for output comparison.

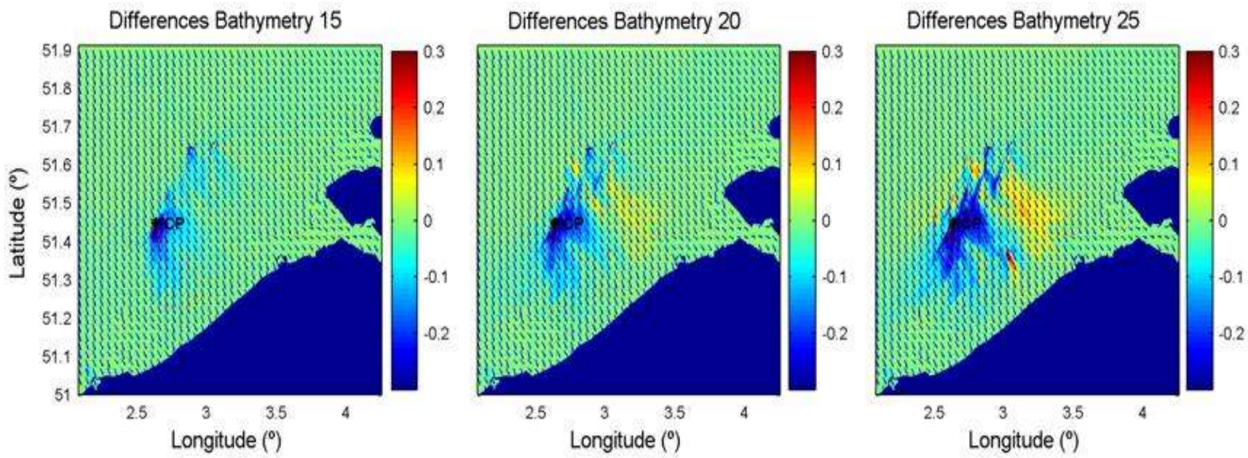


Figure 3.4-7. Differences between significant wave height (m) and vector of wave direction (°) in the original fine-scale bathymetry grid and in the adapted bathymetries (15, 20 and 25 m) from November 25, 2005 at 0h.

The consequence is that more wave energy will pass over the far offshore sandbanks and will need to be dissipated elsewhere, when approaching the coast. To illustrate this, the differences in wave dissipation due to surf breaking are shown in Figure 3.4-8. The decrease at the location of the far offshore banks is obvious. Due to the increased depth, waves will no longer break. More important is the increase in wave dissipation in the area of the Flemish Banks. Although outside the scope of this study, this will definitely have an effect on sediment transport during the storm and will possibly affect the long-term sediment transport trends in this area.

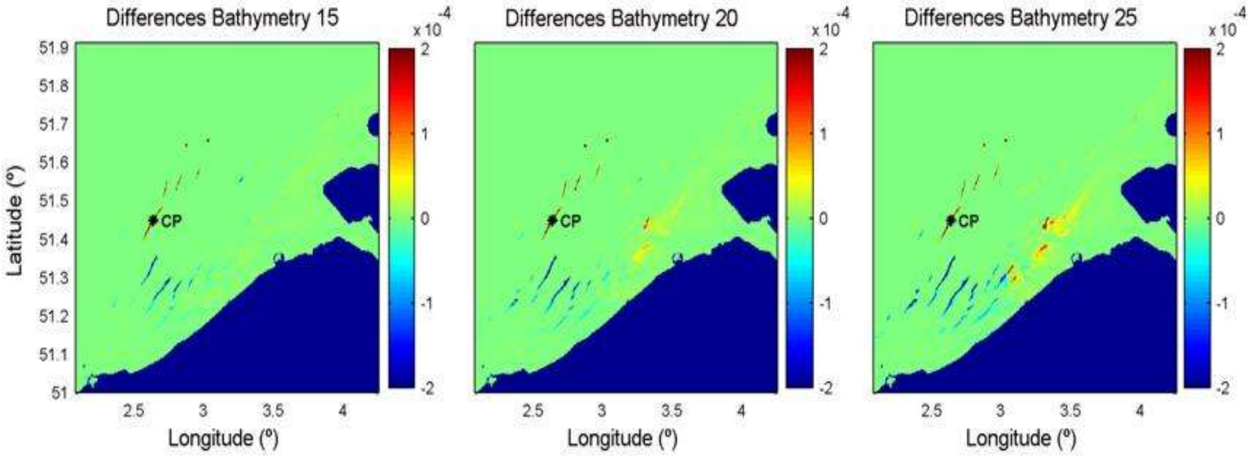


Figure 3.4-8. Differences in dissipation due to surf breaking (m^2/s) in the original fine-scale bathymetry grid and in the adapted bathymetries (15, 20 and 25 m) from November 25, 2005 at 0h.

(3) Close to the coast, there is no longer an effect on wave dissipation, due to surf breaking. All energy has been dissipated before it reaches the coastal area. Similarly one can look at energy dissipation due to bottom friction. There will be an obvious decrease in the area where the bathymetry has been lowered and an increase of bottom friction beyond this area in the wave propagation direction (results not shown here). This increase is no longer visible once excess wave energy has been dissipated by surf breaking. Therefore close to the coast there is no longer a visible effect. One could (wrongly?) conclude that safety levels at the coast are not directly affected by large-scale aggregate extraction at far offshore sandbanks. However, it is clear that there will be an indirect effect due to possible morphological changes in the Flemish Banks area. Changes there will in turn invoke changes in the areas closer to the coast. Such morphological changes are however slow and as usual difficult to distinguish from changes, due to other causes. See Liste Muñoz *et al.* (2011) for detailed results.

d. Human-induced seabed changes are an order of magnitude larger than natural seabed evolution

Results on the long-term evaluation (1999-2010) of hydrodynamic and sediment transport variables show the spatial and temporal variability of natural seabed responses along the BPNS.

In Annex, a case is presented related to marine aggregate extraction. According to the location of the extraction, bed evolution may be depositional or erosional under varying hydro-meteorological conditions, and/or human activities. Depth variability imposed by human activities is an order of magnitude larger than the modelled natural bed evolution. Cases do exist where most negative seabed responses were monitored after moderate extraction activities, only. A combination with intensified current-wave interaction significantly added to the erosional trend.

The long-term numerical modelling results can be integrated into relational databases for further use as a spatial planning tool, for support of environmental monitoring or estimating recovery rates after human activities have ceased. Examples in literature (e.g. Painho et al. 2002) show how Geographic Information Systems (GIS) are able to organize and interface information from a large range of public and private data sources, and combine this information into comprehensible system knowledge in function of management decisions.

4. POLICY SUPPORT

QUEST4D provides both fundamental and applied science in support of a more sustainable exploitation of the Belgian part of the North Sea. Scientists from MUMM are, on a regular basis, advising on marine environmental issues of all human activities at sea (e.g. marine aggregate extraction, windmill farm implantation, disposal operations of dredged material, cables and pipelines). Scientific expertise is provided to the **Federal Public Service Health, Food Chain Safety and Environment (Directorate General Environment DG-ENV, Marine Environment Service)**. As examples, data were used for the proposition of areas complying with the **Habitat Directive** (Degraer *et al.* 2009), for a report on the **Status of the Marine Environment** (BMM 2010) and for the implementation of Europe's Marine Strategy Framework Directive. Together with WL, MUMM also advices on the dredging and disposal of dredged material and beach nourishment. MUMM is responsible for all monitoring activities that relate to assessing human impacts at sea. Apart from shipborne monitoring, MUMM disposes of 2 multisensor tripods delivering data on a quasi continuous basis. On an international level, MUMM takes part in various OSPAR initiatives. Contributions were made to the **Quality Status Report** 2010. MUMM scientists take part in workshops devoted to EU policy.

Q4D significantly adds value to these advices by providing additional data and tools, in-depth analyses and interpretation of the data in a multidisciplinary context. As such, Q4D provides a unique opportunity to combine detailed process-based studies, with modelling and mapping on both the small- and large-scale, but also addressing direct policy-relevant marine environmental issues.

Also on a policy level, major challenges are being faced regarding **anticipation on climate change** (e.g. sea-level rise, increased storminess). The Flemish Authorities are now evaluating plans on coping with large-scale changes and needed large-scale interventions. Meanwhile, dredging companies, together with consultancy firms produced a vision document on **large-scale coastal developments** for Belgian waters, which now also forms part of a political debate. Q4D results are highly relevant in these discussions: on the one hand, it shows how previous human activities already affected sediment processes and benthos to a large extent; on the other hand it provides data and tools that aid better project planning and/or decision making. Q4D scientists organised a discussion meeting, together with project developers and policy makers. Issues of concerns were addresses, together with opportunities.

On a EU policy level, Q4D significantly adds to the scientific basis, needed for the implementation of the **European Marine Strategy Framework Directive** (MSFD), a framework that embodies the principles of environmental protection, improvement and restoration on an integrated basis. An overview is given on where Q4D results can be valorized. Some of the results will be directly applicable within MSFD; others contribute, indirectly, and more research or fine-tuning will be needed, after the lifetime of the project. Generally, Q4D delivers tools and data that are directly of relevance to MSFD descriptors in which **habitat distribution and extent**, **occurrence of sensitive and/or tolerant species** need to be quantified (e.g. descriptor 1, 2 and 6). For soft substrata, integrated sedimentology-benthos studies are crucial.

Continuing efforts have indeed been made on the **mapping and characterization of benthic habitats**. Based on the Q4D SediCURVE@SEA database, new substrate maps have been produced, within a **cross-border** context. These datagrids are also used on a EU level: within **DG MARE Emodnet**-Geology a **seabed sediments map** was produced, that was translated to **broad-scale habitat maps** (Emodnet-EUSeamap). Q4D results on **sedimentation/erosion rates** will also be further valorized in the Emodnet realm. Together with other Geology related results, these are uploaded, as GIS layers, into the **One-Geology** portal (www.onegeology.org; Applying Geoscience for Society) providing tools for visualisation and downloading. Since Emodnet is meant to provide Europe with the necessary data layers for sound management of its marine waters, and underpinning its policy, Q4D directly adds value to these initiatives. Furthermore, initiatives are undertaken of more detailed habitat and species mapping in the southern North Sea. Joint forces between Belgium, the Netherlands, Germany and Denmark will lead to a fully flexible database with full grain size distribution curves, from which custom-made data products can be derived. First coupling of BE-NL sediment databases allowed habitat suitability modeling of the invasive species (Belspo project ENSIS). Detailed substrate maps, based on very high resolution acoustics, are also being produced within Q4D. Based on such maps, Van Lancker *et al.* (2011) provide an overview on how the **fine-scale geomorphology** of the seabed can be used to **predict the occurrences of benthos**. In some cases, biogenic substrates (e.g. with dense aggregations of **bio-engineers**) can be mapped directly. This is now also demonstrated for the ecosystem engineer *Owenia fusiformis* (formerly *Lanice conchilega* beds were mapped), as also the invasive species *Ensis directus*.

Q4D's hypothesis that long-term macrobenthos changes are linked to **increasing eutrophication** is of relevance to MSFD descriptor 5 on human-induced eutrophication.

Specifically related to **seafloor integrity** (descriptor 6), Q4D's substrate mapping over the past 100 yrs has enabled to delineate the **extent of the seabed, significantly affected by human activities** (criterium 6.1). Long-term impact on benthos has been investigated, also, and was coupled to process-based studies providing mechanisms to explain the observed changes. As such the condition of benthic community (criterium 6.2) can also be assessed. In a case study, this aspect is particularly studied along a **gradient of degradation** related to the disposal of dredged material. Both **sensitive and tolerant species** occur in this area, where also beam trawling activity is very high.

Q4D provides data to delineate areas where **permanent alteration of hydrographical conditions** has occurred (descriptor 7). At the very least, the spatial characteristics of these areas can be provided (criterium 7.1); these can be linked to the investigated long-term benthos changes (criterium 7.2). With relevance to **concentrations of contaminants and pollution** (descriptor 8, 10), Q4D's erosion/sedimentation areas can aid in delineating the most likely areas where pollution will be concentrated. A preliminary exercise was done for selecting the best places to sample marine plastics.

Apart from MSFD, Q4D data adds value to other Directives too: especially the combined analysis of beach-foreshore-nearshore provides valuable insights into the physical drivers of ecosystem dynamics of the 1nm zone, of importance in the **Water Framework Directive (WFD)**. The mapping of erosion-sedimentation areas seems highly relevant in this perspective (e.g. towards polluted areas). Moreover, within WFD it is stated that there must be **no temporal deterioration in chemical and biological status for water bodies**, and identifies (Annex VIII) 'material in suspension' as one of the main drivers. Q4D results are highly relevant in this respect.

Finally, it needs emphasis that Q4D datasets are documented and archived following European standards, compliant with the **INSPIRE Directive**. This is guaranteed through incorporation of the data into the EU FP7 Infrastructure projects SeaDataNet (www.seadatanet.org/) and Geo-Seas (www.geo-seas.eu/), both having portals for data distribution. See following section.

Recommendations for a more sustainable development

Q4D's long-term ecosystem change analyses indicate for the last century: (1) **more erosion of the seabed**, implying more erosion of Holocene mud in the coastal zone; (2) **far field deposition** where long-term disposal of dredged material has occurred; (3) deepening of navigational channels with extended erosion towards the slopes of the channels. Most of the significant changes relate to increasing human activities. On a short-term, navigation channels are efficient traps of fine-grained material which are resuspended during and after storms. Highly concentrated benthic layers are formed and are advected away.

Still, changes are wide-spread and are observed in both natural and anthropogenically-steered areas. Overall, more poorly consolidated muds are being observed. Long-term macrobenthos changes are revealing more mud tolerant species today than 100 yrs ago, and a loss in species, typical for clean sands. It is hypothesized that those changes are due to **increasing eutrophication** in the 20th century, corresponding with increased deposition of organic matter. During this period, **beam trawling** has steadily intensified too; locally completely fragmented seafloors are being observed. This probably adds to the increased resuspension of fine-grained material. The **effect** of **climate change** on seabed processes has proven **difficult to investigate**. Increasing storminess has not been assessed as being statistically significant. Still, some of the analysed seabed data point in that direction. If so, even more fine-grained material would be recirculated.

In an era of increasing needs from marine living and non-living resources, a more sustainable development should focus, also, on finding ways to **optimize present-day practices of human activities**. On the one hand, **increasing awareness** is needed on the ways humans affect sediment processes (both water column and seabed) and their implications to marine life; on the other hand, synergies with industry are needed to come to more **sustainable practices**. With increasing sea-level, coastal safety will demand huge quantities of sand. Research has shown that resources are not renewed, and will become depleted on the long-term. **Careful consideration** of their uses is needed.

Q4D anticipates by providing new insights in the functioning of sediment processes; inferring **natural variability** and providing **indicators** where possible. **Environmental targets** can be better defined, using the historical data. Q4D demonstrates also the usefulness/necessity of combining a suite of tools for **monitoring seabed status and change**. Long-term **continuous data from multisensor tripods** have proven highly useful in understanding the basic processes of sediment transport in an area and in assessing natural from anthropogenically-induced processes; **seabed mapping**, in high resolution, allows characterization and the study of processes along gradients of change. Human alterations, as also hotspots of biodiversity are being identified. **Modelling** is a necessity to better understand the impact of sediment processes and to extrapolate findings over vast areas. Prediction of changes, of impact scenarios needs modelling. It is believed that more efforts are needed on integrative monitoring practices within a transnational set-up. Coastal and seafloor observatories would be a leap forward, though in combination with seabed mapping, both on a small- and large-scale. Well-designed sampling schemes, remain crucial. To conclude, a strong plea is held to increase efforts in building scientific knowledge bases and **face, together with all stakeholders, one the grand challenges of the 21st century**, being Seas & Oceans (Ostend Declaration, EurOCEAN 2010).

5. DISSEMINATION AND VALORISATION

5.1 Dissemination

Data

In the frame of the project, a wide range of valuable environmental measurements were carried out. Central archival of the **data and its metadata** promotes the re-use of this data for several scientific and support purposes. In-situ measurements, as well as seabed data are made available. Model results are provided too, currently on demand, but later as on-line queries. Data are disseminated via http://www.mumm.ac.be/datacentre/Databases/QUEST4D/.

European data standards and exchange formats are taking into account; as such in the near future data can be downloaded though Europena data portals such as Seadatanet and Geo-Seas, both pan-European data management infrastructures (EU FP7-I3). This will increase the visibility of the research and ensure its support to the implementation of European Directives. The data portals can be found at http://www.seadatanet.org/ and http://www.geo-seas.eu/. Data will be converted to standard transport formats such as the SeaDataNet ODV4 ASCII file format, including a mapping to common vocabularies. This format interacts with the freely available analysis and presentation tool Ocean Data View. GIS layers of the main results will be disseminated also. This will be an update of the GIS@SEA DVD that was produced as a result of the Belspo Marebasse project (Van Lancker et al., 2007). The DVD, together with the report, was widely consulted, both nationally and internationally and proved being an important resource for environmental impact studies (e.g. w.r.t. consultancy firms).

Scientific outreach

Various papers were published in **peer-reviewed journals** (Section 6). Results were presented at **national and international conferences and workshops** (oral and poster presentations; invited and keynote) (Section 6). Quest4D scientists participated in the writing of an an extensive chapter on 'Coast and Sea' (75p) (Van Lancker *et al.* submitted), within the frame of a handbook on the Geology of Flanders. Target audience is the young professional, students and the **public at large** (in Dutch).

Educational outreach

Several **PhD students** and post-docs interacted with the project (M. Baeye and S. Papili, UGent Marine Geology; M. Rabaut, UGent, Marine Biology Section; E. Zeelmaekers and R. Adriaens at KUL, Regional Geology; A. Giardino, J. Portilla, L. Fernandez, A. Ullmann, M. Liste Muñoz J. at KUL, Hydraulics; Vanlede, WL/Delft University; and P. Chen, National Sun Yat-Sen University, Taiwan). Quest4D objectives formed subject of several **Master theses**.

Q4D results and expertise are being used in **courses** taught within the programmes Oceans and Lakes (Joint Master of UGent, VUB and Antwerp University) (In-situ and remote sensing of aquatic environments, Van Lancker & Ruddick) and the European Master on Biodiversity and Conservation (EMBC) (Environmental Impact Assessment in the Marine Environment, Degraer & Van Lancker). Joint RV Belgica **Education/Geology cruises** have been set-up in 2007, 2008, 2009 and 2010. During 1 week, Q4D related measurements are carried out, whilst training students at sea. Results obtained form part of master theses and provide added value to the project. SWAN + COHERENS v2 **models are being used** for project work for civil engineering students at KUL and KHBO. Active participation took place also during the **Ocean School 010. "Education at Sea -Education for the Sea"**. Amongst others, visions were discussed on the competences expected from young scientists graduating as MSc in Ocean Science programmes.

5.2 Valorisation of data and expertise

Valorisation of results is done on a regular basis. A **project website** with a public and restricted area is available (http://www.vliz.be/projects/quest4D). A **leaflet** (http://www.vliz.be/projects/quest4D/docs/folder%202008.pdf) was distributed at national and international fora. As such, Q4D results were picked by the National University of Galway and V. Van Lancker was invited for a seminar on the Quest4D research; scientists from the Irish marine sciences community were invited. Also on a national level, interest was gained from scientists from other projects and resulted in data delivery or advice (e.g. on likely sedimentation areas of marine plastics).

Towards the **public at large**, publicity was made at the foundation "SeaOnScreen" (http://www.seaonscreen.org, with i.e. posters, 'newspaper', animations) with the aim of showing the public and politicians the value of the North Sea. A **series of posters** was created, highlighting exploration and characterization of the seafloor. The posters were used during the "Wetenschapsfeest" (17-19/10/2008), an initiative of the Flemish Government and Technopolis. Further active participation took place at various initiatives (e.g. Ostend aan Zee, Planeet Zee, UGent aan Zee). Dedicated presentations, posters, instrumentation and cores were used as educational material.

V. Van Lancker participated in a **public debate on Climate Change**, organised by Natuurpunt. **Large-scale coastal development**, in anticipation of Climate Change, was also discussed at the workshop "Open dialogue Vlaamse Baaien 2100" (16/12/2009), together with industry and government representatives.

Cross-fertilisation with other projects

Apart from data delivery to directly policy related projects (Section 4), Quest4D results are valorised in **various projects, nationally and internationally.** Nationally, cooperation exists with the Belspo projects: CLIMAR w.r.t. the effect of climate change on seabed processes; EnSIS, w.r.t. the mapping of the Ensis habitat, being the most important invasive species on the BPNS; and WESTBANKS, w.r.t. the mapping of ecosystem engineers. For some of these projects, **Q4D physical datagrids** are crucial for the **modelling of habitat suitability** of several species. On an international level. Quest4D results are directly valorised within **Emodnet**-Geology (DG MARE). Seabed sediments data was standardised and harmonised into an integrated seabed sediments map covering the North Sea and the Baltic Sea. This map is now uploaded in the **One-Geology portal**. Within this project, the SediCURVE@SEA database will be further valorised in a joint venture of Belgium, The Netherlands,, Germany and Denmark. A fully custom-made database will be developed where seabed parameters can be delivered on demand (e.g. with relevance to resource, (fish)habitat and sediment transport mapping). The sediment data have been used also for the prediction of sole behaviour in the southern North Sea (Belpo Solemod; Lacroix *et al.* 2011a,b) This links up with the initiatives undertaken within the FP7 I3 project **Geo-Seas** (www.geoseas-eu.net), being a pan-European Infrastructure on Geological and Geophysical data. Here, MUMM leads on the task '**Standardisation and harmonisation in seabed habitat mapping**'. A recommendation document with case studies is foreseen. Quest4D results will form part of this document. From a **modelling** perspective, Research initiated in Q4D on the **effect of climate change scenario's on surge levels** at the Belgian Coast and at surge level along the Scheldt river is now used and elaborated upon in the EU-project THESEUS (Innovative technologies for safer European coasts in a changing climate; http://www.theseusproject.eu/).

Organised workshops and final conference

On May, 14th 2009,an **international discussion workshop** was organised entitled '**Sediment dynamics and increasing anthropogenic pressure: ways forward?** (Conveners: Van Lancker, Fettweis & Vanlede). The maximum of participants was reached (50). 5 invitees from abroad successfully added value to the discussions.

On January 15th 2010, a second **workshop on policy and management questions related to sediment- and morphodynamics of the Belgian coastal zone** was organised (Conveners: Toon Verwaest and Vera Van Lancker). The following end-users addressed specific questions/interests: Maritime Access (Department of Mobility and Public Works, Flemish Government) raised questions related to the management of (1) maintenance dredging works in navigation channels and the outer harbour; (2) deepening dredging works in the navigation channel; (3) harbour infrastructure; and (4) disposal of dredged material. Following needs were expressed, specifically: (1) Estimation of individual and cumulative effects of historical, present-day and future activities on sediment budgets and morphodynamics against a reference situation; natural vs anthropogenically induced evolution?; (2) Increase of process knowledge and the reconstruction of morphological evolution and trends since first large-scale human activities, and more specifically related to the behaviour of high concentration benthic layers; and (3) A sediment balance, related to the coastal area and cross-border areas; and sediment turnover in morphological structures, eg rates of sediment erosion and deposition of the sandbank areas. The Belgian Navy was particularly interested in wave-current interaction, as also in the spatial distribution of beam trawling on the Belgian part of the North Sea.

To present the final results of Quest4D, a **conference** was held entitled **"Human footprint on the seafloor. Keys from the Past, Doors to the Future"** (Brussels, Natural History Museum, September 2nd 2011; Conveners: Vera Van Lancker & Kevin Ruddick), and organised in conjunction with the Belspo STEREOII project BELCOLOURII. 104 participants, with experts from BE, NL, FR, UK, and IRL could took part in discussions on **assessing human impacts on the marine environment**. Against a background of future intensifications of human activities (e.g. **large-scale engineering works**), debates were held on achieving good environmental status following the **European Marine Strategy Framework Directive (MSFD)**, as also on **Integrated Monitoring**. Mostly awareness was raised on environmental issues to consider, though the required scale of assessment was felt to be too vague, especially when considering the transnational context. From the monitoring debate, the need for both integrated research, as well as for integration of (new) technologies was flagged, which together with dedicated modelling should support ecosystem-based approaches to the management of the marine environment.

Follow-up committees

Valorisation took place during meetings with a **follow-up committee**, consisting of governmental organisations (Flemish/Federal), industrial groups and the main users of the EEZ. An overall kick-off meeting took place in Brussels on 26/03/07. End-users meetings were held at 19/11/07, 27/06/08, 14/05/09 (see above) and 15/01/2010 (see above). On December, 6th 2010, an end-user workshop was organised devoted to the inferred long- to medium-term morphological evolution of the Belgian coastal zone. The final conference (02/09/11)was regarded the last end-user meeting. Ad hoc technical meetings took place with most of the end-users, to ensure exchange of expertise, data or equipment. **Joint publications with end-users** took place and are foreseen in the near future.

6. PUBLICATIONS

6.1 Main reports QUEST4D

Van Lancker, V., Du Four, I., Degraer S, Fettweis, M., Francken, F., Van den Eynde, D., Devolder, M., Luyten, P., Monbaliu, J., Toorman, E., Portilla, J., Ullmann, A., Verwaest, T., Janssens, J., Vanlede, J., Vincx, M., Rabaut, M., Houziaux, J.-S., Mallaerts, T., Vandenberghe, H., Zeelmaekers, E. and Goffin, A. (2009). QUantification of Erosion/Sedimentation patterns to Trace the natural versus anthropogenic sediment dynamics (QUEST4D). **Final Report Phase 1**. Science for Sustainable Development. Brussels : Belgian Science Policy, 63p + Annexes.

Van Lancker, V., Baeye, M., Du Four, I., Degraer, S., Fettweis, M., Francken, F., Houziaux, J.S., Luyten, P., Van den Eynde, D., Devolder, M., De Cauwer, K., Monbaliu, J., Toorman, E., Portilla, J.,Ullman, A., Liste Muñoz, M., Fernandez, L., Komijani, H., Verwaest, T., Delgado, R., De Schutter, J., Janssens, J., Levy, Y., Vanlede, J., Vincx, M., Rabaut, M., Vandenberghe, H., Zeelmaekers, E. and Goffin, A. (2011). QUantification of Erosion/Sedimentation patterns to Trace the natural versus anthropogenic sediment dynamics (QUEST4D). **Draft Final Report**, January 2011. Science for Sustainable Development. Brussels: Belgian Science Policy, 93 pp. + Annex. (http://www.vliz.be/projects/quest4D/data.php#reports)

6.2 Peer-reviewed publications *(cooperative papers are indicated)*

2008

Du Four, I. and Van Lancker, V. (2008). Changes of sedimentological patterns and morphological features due to the disposal of dredge spoil and the regeneration after cessation of the disposal activities. *Marine Geology* 255(1-2), 15-29. (UGent RCMG)

Fettweis, M. (2008). Uncertainty of effective density and settling velocity of mud flocs derived from in-situ measurements. Estuarine, Coastal and Shelf Science, 78(2), 426-436. (MUMM)

2009

Fettweis, M., Houziaux, J.-S., Du Four, I., Van Lancker, V., Baeteman, C., Mathys, M., Van den Eynde, D., Francken, F. and Wartel, S. (2009). Long-term influence of maritime access works on the distribution of cohesive sediment: Analysis of historical and recent data from the Belgian nearshore area (southern North Sea). Geo-Marine Letters. 29, 321-330. (MUMM/RBINS-Invertebrates/UGent-RCMG)

2010

Fettweis, M., Francken, F., Van den Eynde, D., Verwaest, T., Janssens, J. and Van Lancker, V. (2010). Storm influence on SPM concentrations in a coastal turbidity maximum area with high anthropogenic impact (southern North Sea). Continental Shelf Research 30(13), 1417-1427. (MUMM/WL)

Giardino, A., Van den Eynde, D. and Monbaliu, J. (2010). Wave effects on the morphodynamic evolution of an offshore sand bank. Journal of Coastal Research, SI 51, 127-140.

Ullmann, A., Monbaliu, J. (2010). Changes in atmospheric circulation over the North Atlantic and sea surge variations along the Belgian coast during the 20th century. International Journal of Climatology, 30, 558-568. (KUL)

Van den Eynde, D., Giardino, A., Portilla, J., Fettweis, M., Francken, F. and Monbaliu, J. (2010). Modelling The Effects Of Sand Extraction On The Sediment Transport Due To Tides On The Kwinte Bank. Journal of Coastal Research, SI 51, 106-116.

Van Lancker, V., Bonne, W., Uriarte, A. and Collins, M.B. (Eds) (2010). *European Marine Sand and Gravel Resources, Evaluation and Environmental Impact of Extraction*. Journal of Coastal Research, Special Volume 51, 226p. (20 research papers) (Online available for free at: http://www.cerf-jcr.org/index.php?option=com_contentandview=categoryandid=29andItemid=78)

Van Lancker, V., Bonne, W., Velegrakis, A. and Collins, M.B. (2010). Aggregate extraction from tidal sandbanks: is dredging with nature an option? Introduction. Journal of Coastal Research SI51, 53-62.

Van Lancker, V.R.M., Bonne, W., Bellec, V., Degrendele, K., Garel, E., Brière, C., Van den Eynde, D., Collins, M.B. and Velegrakis, A.F. (2010). Recommendations for the sustainable exploitation of tidal sandbanks. Journal of Coastal Research SI51, 151-161.

2011-2012

Baeye, M., Fettweis, M., Voulgaris, G. and Van Lancker, V. (2011). Sediment mobility in response to tidal and wind-driven flows along the Belgian inner shelf, southern North Sea. Ocean Dynamics. doi:10.1007/s10236-010-0370-7 (UGent RCMG, MUMM)

Baeye, M., Fettweis, M., Legrand, S., Dupont, Y. and Van Lancker, V. Seabed Mine Burial in High Turbidity Area, Belgian Coastal Zone. Continental Shelf Research (in press) (UGent-RCMG – MUMM)

Fettweis, M. and Nechad, B. (2011). Evaluation of in situ and remote sensing sampling methods for SPM concentrations, Belgian continental shelf (southern North Sea). Ocean Dynamics. 61, 157-171. doi:10.1007/s10236-010-0310-6 (MUMM)

Fettweis, M., Baeye, M., Francken, F., Lauwaert, B., Van den Eynde, D., Van Lancker, V., Martens, C. and Michielsen, T. (2011). Monitoring the effects of disposal of fine sediments from maintenance dredging on suspended particulate matter concentration in the Belgian nearshore area (southern North Sea). Marine Pollution Bulletin, 62, 258-269. doi:10.1016/j.marpolbul.2010.11.002 (MUMM, UGent RCMG)

Houziaux, J.-S., Fettweis, M., Francken, F. and Van Lancker, V. (2011). Historical (1900) seafloor composition in the Belgian-Dutch part of the North Sea: A reconstruction based on calibrated visual sediment descriptions. Continental Shelf Research, 31, 1043-1056. (MUMM)

Van Lancker, V., Moerkerke, G., Du Four, I., Verfaillie, E., Rabaut, M. and Degraer, S. (2012). Fine-scale geomorphological mapping for the prediction of macrobenthic occurrences in shallow marine environments, Belgian part of the North Sea, pp. 251-260. In: Harris, P. and Baker, E.K. (Eds.). *Seafloor Geomorphology as Benthic Habitat: GeoHab Atlas of seafloor geomorphic features and benthic habitats*. Elsevier Insights. (MUMM/UGent-RCMG/UGent-Marbio)

In revision and submitted

Baeye, M., Fettweis, M., Nechad, B. and Van Lancker, V. Evaluation of MODIS satellite images for the assessment of spatio-temporal SPM concentration variation in the southern North Sea. Estuaries & Coasts (submitted) (UGent-RCMG, MUMM)

Chen, P., Fettweis, M., Van den Eynde, D., Yu, J.C.R. Numerical simulation of flocculation behaviours in coastal seas. Geo-Marine Letters (submitted) (MUMM)

Fettweis, M., Baeye, M., Lee, B.J., Chen, P. and Yu, J.C.R. Hydro-meteo influences and multimodality of suspended particle size distributions in a mixed sediment environment. Geo-Marine Letters (in revision) (MUMM-UGENT RCMG – KUL)

Rabaut, M., Du Four, I., Van Lancker, V., Degraer, S. and Vincx, M., (in revision). Ecosystem engineers stabilize sand bank systems: investigating valuable *Owenia fusiformis* microhabitats using multibeam and side-scan sonar. (UGent-Marbio/MUMM)

Ullmann, A., Sterl, A., Van den Eynde, D. and Monbaliu, J. (submitted). Atmospheric pressure and sea surges along the Belgian coast during the 20th century and changes in sea-surge height under climate change. Continental Shelf Reseach. (KUL/MUMM) (Q4D-CLIMAR cooperation)

Van Lancker, V., Deronde, B., De Vos, K., Fettweis, M., Houthuys, R., Martens, C. and Mathys, M. (submitted). Hoofdstuk 6. Kust en Zee, pp 1-75. In: Borremans *et al. Geologie van Vlaanderen*. Genootschap van Gentse Geologen. Academia Press.

6.3 Others

2007

Bolaños, R. Osuna, P., Wolf, J., Monbaliu, J. and Sanchez-Arcilla, A. (2007). Wave-current coupling in two different environmental conditions. WISE Workshop, Australia. (abstract + presentation)

Bolaños, R. Osuna, P., Wolf, J., Monbaliu, J. and Sanchez-Arcilla, A. (2007). Development of a fully coupled wave-current interaction model. The POLCOMS-WAM system. Liege Colloquium. (abstract + presentation)

Dezeure, B. (2007). *Sedimentation rates at dumpsites of dredged material.* Thesis submitted to obtain the degree of Master in Science in Advanced Studies in Marine and Lacustrine Sciences. Unpublished Msc Thesis, Gent (B): Universiteit Gent (Renard Centre of Marine Geology), 38 pp.

Du Four, I., Dezeure, B., Degraer, S. and Van Lancker, V. (2007). Regional Impact Assessment of Long-Term Dumping in the Sierra Ventana Region, Belgian Continental Shelf. CoastGIS'07 – 8th International Symposium on GIS and Computer Mapping for Coastal Zone Management. Santander (ESP), 8-10/10/2007. Co-publication of RCMG with SMB.

Fettweis, M. (2007). Experience and problems with SPM concentration and particle size measurements. Workshop "In-situ measurements of SPM characteristics - Problems and solutions", Wilhemshaven, July 3-5.

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Monbaliu, J. (2007). Coastal defence: How to deal with climate change? Seamocs workshop on Implications of climate change for marine and coastal safety. Palmse (near Tallinn, Estonia), 11-12 Oktober, 2007 (abstract+presentation).

Monbaliu, J., Osuna, P. Wolf, J., Bolaños, R. and Sanchez-Arcilla, A. (2007). 3D Wave current coupling – how easy is it? WISE Workshop, Australia. (abstract + presentation)

Nakas, G. (2007). *Identifying hotspots of biodiversity through classification of sonar data.* Thesis submitted to obtain the degree of Master in Science in Advanced Studies in Marine and Lacustrine Sciences. Unpublished Msc Thesis, Gent (B): Universiteit Gent (Renard Centre of Marine Geology/Section Marine Biology), 39 pp

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Van Kessel, T., Vanlede, J. and De Kok, J. (2007). Development of a mud transport model for the Scheldt estuary. Proceedings INTERCOH'07 – Brest, France.

Van Lancker, V. (2007). Effects of development and use on eco-morphology and coastal habitats. First BeNCoRe Conference: State of the Art and future of Belgian Coastal Research. BeNCoRe. Leuven (B), 26/04/2007. (invited)

Van Lancker, V. (2007). Sand Mining and nourishment. International Anniversary Symposium of the Netherlands Centre of Coastal Research (NCK). NCK. Ijmuiden (NL), 14-15/06/2007. (Keynote)

Van Lancker, V. (2007). Morfologische en sedimentologische context van de Baai van Heist Seminarie "De Zandbank te Heist, een boeiend fenomeen". Coördinatiepunt Duurzaam Kustbeheer/AMINAL. Heist (B), 19/10/2007. (invited)

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Verwaest, T. (2007). Using simple semi-empirical models for integrated assessment of scenarios for a navigation channel; the case of the port of Ostend, Belgium. Proceedings Coastal Sediments '07, 13-17/05/2007, New Orleans, USA.

Wolf, J., Osuna, P., Bolaños, R. , Monbaliu, J. and Sanchez-Arcilla, A. (2007). Coupled wave and current modelling in the MARIE project. EGU Vienna. (abstract + presentation)

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Du Four, I., Verfaillie, E., Rabaut, M. and Van Lancker, V. (2008). Mapping of the seabed of the Belgian part of the North Sea to assist in a science-based approach to management. VLIZ Jongerendag. VLIZ. Brugge (B), 29/02/2008. (invited). Co-publication of RCMG with SMB.

Du Four, I., Veys, K. and Van Lancker, V. (2008). Balancing the impact of the natural versus the anthropogenically induced sediment dynamics, North of the Vlakte van de Raan (Belgian part of the North Sea). Littoral 2008. A Changing coast: challenge for the environmental policies. 9th International conference. Venice (IT), 25-28/11/2008 (abstract+ paper+presentation).

Fettweis, M. (2008). Uncertainty of excess density and settling velocity of mud flocs derived from in situ measurements. Particles in Europe workshop, October 13-14, Bologna (Italy).

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Veys, K. (2008). *Natural versus Anthropogenically-induced sedimentation, North of the Vlakte van de Raan (Belgian part of the North Sea).* Thesis to obtain the degree of Master in Science in Advanced Studies in Marine and Lacustrine Sciences. Gent (B): Universiteit Gent (Renard Centre of Marine Geology), 29 pp + Annex.

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Other activities *(international only)*

2007

Van Lancker, V.: **moderator** of the Technical Session A: Longterm morphodynamics of estuaries. Conference River, Coastal and Estuarine Morphodynamics: RCEM2007. Twente University. Enschede, 17-21/09/2007.

Fettweis, M.: **co-organiser** of the Workshop "In-situ measurements of SPM characteristics - Problems and solutions", Wilhemshaven, July 3-5 2007.

2008

Van Lancker, V.: **invited lecturer** on 'Interaction Human – Physical Environment'. EMSc MER. European Master of Science in Marine Environment and Resources. Joint European Postgraduate Studies. 2nd International Postgraduate Course. Research in Marine

Environment and Resources (RIMER). AQUARIUM, Donostia-San Sebastian (ESP), 2-11/07/08.

Fettweis, M.: **co-convener** of the Workshop "Particles in Europe (PIE)", Bologna, October 13-14 2008

2010

Degraer, S. and Van Lancker, V.: **organization and chairing** a session (oral and poster) on 'Marine Habitat Mapping: Where Physical Oceanographers, Marine Ecologists, GIS Experts, and Habitat Suitability Modelers Meet'. Ocean Sciences 2010. Portland, Oregon (USA), 22-26/02/2010.

Van Lancker, V.: **panel leader** within a session on vision of Academia on the competences expected from young scientists graduating as MSc in Ocean Science programmes. Ocean School 010. "Education at Sea - Education for the Sea". The Royal Academy of Science and Arts in Belgium – Flanders Marine Institute (VLIZ). Ostende (B), 16-17/02/2010.

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9. ANNEXES

The annexes are available on our website:

http://www.belspo.be/belspo/SSD/science/pr_terrestrial_en.stm