Quantification of Erosion/Sedimentation patterns to Trace the natural versus anthropogenic sediment dynamics

"QUEST4D"

ANNEXES

Contents

Annex 1. Database management of complex datasets. Developments for benthic tripod data and model results

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1. Tripod data

ADV, CTD, OBS and LISST metadata resulting from the tripod moorings were documented and stored in an Oracle10g Relational Database Management System. These metadata are used as pointer to the real measurements in files on the server. The database is implemented as an extension of the IDOD database that is now able to handle a wide range of high resolution measurements (discrete profiles, time series and trajectories).

The conceptual scheme was based on the detailed analysis of data sets, discussions with data originators, information from the British Oceanographic Data Centre, existing international guidelines and the existing IDOD database structure. The structure is visualized in Figure A1-1 and shows all metadata documenting a given file containing a data series. Every file is described by the set of parameters and units that it contains. To define the set and order of parameters, present in the file, the entities DS PARAM SET and DS PARAM COMP are introduced. The description of the entity DS FILE, with its attributes, is given in more detail in Table A1-1.

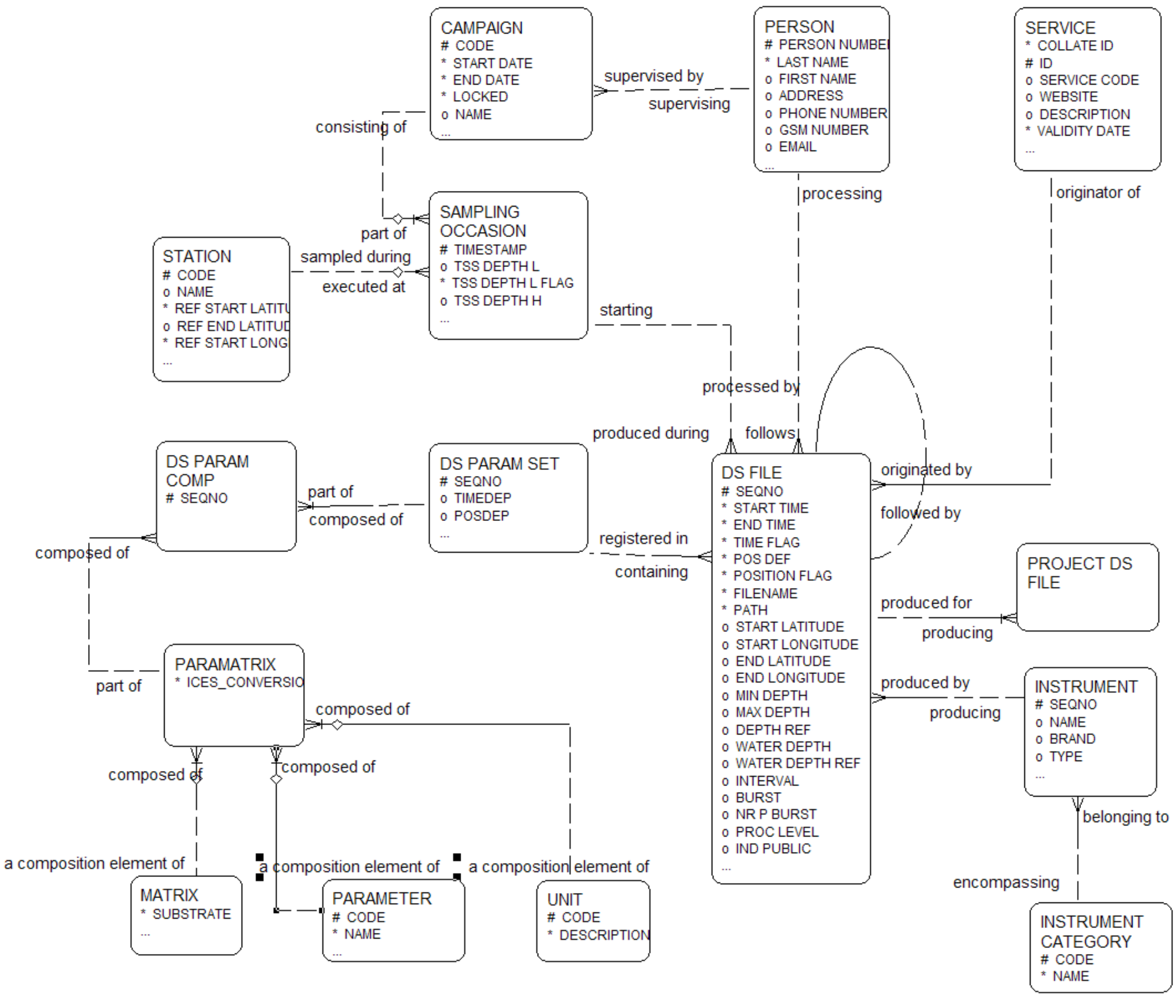

Figure A1-1: Conceptual scheme for data series.

Table A1-1: Description of the attributes of the entity `DS FILE`.

Attribute Name	Opt.	Format	Length	Dec.	Attribute Description
SEQNO	N	NUMBER	11	0	Unique identification of a data file.
START TIME	N	DATE			Date and time of the first measurement in the data serie (UTC).
END TIME	N	DATE			Date and time of the last measurement in the data serie (UTC).
TIME FLAG	N	NUMBER	1	0	Flag describing the quality of start and end time (e.g. time suspect).
POS DEF	N	VARCHAR2	2		Definition of position (fixed point, fixed line, line trajectory, fixed box, box trajectory).
POSITION FLAG	N	NUMBER	1	0	Flag describing the quality of the position.
FILENAME	N	VARCHAR2	80		Name of the file containing the data.
PATH	N	VARCHAR2	200		Full path name of the file.
START LATITUDE	Y	NUMBER	25	15	Start latitude of the sample.
START LONGITUDE	Y	NUMBER	25	15	Start longitude of the sample.
END LATITUDE	Y	NUMBER	25	15	End latitude of the sample. Blanco in case of point measurement.
END LONGITUDE	Y	NUMBER	25	15	End longitude of the sample. Blanco in case of point measurement.
MIN DEPTH	Y	CHAR			Depth or minimum depth in data series in case of varying depth expressed in meter. Depth is entered as positive number, height above as negative. The value is relative to depth reference.
MAX DEPTH	Y	CHAR			Insert maximum sampling depth in case of varying depth or depth bins expressed in meter. Depth is entered as positive number, height above as negative. The value is relative to depth reference.
DEPTH REF	Y	VARCHAR2	10		Terms used to describe the zero point (datum) for vertical co-ordinate reference systems.
WATER DEPTH	Y	NUMBER	7	2	Depth of water column in meter.
WATER DEPTH REF	Y	VARCHAR2	10		Terms used to describe the zero point (datum) for vertical co-ordinate reference systems.
INTERVAL	Y	NUMBER	7	2	Interval between data cycles in units as expressed in 'interval unit'. If no degree of regularity is present, it should be left empty.
BURST	Y	NUMBER	7	2	Interval during which measurements are done in units as expressed in 'interval unit'.
NR P BURST	Y	INTEGER	5		Number of measurements per burst.
PROC LEVEL	Y	VARCHAR2	5		A flag to indicate the processing level.
IND PUBLIC	Y	NUMBER	1	0	Indicates whether the data serie can be made public.
INTERVAL UNIT	Y	VARCHAR2	3		Units in which 'interval' and 'burst' are expressed.
POSITION INSTRUMENT	Y	VARCHAR2	40		Instrument used to determine the latitude and longitude (e.g. DGPS : Differential global positioning system).
VERSION DATE	Y	DATE			Date of creation of the data file.
POSITION REFERENCE	Y	NUMBER	1	0	Reference system used to determine the position (e.g. WGS84, ED50)
ORIG FILENAME	Y	VARCHAR2	80		Name of the file by data originator.
COMMENTS	Y		4000		Any additional comment by data originator or processor giving more information on quality and processing.

Before data series could be routinely archived, a data format and processing level was agreed with the concerned scientists. ADV data files also contain measurements from the CTD and OBS sensors. As the measurement depth is a necessary metadata parameter, and sensors were installed at different heights, the files needed to be recreated. Data were loaded in the database, metadata was extracted to feed the table documenting the data files (DS FILES), after which the data were rewritten in a file for each sensor and measurement campaign. Different PL/SQL procedures were written to automate the process, as shown in Figure A1-2.

The user can query the data by entering his selection criteria in the on-line interface. Selection can be based on the parameter contained in the file or the measurement instrument can be the first step in data retrieval (Figure A1-3).

Results are shown as a list of detailed meta information that can be used to select the requested files. After selection, the files are compressed and put on a ftp-site (see Figure A1-4).

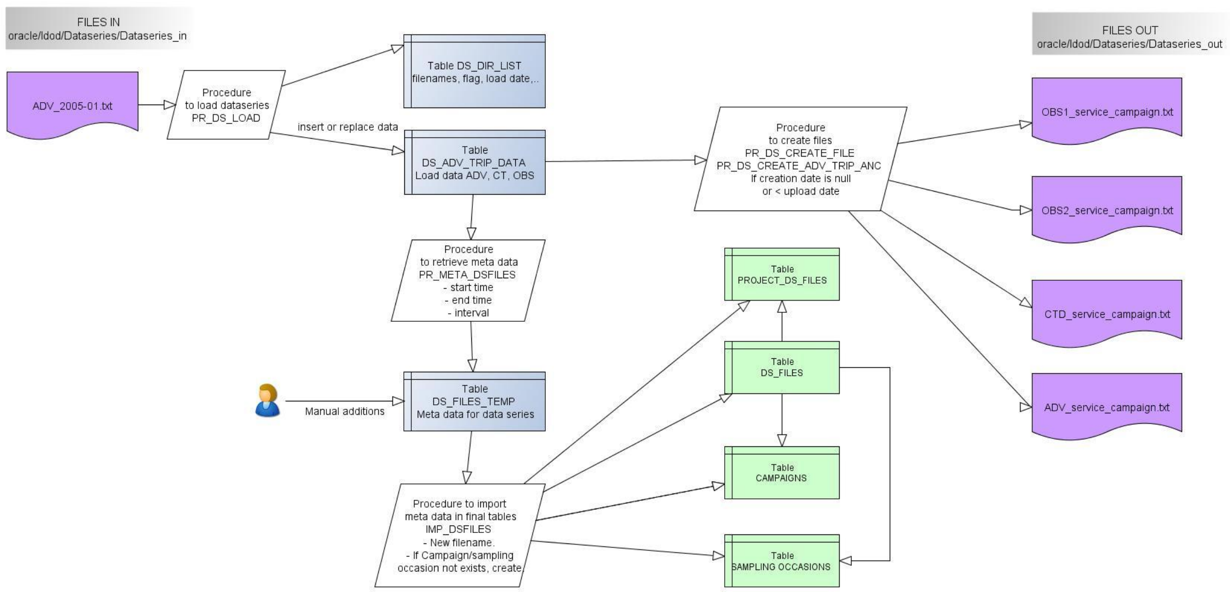

Figure A1-2: Import/export flow for ADV, CTD and OBS data from tripod moorings.

Table A1-2: Parameters for ADV, CTD, OBS and LISST data.

CODE	NAME	ABBR_NAME
AMP1	Signal return amplitude by beam 1 of in-situ accoustic current meter	Signal return amplitude 1
AMP2	Signal return amplitude by beam 2 of in-situ accoustic current meter	Signal return amplitude 2
AMP3	Signal return amplitude by beam 3 of in-situ accoustic current meter	Signal return amplitude 3
CDIR	Current direction by in-situ accoustic current meter	Current direction
CVEL	Current velocity by in-situ accoustic current meter	Current velocity
CVELEAST	Eastward current velocity by in-situ accoustic current meter	Eastward current velocity
CVELNOR	Northward current velocity by in-situ accoustic current meter	Northward current velocity
CVELUP	Upward current velocity by in-situ accoustic current meter	Upward current velocity
DEPTHAB	Depth above surface of the bed	Depth above surface of the bed
DEPTHSL	Depth below sea surface by pressure sensor	Depth below sea surface
DEPTHSLC	Depth below sea surface by CTD	Depth below sea surface
M_TIMER	Date and time of model run	Time of model run
OBS	Optical backscatter instrument output	Optical backscatter
ODAY	Ordinal date (day of the year starting at 1 (01 Jan 00:00))	Day of the year
PITCH	Orientation, pitch, of measurement platform	Pitch
PSALC	Practical salinity of the water body by CTD	Salinity
QUAL1	Quality parameter for accoustic receiver in %	Quality Amplitude 1
QUAL2	Quality parameter for accoustic receiver in %	Quality Amplitude 2
QUAL3	Quality parameter for accoustic receiver in %	Quality Amplitude 3
ROLL	Orientation, roll angle, of measurement platform	Roll
SPM	Suspended particlate matter by in-situ OBS sensor calibrated against sample	Suspended particulate matter
SPMOB	Suspended particlate matter by in-situ OBS sensor calibrated against sample	Suspended particulate matter
TEMPC	Temperature by CTD	Temperature
TIME	Date and time	Time
TURBOB	Turbidity by OBS	Turbidity
YEAR	Year	Year
PVC1	Particles 0-2.73 μm volume concentration	
PVC2	Particles 2.73-3.22 μm volume concentration	
…	…	

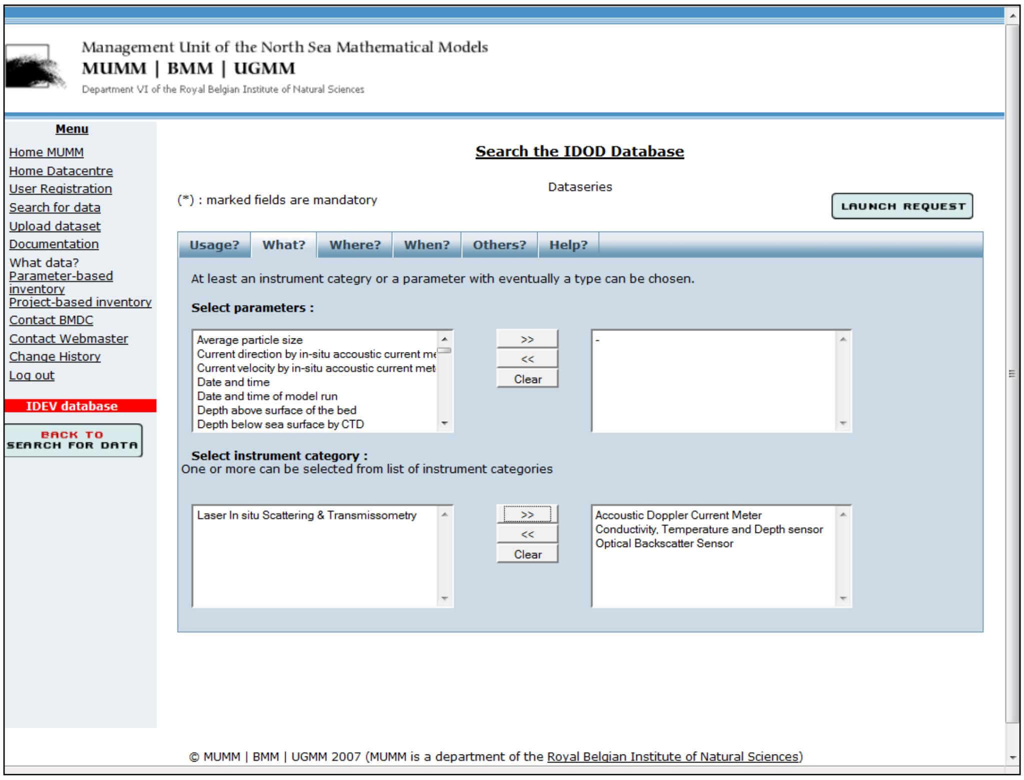

Figure A1-3: Online query for data series.

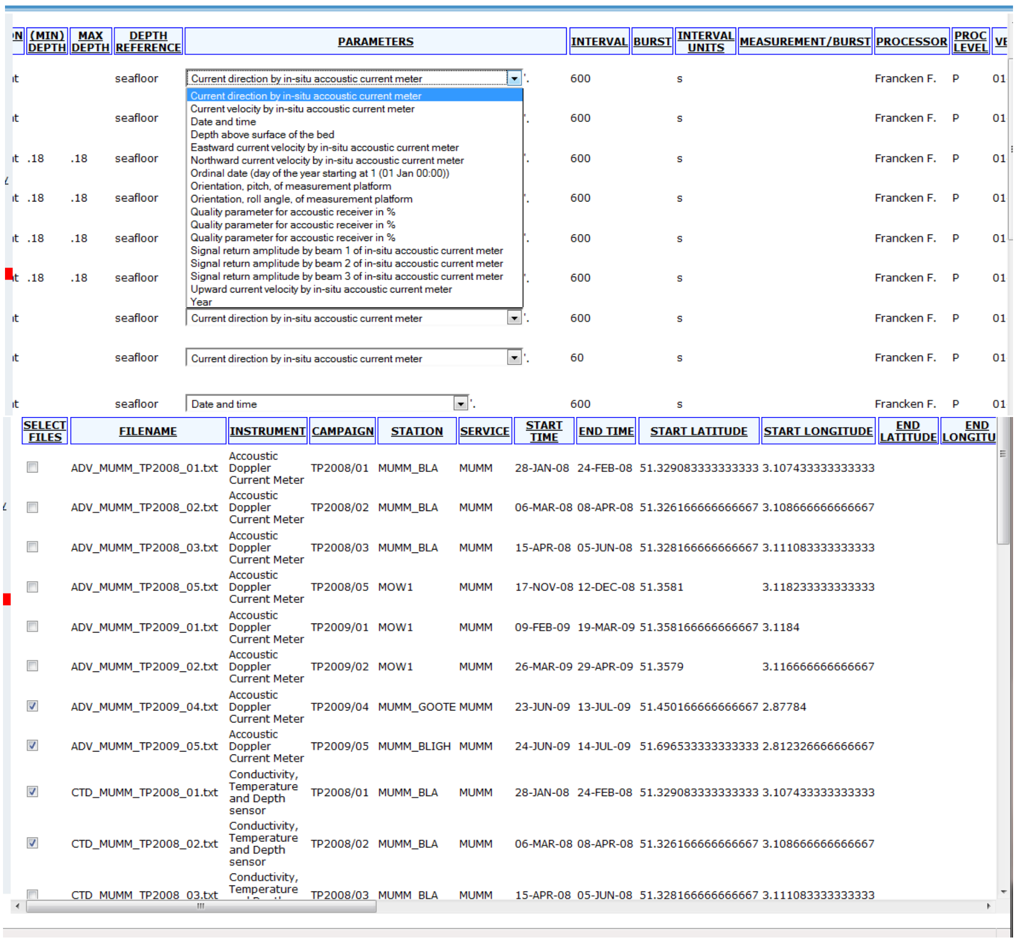

Figure A1-4: User interface, showing list of query results for data series.

2. Model data

The operational model OPTOS-BCZ produces twice a day, 5 days of forecasts and 12 hours of hind casts for sea level, currents, temperature, salinity at a ten minute interval.

Results are stored for 10 stations of interest for the Quest4D project. Data are organized in a file per parameter per station, with different columns to represent the 10 relative depths at that station.

Data are loaded in temporary tables and subsequently treated by PL/SQL procedures to preserve only the best calculations and to transpose the data as vertical profiles. The values for the different parameters are finally loaded in one table (MOD_RESULTS). An additional column (m_height) is added to store the height above surface of the bed, calculated using the mean water depth, the modelled surface elevation and the relative height in the water column. Information on the full parameter name and the unit used are retrieved via the entities DS PARAM SET and DS PARAM COMP, as shown in Figure A1-5. The full parameter names of currently stored model data are displayed in Table A1-3.

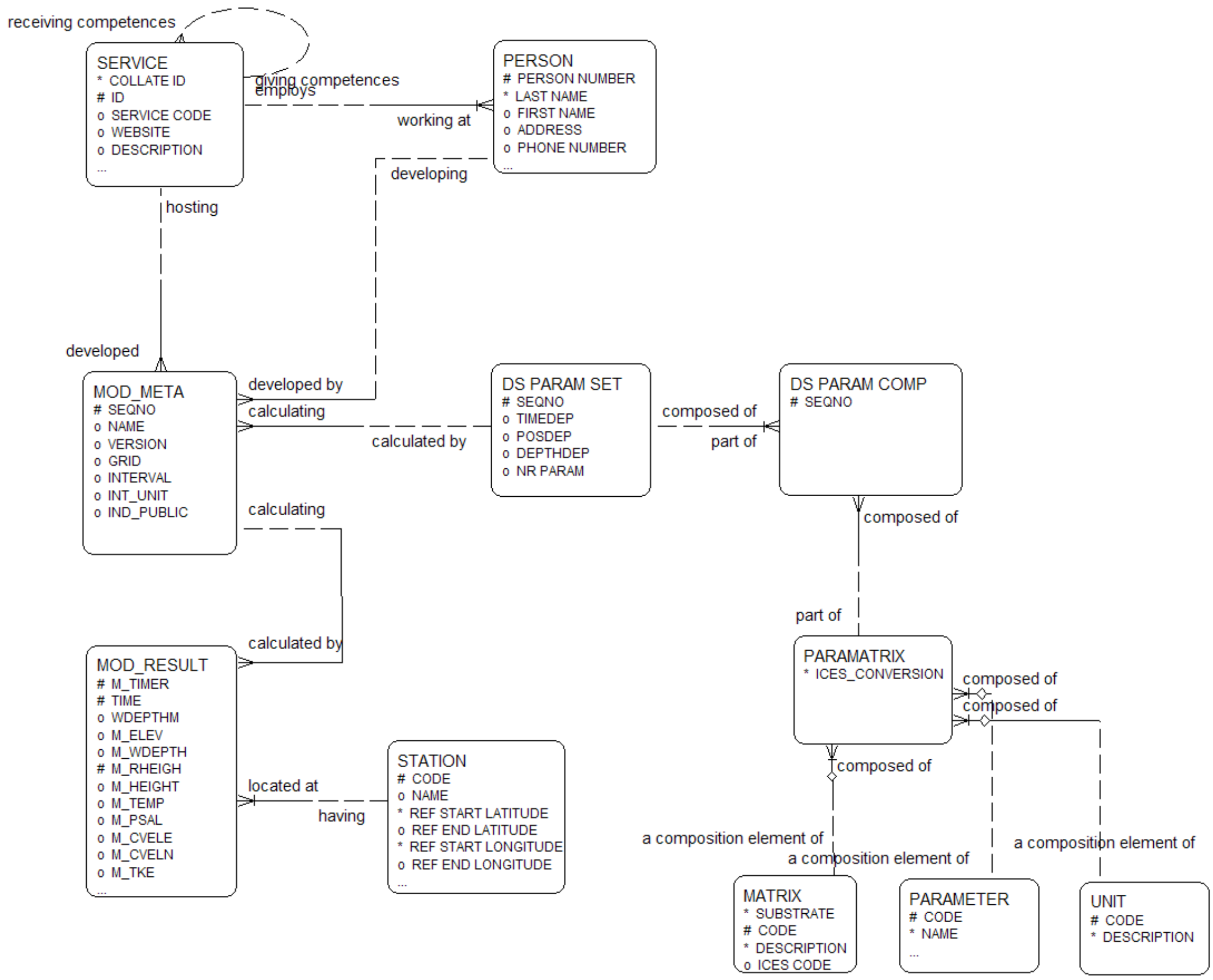

Figure A1-5: Conceptual scheme for operational model results at relevant stations.

Table A1-3: Parameters for operational model results.

CODE	NAME	ABBR_NAME
M_TIMER	Date and time of model run	Time of model run
M_ELEV	Surface elevation (Mean Sea Level datum) of the water body by model calculation	Surface elevation (msl)
M_WDEPTH	Sea-floor depth below instantaneous sea level in the water body by model calculation	Water column depth (instantaneous)
M_RHEIGH	Relative height above surface of the bed in the water body by model calculation	Relative height (surface of the bed)
M_HEIGHT	Height above surface of the bed in the water body by model calculation	Height above surface of the bed
M_PSAL	Practical salinity of the water body by model calculation	Salinity
M_TEMP	Temperature by model calculation	Temperature
M_CVELE	Eastward current velocity by model calculation	Eastward current velocity
M_CVELN	Northward current velocity by model calculation	Northward current velocity
M_TKE	Turbulent kinetic energy by model calculation	Turbulent kinetic energy
M_DISS	Turbulent dissipation rate by model calculation	Turbulent dissipation rate
M_BSTOT	Norm of the total bottom stress by model calculation	Norm of the total bottom stress

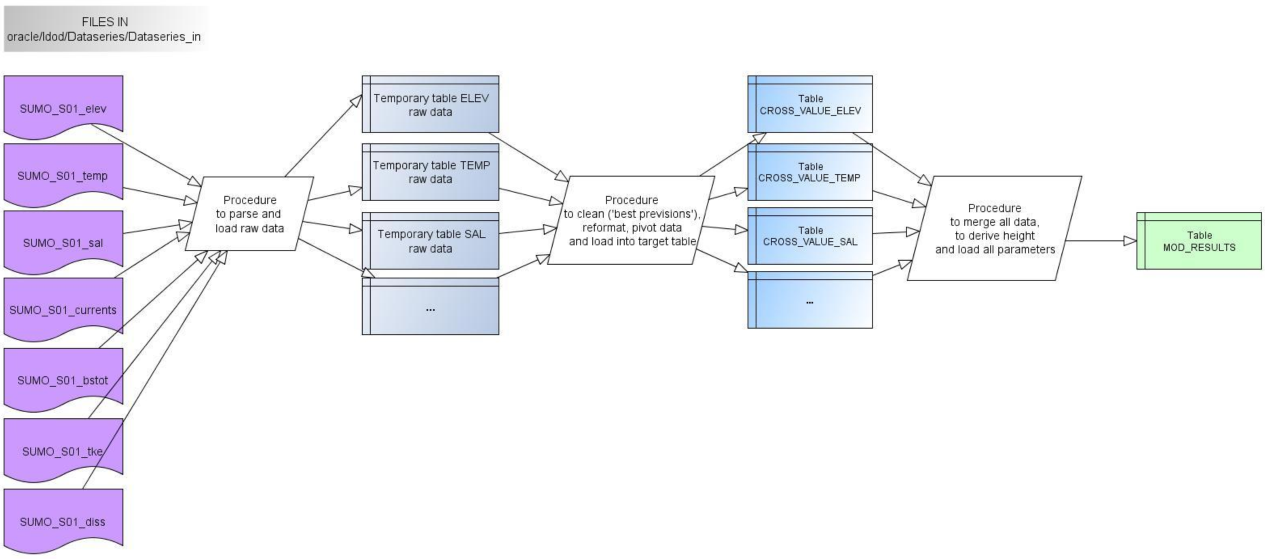

Figure A1-6: Flow of model data.

Annex 2. Decadal morphological trend analysis along the beach, shoreface and coastal zone of the Belgian part of the North Sea

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This Annex presents all the results of the morphological trend analyses over the past decade. They relate to the beach, shoreface and coastal zone in Belgian waters.

Figures A2-1 to A2-10 show the erosion trends of beach and shoreface along the Belgian coast, based upon topo-bathymetric datasets between 1997 and 2010. Each Figure contains 4 panels, presenting the following:

- The uppermost panel shows the erosion trend (in cm/year), calculated for each grid cell as the slope of the linear least squares approximation of the time series of topo-bathymetrical data available in that cell. Also shown are the high water line (red), the low water line (black), and the seaward boundary of the shoreface (green).
- The second panel visualizes for each grid cell the R^2 value of the linear least squares approximation, and gives and indication of the significance of the erosion trend. Additionaly, this panel also contains the high water line, the low water line and the seaward shoreface boundary.
- The third panel shows again the erosion trend, but only for grid cells where $R^2 > 0.5$. Below this threshold value, the morphological evolution is not considered to follow a consistent (linear) trend and topo-bathymetrical changes have a more random-like character. The red lines are depth contours and give an indication of the topology.
- The last panel presents a map of the most recent topo-bathymetry. Also shown on this map is the zero erosion contour (black line), which is in fact the boundary between erosive and sedimentary zones. The coloured bars in this panel give a rough overview of the beach nourishments and scrapings, performed along the Belgian coast. Green bars indicate that no nourishment took place in the analyzed period (1997 up till now), in light purple zones beach scrapings took place (consisting of adding sand above the high water line, typically a few 1.000m³ each time and per section, usually but not always executed on a regularis basis); the darker purple gives the zones where nourishments have been performed (consisting of adding sand to the whole beach, typically a few 10.000m³ per section, usually executed only once). The blue colour indicates the sections where excavation took place (only in a small area, west of the Zeebrugge harbour).

The small grey squares next to the scale bars and the legends indicate to which panels they apply.

Figures A2-11 to A2-13 present similar results as the previous figures, but now for the coastal zone (~15 km in sea). Figures A2-14 and A2-15 show different zones where the erosion or sedimentation trend are summed to give the total volumetric trend for each of these zones (based on the beach and shoreface datasets). The different zones were marked out, based on a common erosion or sedimentation trend, and can in many cases be linked to human interference (large infrastructure works) or otherwise –in the case of natural evolution– to distinctive morphological features (gullies and the transition zone from shoreface to sea floor). Note that many zones that are highlighted in Figures A2-14 and A2-15 end abruptly, because of the limited spatial extent of the datasets. Most of these zones would extend beyond the limits of the datasets.

Finally, Table A2-1 gives the total volumetric trend for 4 areas along the Belgian coast. The numbers presented in this Table result from summation of the erosion trend over all grid cells of the erosion/sedimentation maps presented in Figures A2-1 to A2-10. For this purpose, the Belgian coast was divided in 4 large parts, and summation was performed for all 4 parts and for the wet beach, as well as for the shoreface.

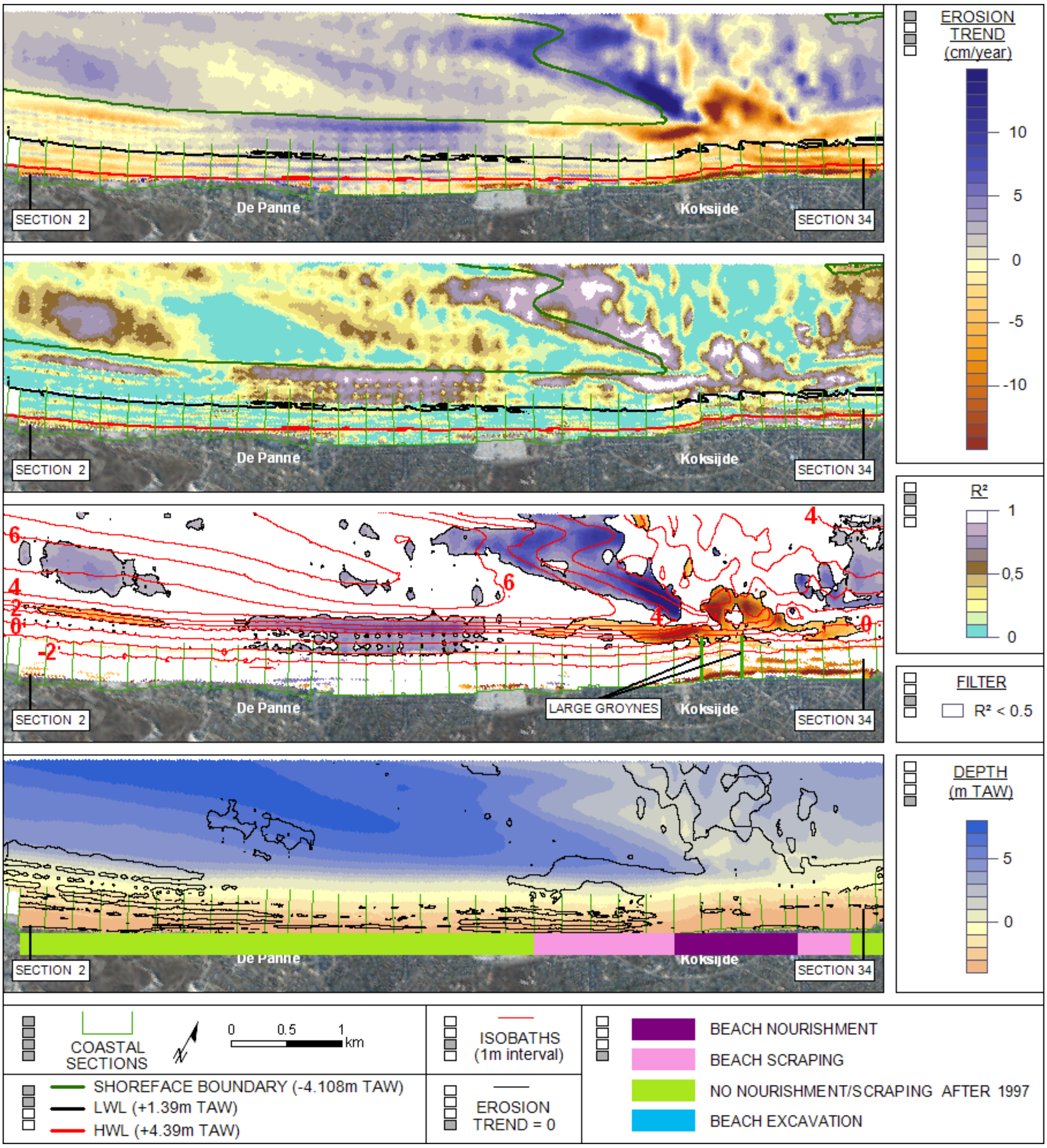

Figure A2-1. Erosion and sedimentation trends for beach and shoreface (sections 2-34).

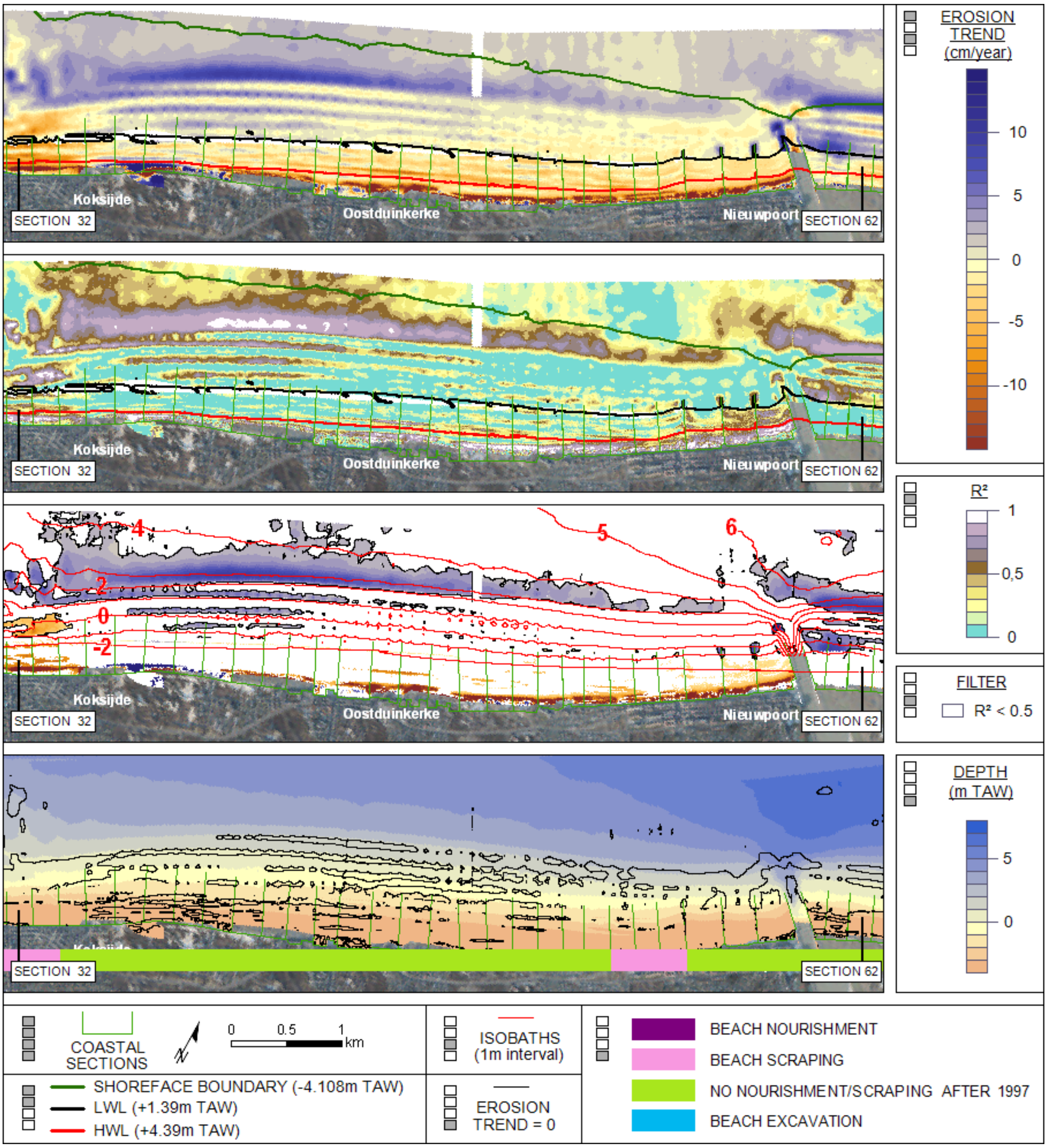

Figure A2-2. Erosion and sedimentation trends for beach and shoreface (sections 32-62).

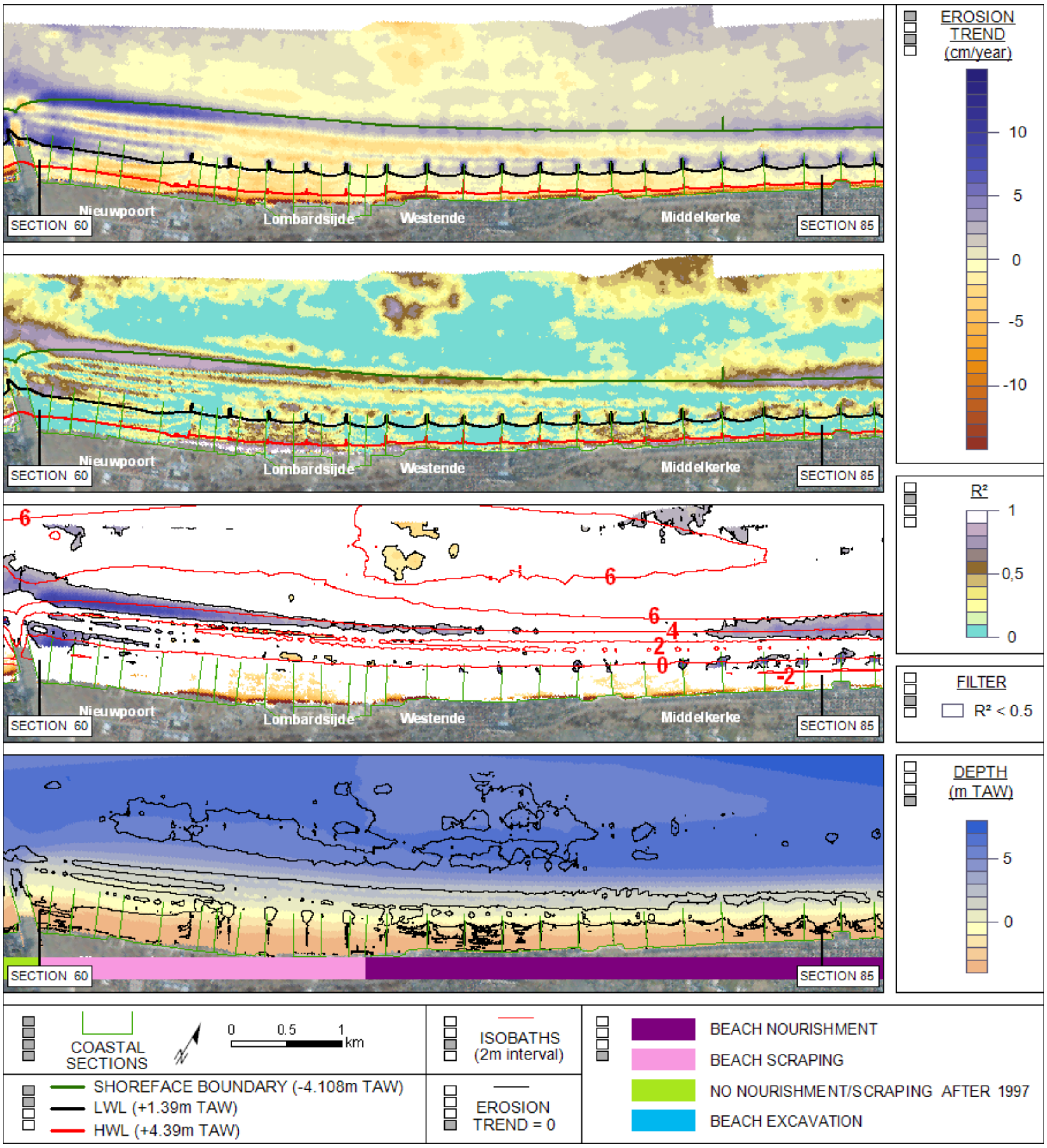

Figure A2-3. Erosion and sedimentation trends for beach and shoreface (sections 60-85).

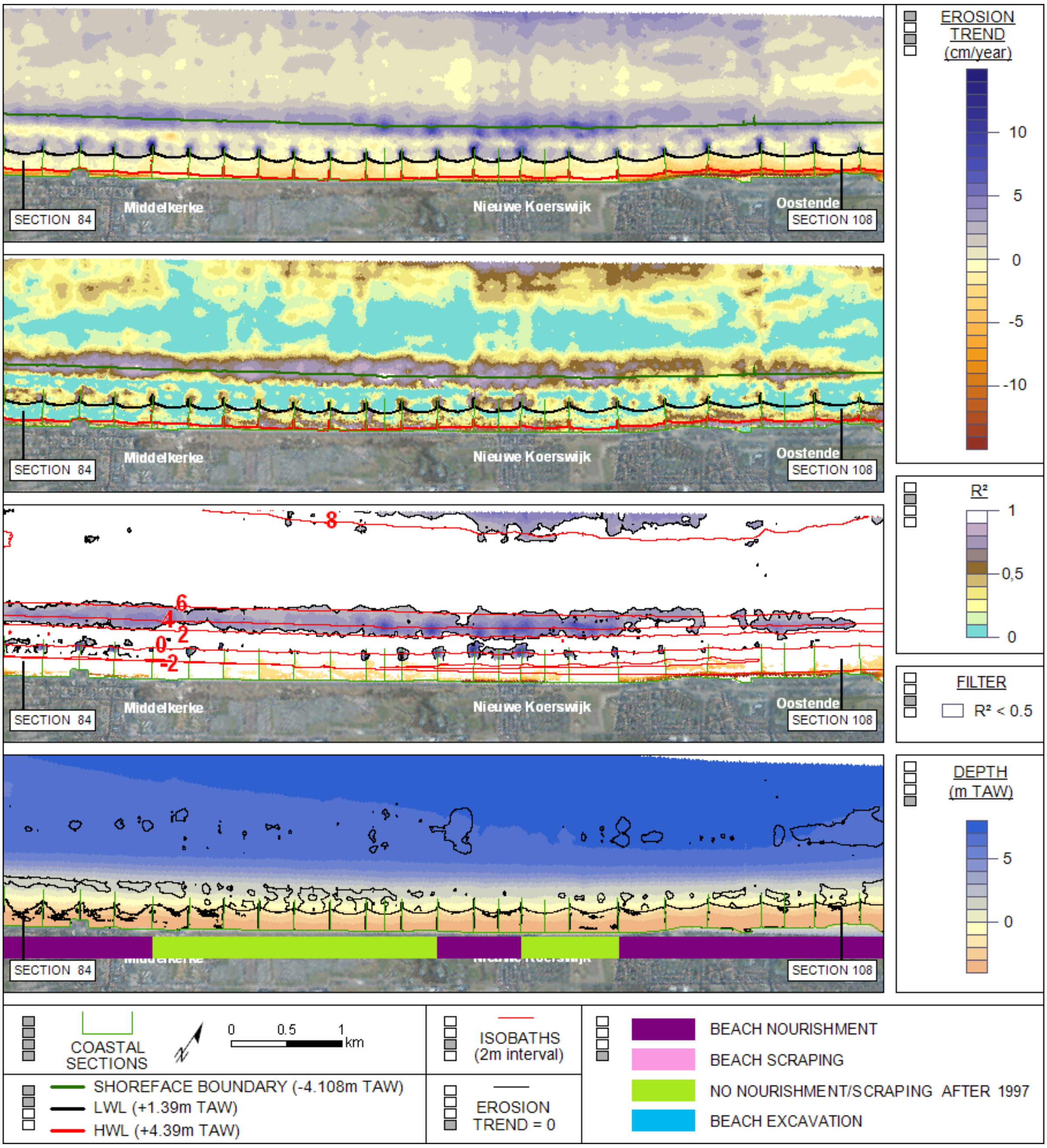

Figure A2-4. Erosion and sedimentation trends for beach and shoreface (sections 84-108).

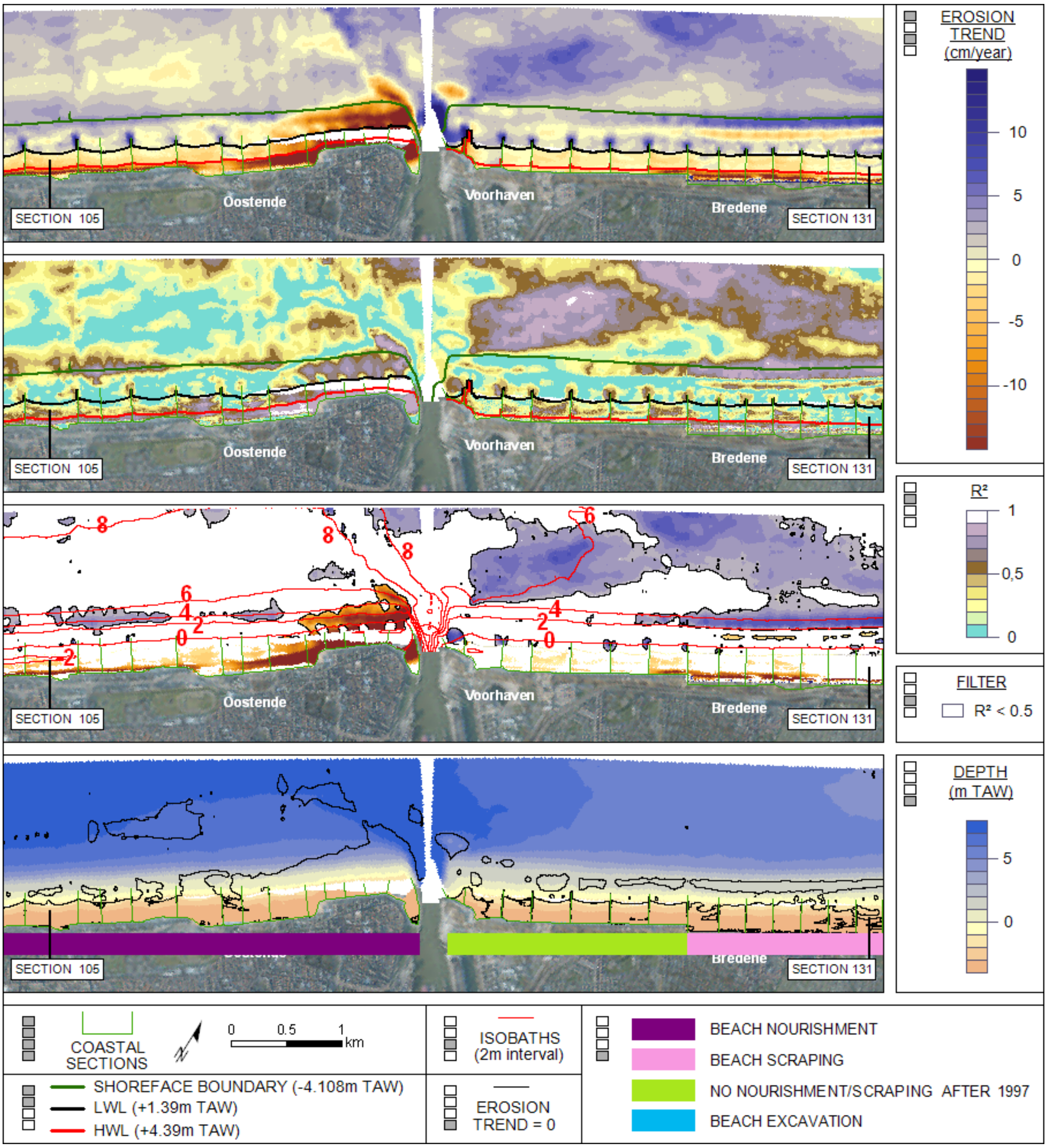

Figure A2-5. Erosion and sedimentation trends for beach and shoreface (sections 105-131).

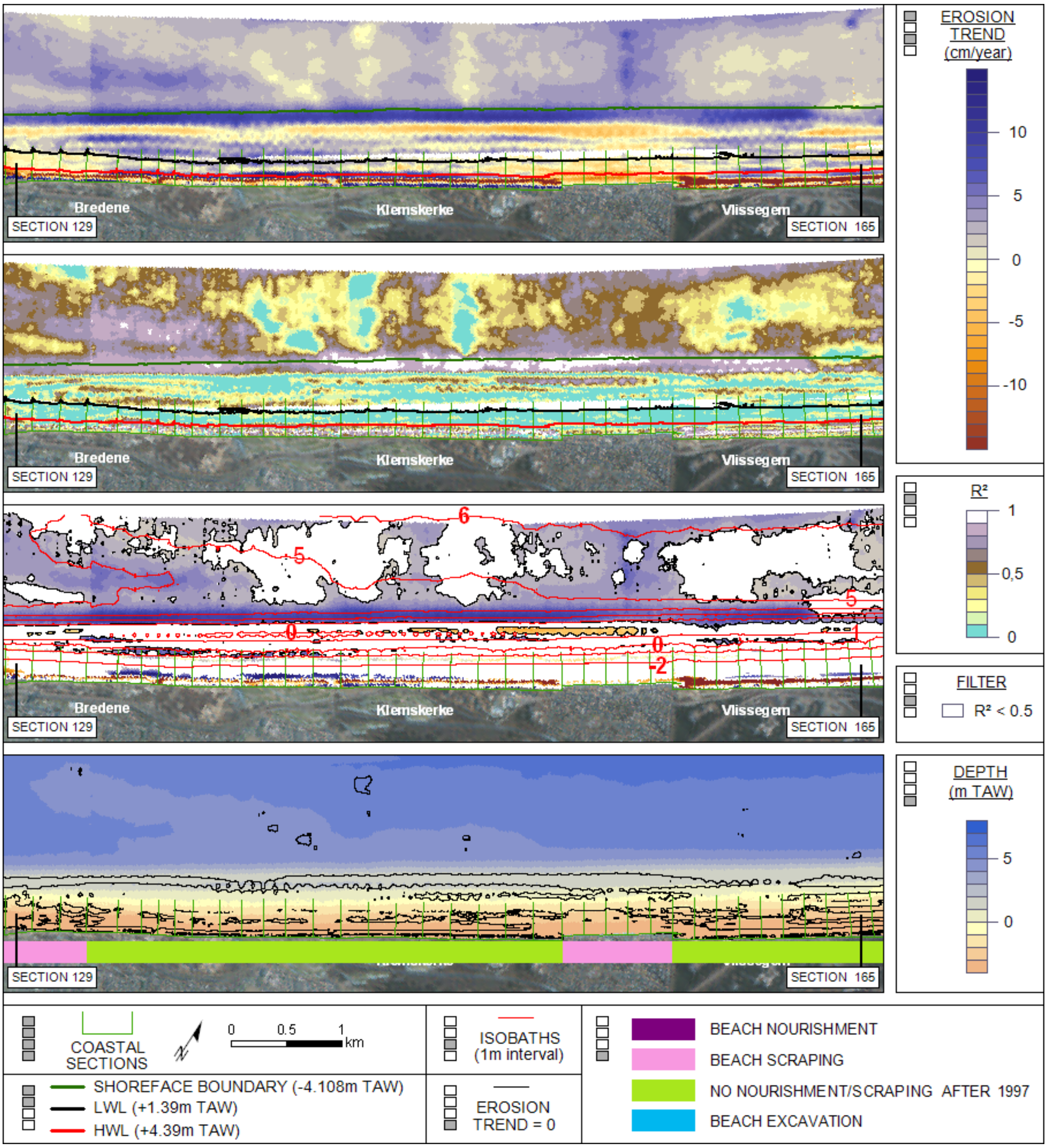

Figure A2-6. Erosion and sedimentation trends for beach and shoreface (sections 129-165).

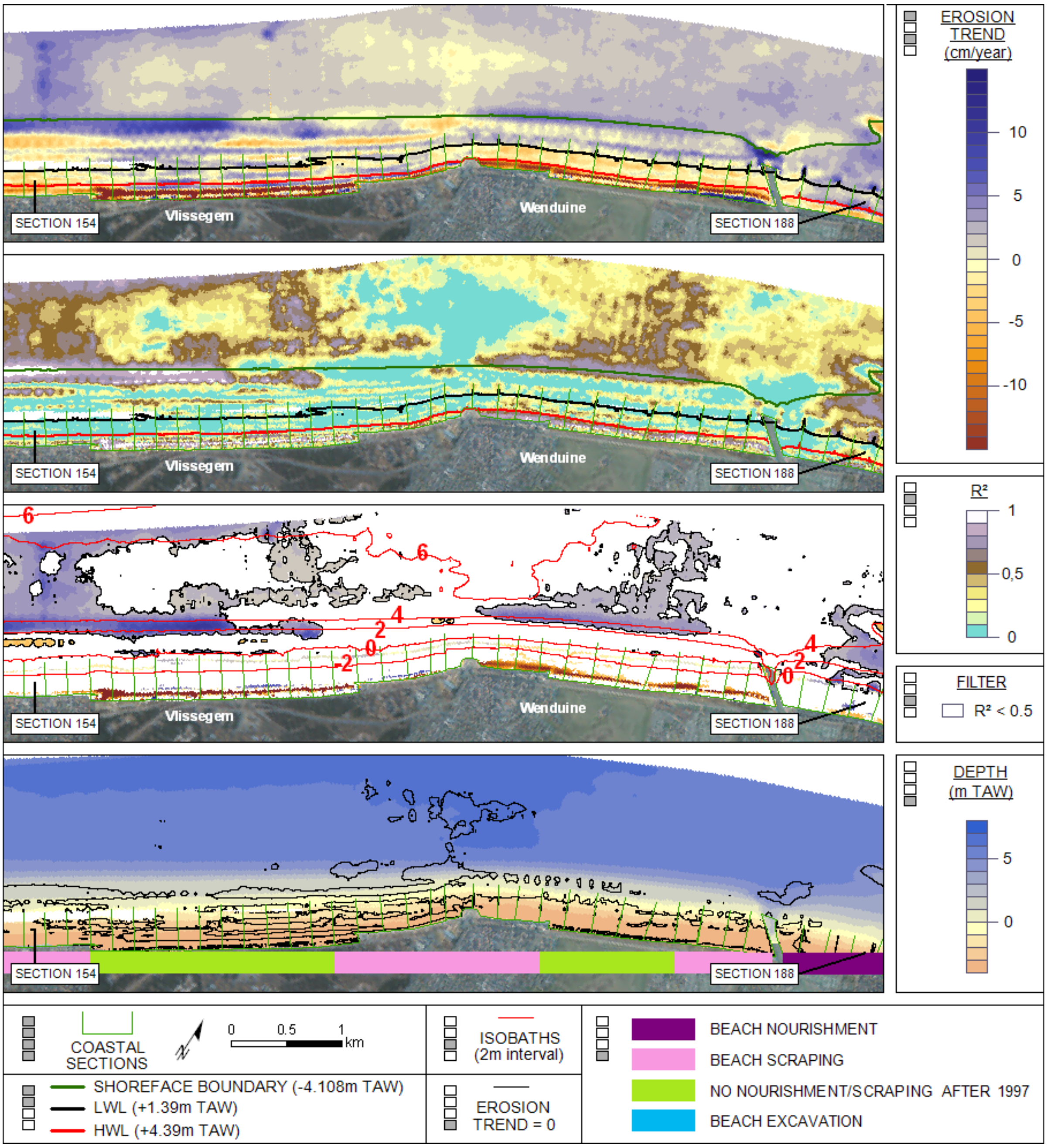

Figure A2-7. Erosion and sedimentation trends for beach and shoreface (sections 164-188).

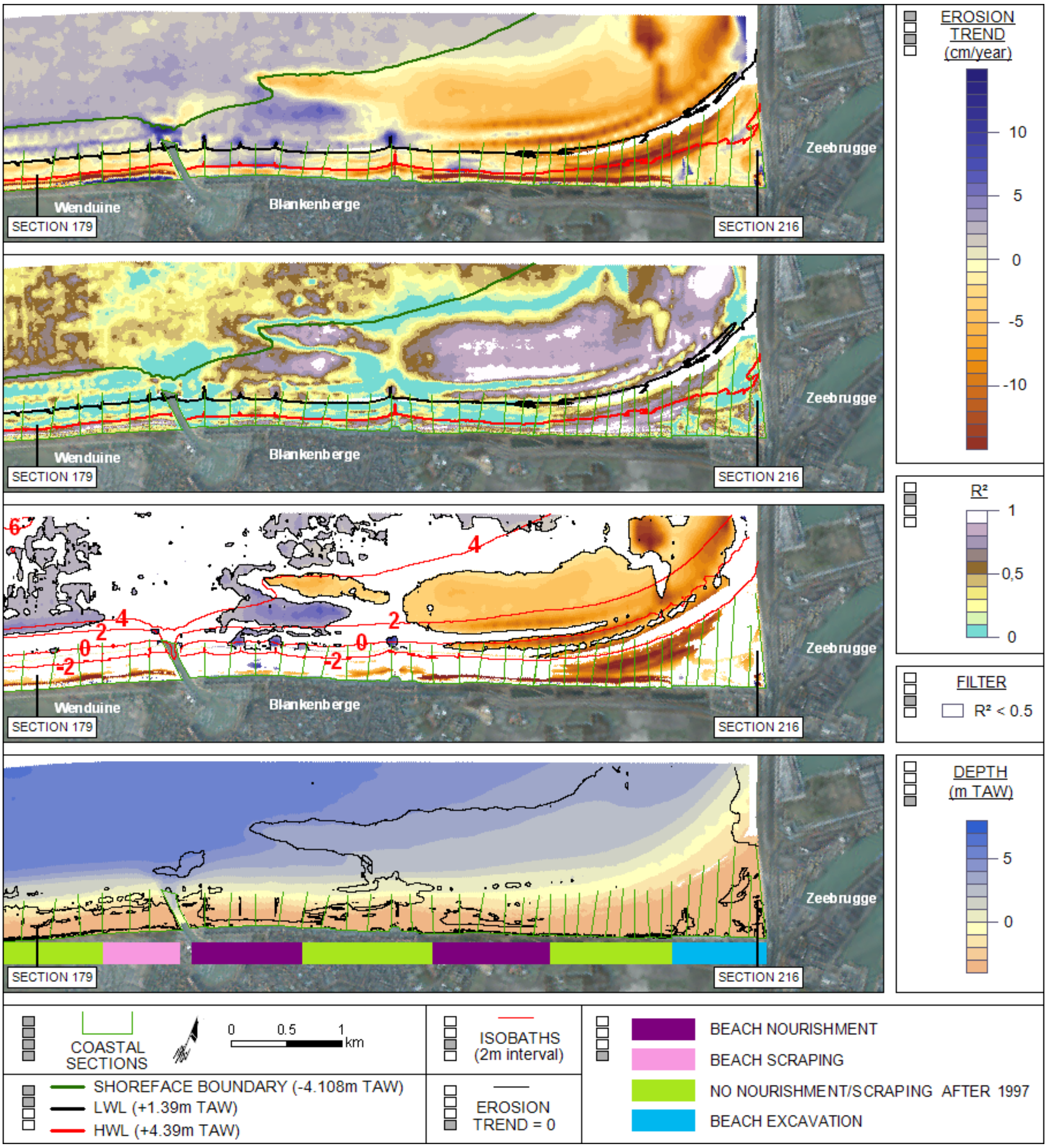

Figure A2-8. Erosion and sedimentation trends for beach and shoreface (sections 179-216).

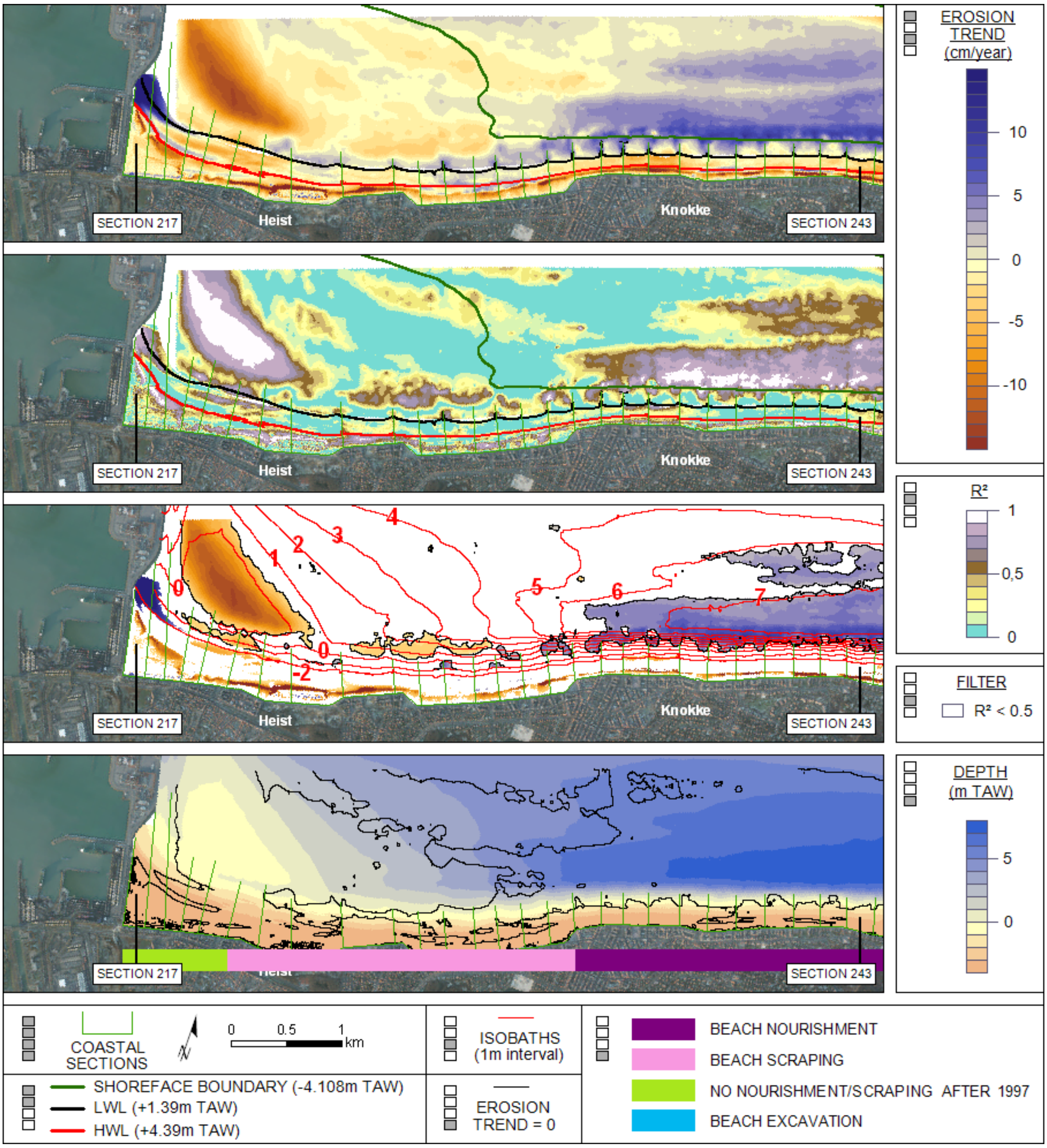

Figure A2-9. Erosion and sedimentation trends for beach and shoreface (sections 217-243).

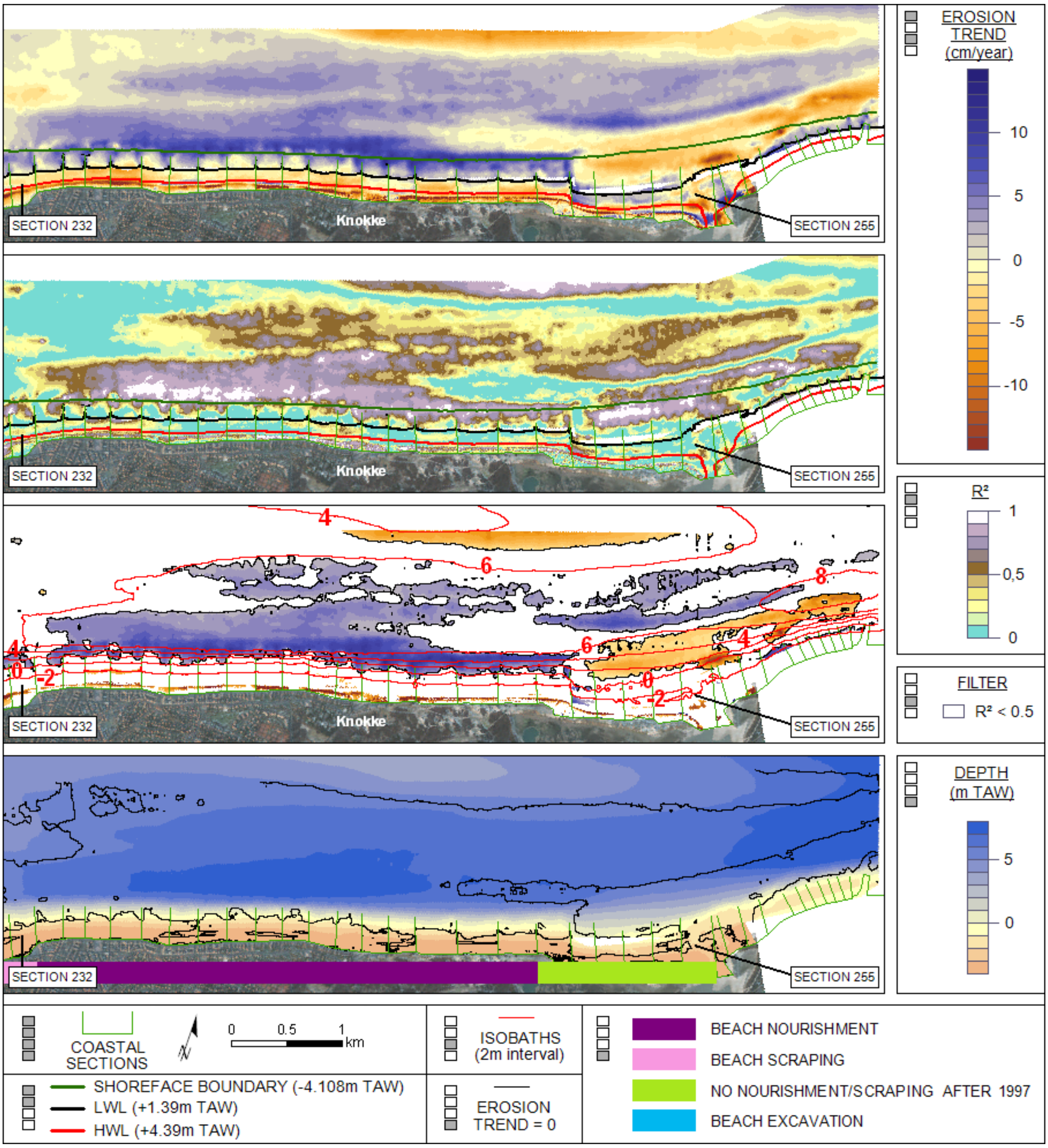

Figure A2-10. Erosion and sedimentation trends for beach and shoreface (sections 232-255).

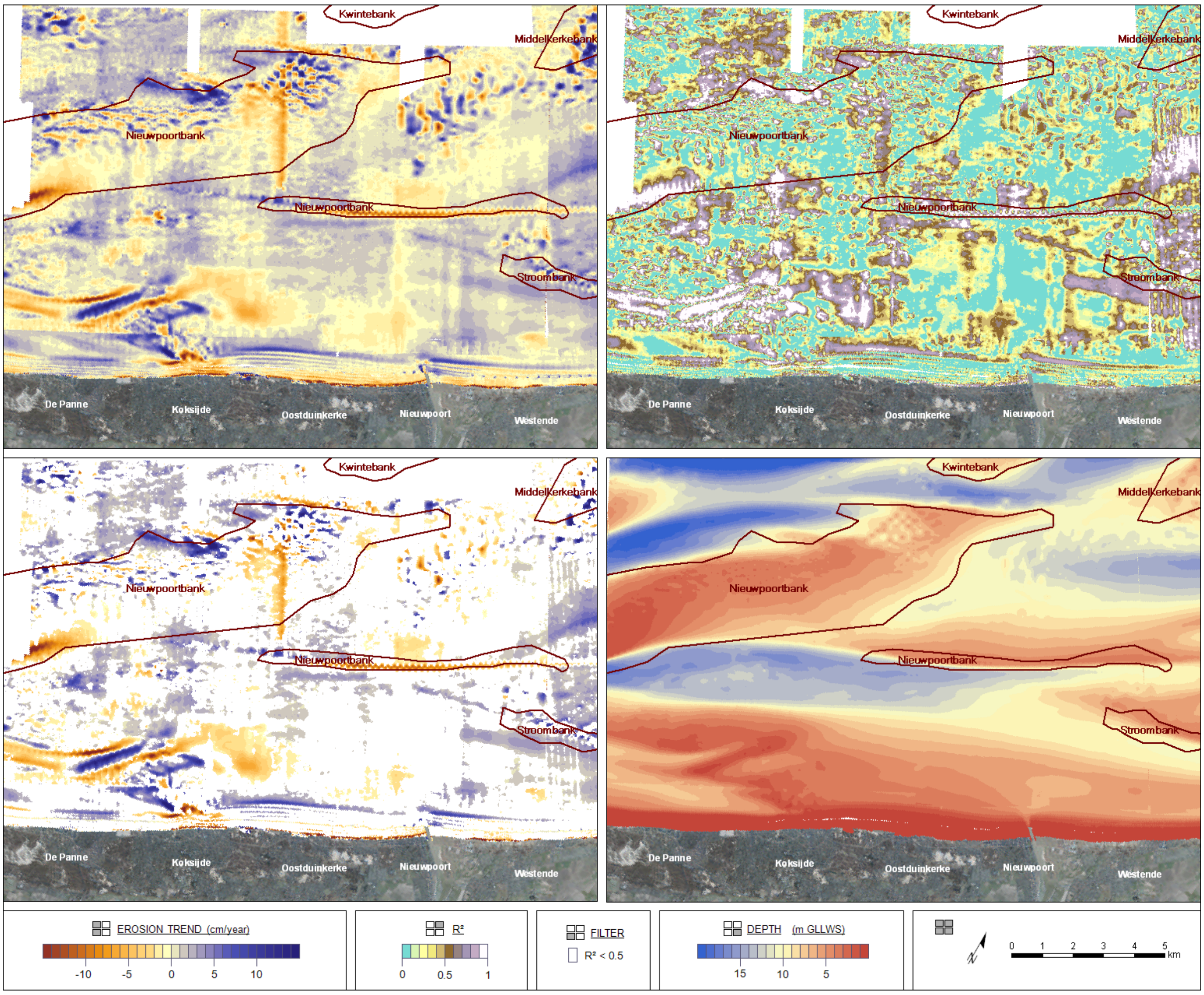

Figure A2-11. Erosion and sedimentation trends for the coastal region between the French border and Westende.

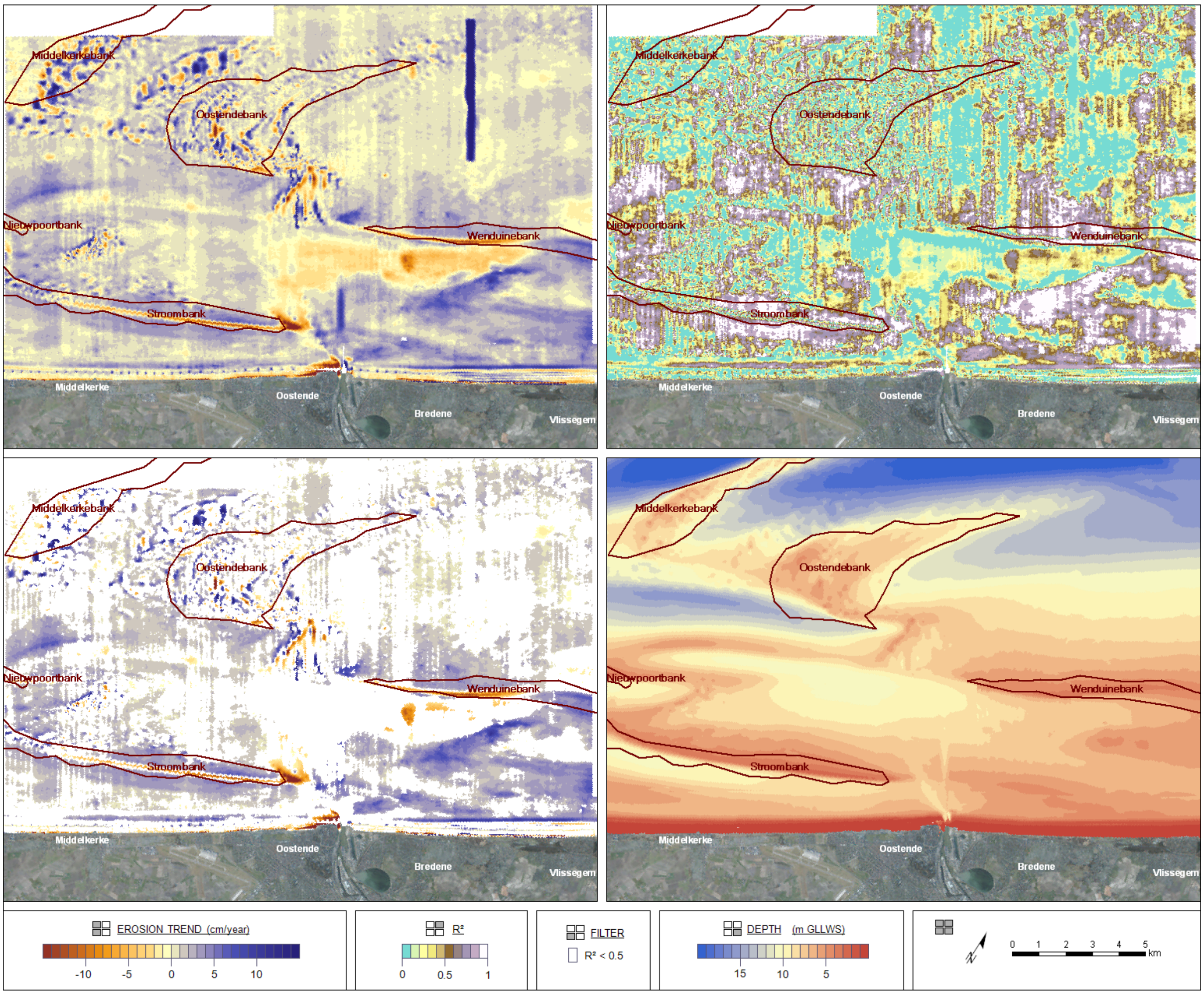

Figure A2-12. Erosion and sedimentation trends for coastal region between Westende and De Haan.

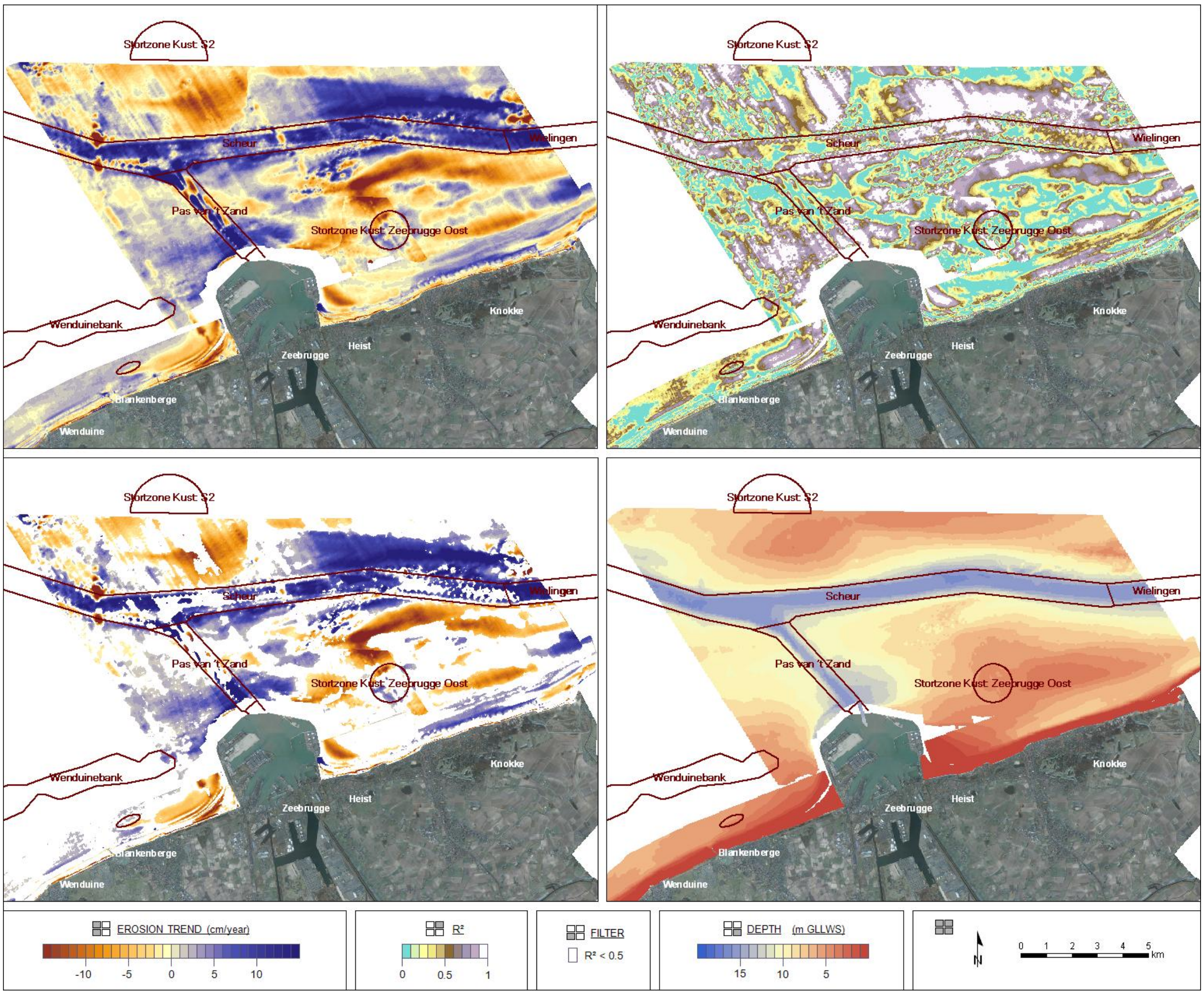

Figure A2-13. Erosion and sedimentation trends for coastal region between Blankenberge and the Dutch border.

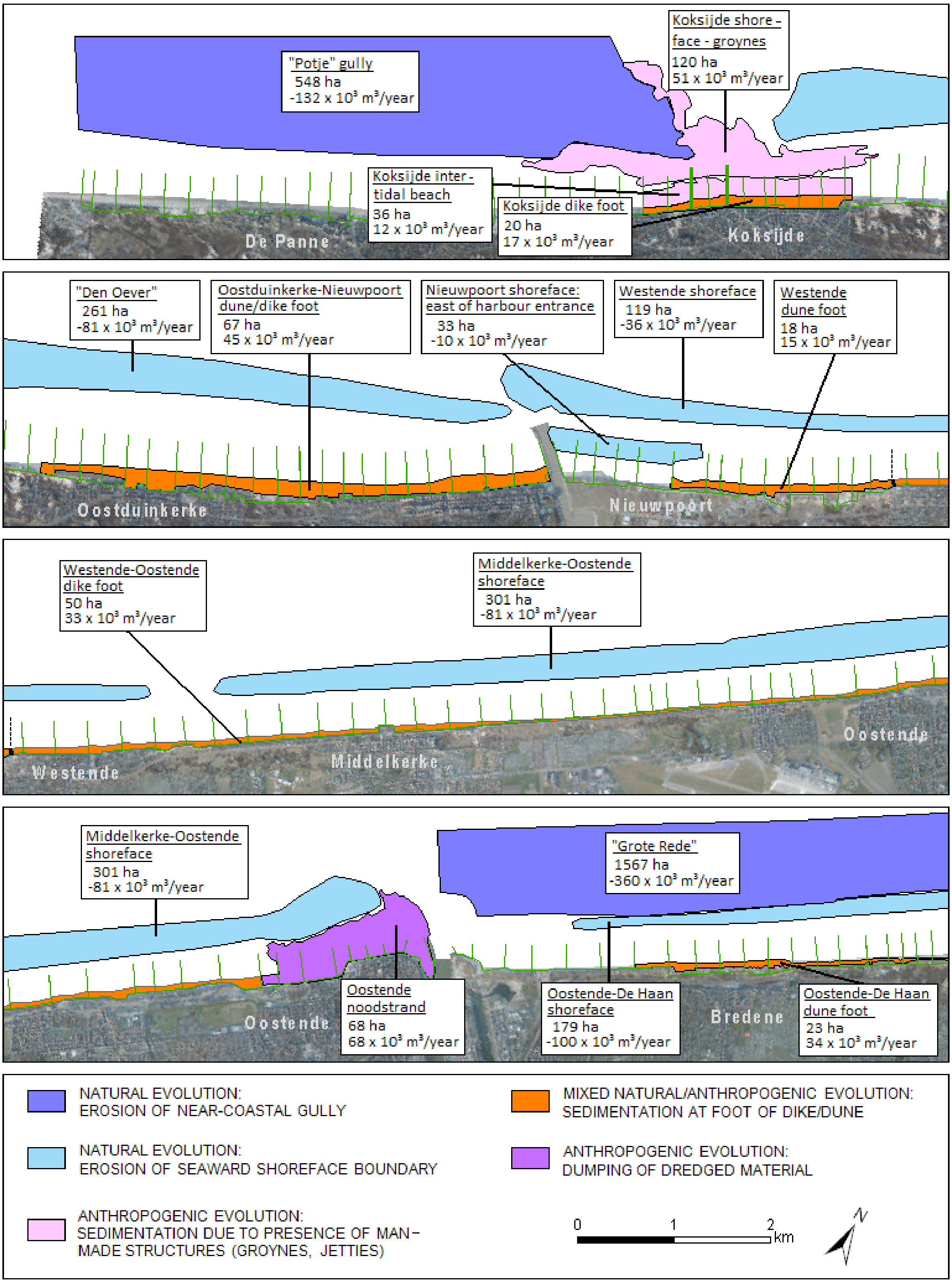

Figure A2-14. Highlighted zones, based on a common erosion or sedimentation trend (part 1).

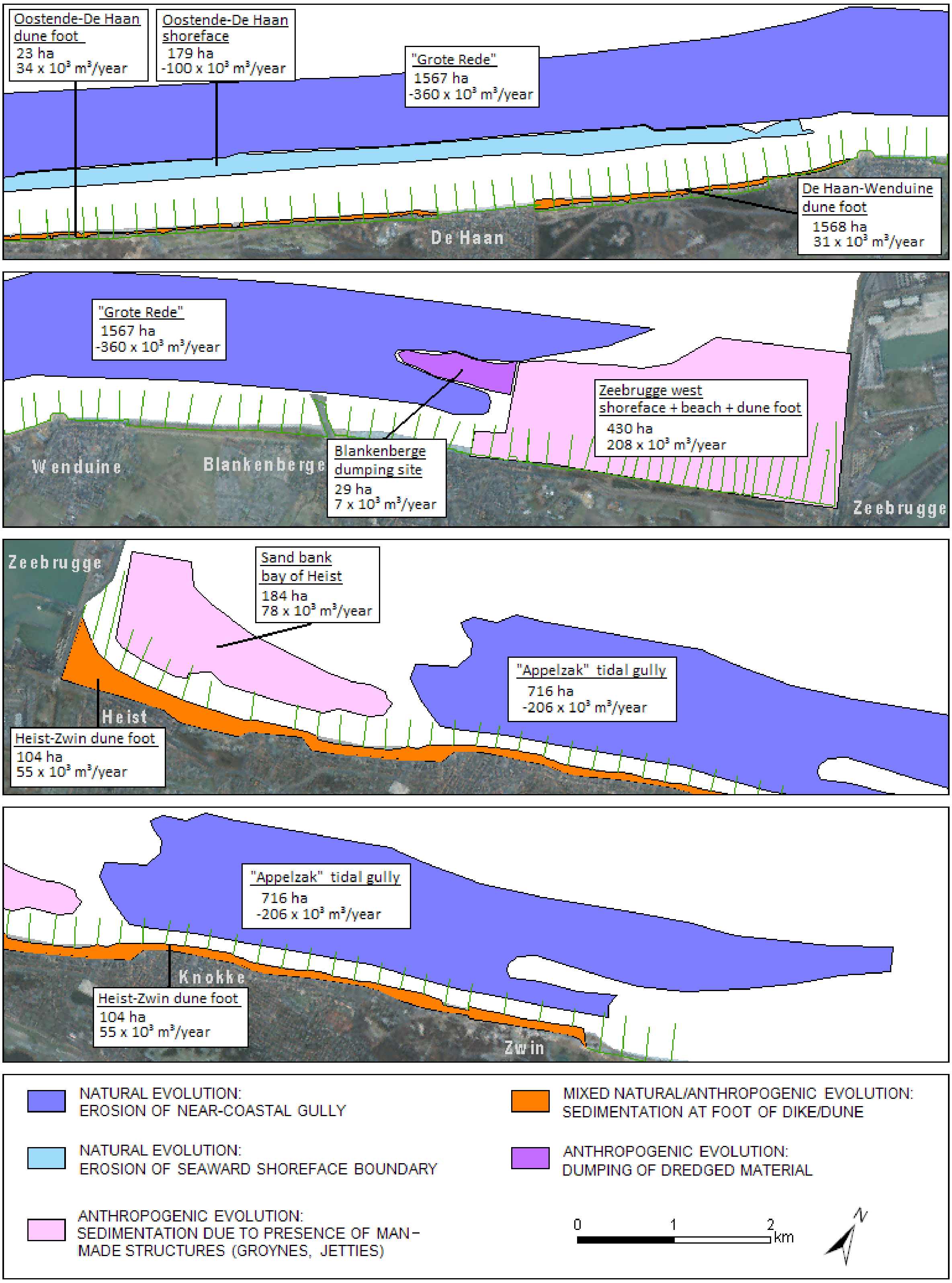

Figure A2-15. Highlighted zones, based on a common erosion or sedimentation trend (part 2).

Table A2-1. Total volumetric trends for the wet beach (zone between high and low water mark) and for the shoreface (zone between low water mark and -4.108m TAW)

zone	area (ha)	accreted volume (x 10^3 m^3/year)
French border - Nieuwpoort: wet beach	283	34
French border - Nieuwpoort: shoreface	1023	**-133**
Nieuwpoort - Oostende: wet beach	254	36
Nieuwpoort - Oostende: shoreface	577	**-46**
Oostende - Zeebrugge: wet beach	304	38
Oostende - Zeebrugge: shoreface	958	**0**
Zeebrugge - Dutch border: wet beach	135	13
Zeebrugge - Dutch border: shoreface	467	63

Annex 3. Long-term disposal of dredged material alters significantly prevailing hydrographic conditions? A discussion based on the Vlakte van de Raan, Belgian-Dutch coastal zone

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Introduction

Every year, about 11 million tonnes of dry material is dredged and disposed of in Belgian waters, constituting for more than 70 % out of fine-grained material (Lauwaert et al., 2009). Resuspension is rapid and redistribution takes place away from the disposal grounds. Some part recirculates back towards the dredged areas, raising the question of the efficiency of the dredging strategy.

The effect of long-term disposal of dredged material is being discussed in the area of the Vlakte van de Raan (location, Figure A3-1), the ebb tidal delta of the river Scheldt in the Belgian-Dutch coastal zone. Disposal activities have a history of 40 yrs, starting in the '70's on the western part of the ebb tidal delta. The designated area has been displaced several times (1980, 1984 and 1999), when depths became too shallow for disposal operations. Main disposal grounds are S1 and S2, both still active (Figure A3-2).

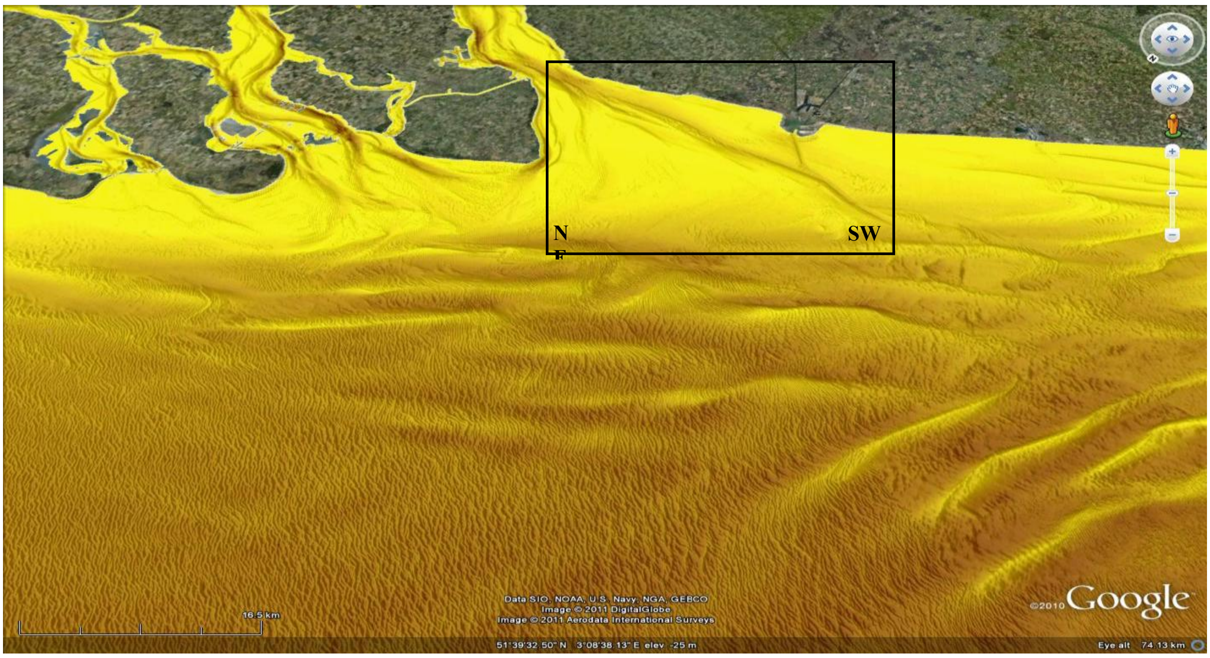


Figure A3-1. Delta's from the rivers Rhine, Meuse and Scheldt impacting on the Belgian-Dutch coastal zone. Note the complex offshore bathymetry with sandbanks and gullies. Bathymetric data compiled from Flemish Hydrography and Deltares 2011 (Nederlandse Hydrografische Dienst & Rijkswaterstaat Dienst Noordzee). Rectangle indicates the Vlakte van de Raan.

The Vlakte van de Raan is situated in the turbidity maximum of the Belgian-Dutch coastal zone (see Baeye, 2012 for a comprehensive overview). Its delta front forms the transition between high and lower levels of suspended particulate matter (SPM) (Figure A3-2).

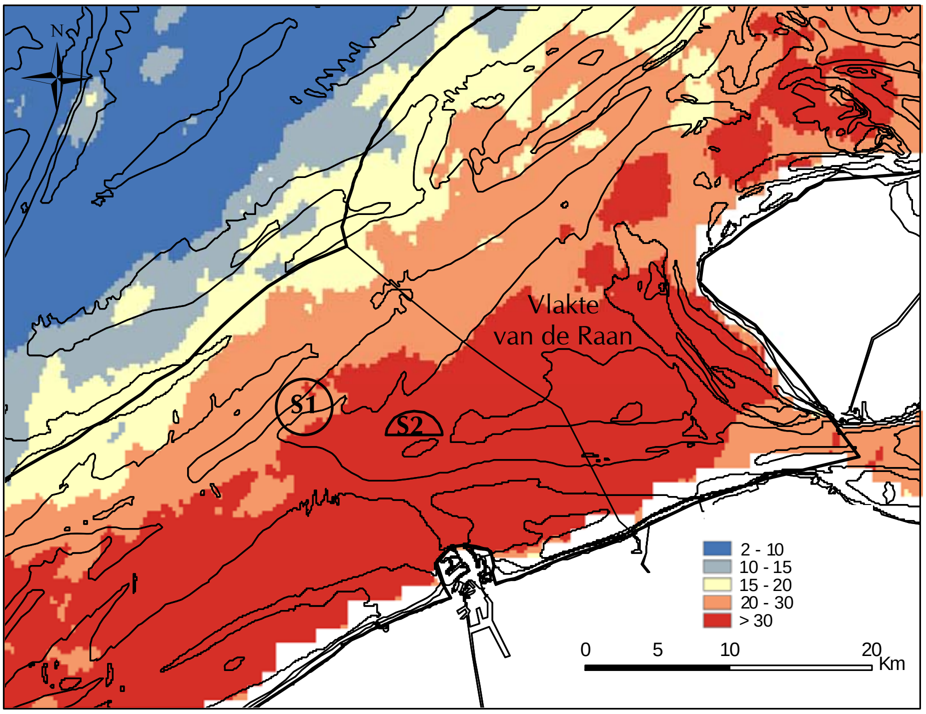


Figure A3-2. Distribution pattern and maximum amount (mg/l) of suspended particulate matter, as derived from MERIS satellite imagery in 2003. The delta front is at the edge of the turbidity maximum area. Disposal grounds S1 and S2 are indicated.

The effects of disposal activities on the ecosystem have been discussed widely (e.g. Bolam et al., 2011). Mostly, macrofauna is impoverished on the disposal grounds, still studies indicated a particularly rich macrofauna in the vicinity of those areas (e.g. Van Lancker et al., 2007, Figure A3-3). This triggered a series of hypotheses that were tested in the frame of the QUEST4D project.

The disposal ground S1 has been mapped in detail (e.g. Van Lancker et al., 2007); new surveys focussed now on the delta front and adjacent seabed, with depths ranging between -24 and -12 m MLLWS (Mean lowest low water Spring). Main hypotheses were:

- Long-term disposal of dredged material causes regional sedimentation in the area;
- Increased biodiversity near the Belgian-Dutch border is due to increasing availability of fines, due to disposal activities.

The relevance of the research fits well within the European Marine Strategy Framework Directive (MSFD, CEC, 2008). This contribution specifically discusses the influence of long-term disposal on hydrographic conditions, one of the descriptors to assess good environmental status (GES). Hydrographic conditions include, but are not limited to salinity, temperature, pH and hydrodynamics. GES for hydrographical conditions would be achieved if the nature and scale of any long-term changes to the prevailing hydrographical conditions from anthropogenic activities (individual and cumulative) in the marine environment do not lead to significant negative impacts at a species, population or ecosystem level (Cardoso et al., 2010). The spatial scale at which those effects take place are of particular interest. Within MSFD context pressure mapping is vital and relates to the effects of smothering, abrasion, extraction and sealing (e.g. Foden et al., 2011). Related to disposal activities, smothering (e.g. burial) is of highest concern, though important abrasion takes place where the material is dredged (e.g. Janssens and Verwaest, this report). The present paper provides an overview of the effects of long-term disposal activities on surficial sediments, morphology, hydrographic conditions and benthos.

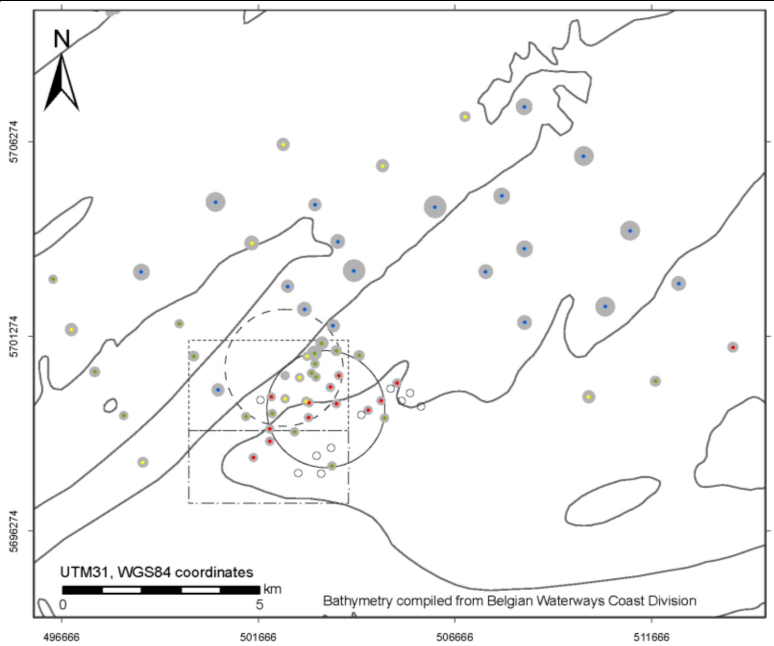


Figure A3-3. Macrobenthos densities and communities along the western part and delta front of the Vlakte van de Raan (Belgian part). Low species densities to no fauna (open circles) characterize the disposal ground; densities (sized circles) amount up to more than 25.000 ind m^{-2} to the northeast and up to 43 species per 0.1 m² are found (Macrodat@UGent; Degraer et al., 2006). Along the delta front the *Abra alba* community thrives (blue dots), being the most rich and diverse community on the Belgian part of the North Sea (Van Lancker et al., 2007).

Methodology

In the period 2006-2011, successive measurements and observations with *RV Belgica* were conducted in the area of the Vlakte van de Raan (Figure A3-4).

High resolution multibeam acoustic data were acquired (Kongsberg Simrad EM1002/99kHz and EM3002/300 kHz) for seabed mapping and habitat characterization (yearly surveys in the period 2006-2011). Depth and backscatter data were processed and data grids were produced at a resolution of $<=$5m. This allowed quantifying fine-scale sediment and terrain variation, as also bioturbation. Some species, when forming dense colonies, are indeed able to alter the acoustic response of the seafloor (e.g. Degraer et al., 2008; Van Lancker et al., 2012) and can be distinguished through fine-scale terrain analyses.

Seabed evolution in the period 1979 to 2006 was studied, based on bathymetric data obtained from Maritime Entrance, Flemish Authorities (data on Westerscheldemonding 1979, 1980, 1984).

Sediment and macrobenthos samples were taken along the delta front, both in the Belgian and Dutch sector. Macrobenthos samples were sieved using a 1 mm mesh and fixed in an 8 % formaldehyde-seawater solution. After staining with Bengal rose, all organisms were sorted out and identified to species level, when possible. Densities were expressed as the number of individuals per square meter (ind m^{-2}). Sediment information was further available from the sediSURF (Van Lancker et al., 2007) and sediCURVE database (Van Lancker, 2009), respectively containing predefined sediment parameters (e.g. median grain-size) and full distribution curve data. The latter is more standardized, as it allowed calculating sediment parameters in a uniform way.

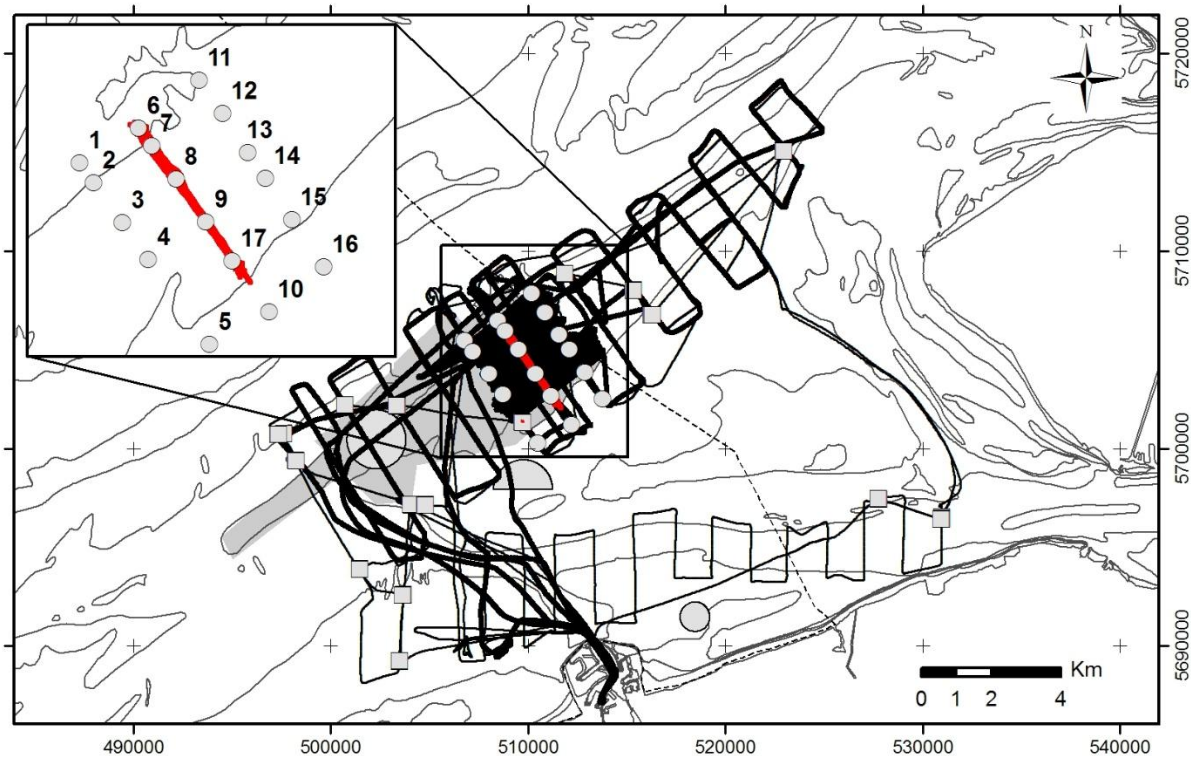


Figure A3-4. Overview of the acquired datasets in the Vlakte van de Raan area: (1) reconnaissance multibeam surveys along tracklines 2 km apart, north (-10 to -20 m) and south slope; (2) full-coverage multibeam surveys along the Belgian delta front and the disposal ground S1 (grey filled polygon); (3) 13-hrs ADCP tracks (currents and backscatter), together with vertical profiling of CTD, LISST, OBS (red line); (4) sediment and macrobenthos samples in the delta front area (grey dots and rectangles). The circle and half circle represent the disposal ground S1 and S2 respectively.

A hull-mounted Acoustic Doppler Current Profiler (ADCP/300 kHz, RDI) recorded current and backscatter data along 1 transect that was sailed up and down the slope of the delta front over a 13-hrs cycle (March, 22 2011) (Figure A3-5). Analyses were restricted to the data of the downslope transects. During the upslope transects, vertical profiling was conducted using a Seacat profiler with sensors measuring conductivity, depth and temperature (CTD), turbidity (OBS, optical backscatter) and in-situ particle sizes (LISST or Laser In-situ Scatterometer and Transmissometer) at 2 locations: midway (slope position; 'sl') and at the northern end of the transect (gully position; 'g'). During the 13-hrs cycle, 10 vertical profiles were taken at the gully position, and 9 on the slope. The acoustic backscatter was converted into SPM concentrations, based on calibration with SPM amounts, derived from water samples (Figure A3-6).

Apart from observations and in-situ measurements, hydrodynamic and sediment transport modelling was performed. Firstly, estimations were needed on expected natural sedimentation in the area. Therefore slack tide ratios were calculated using a bottom shear stress of less than 0.5 Pa (from erosion resistance measurements of bed samples, Fettweis et al., 2010). Secondly, the influence area of the disposal of dredged material needed evaluation and therefore its dispersion was modelled following Van den Eynde and Fettweis (submitted). Disposal activity data (Flemish Authorities, Maritime Entrance) were used for the period that the ADCP transects were sailed. Both approaches make use of the three-dimensional baroclinic hydrodynamic model COHERENS (V2.0, Luyten 2011).

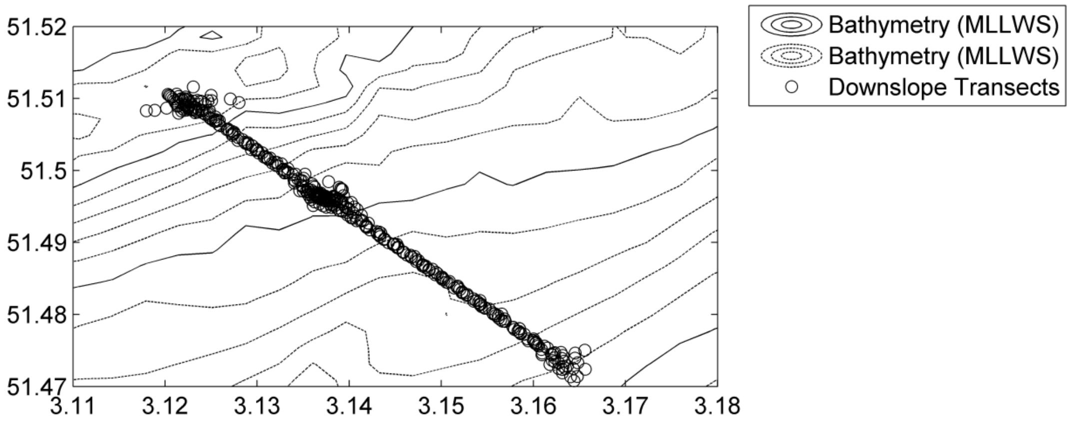


Figure A3-. ADCP transects (upslope & downslope) over a 13-hrs period. Vertical profiling of turbidity, CTD and in-situ particle size (LISST) was carried out at a slope (midway) and gully position (north).

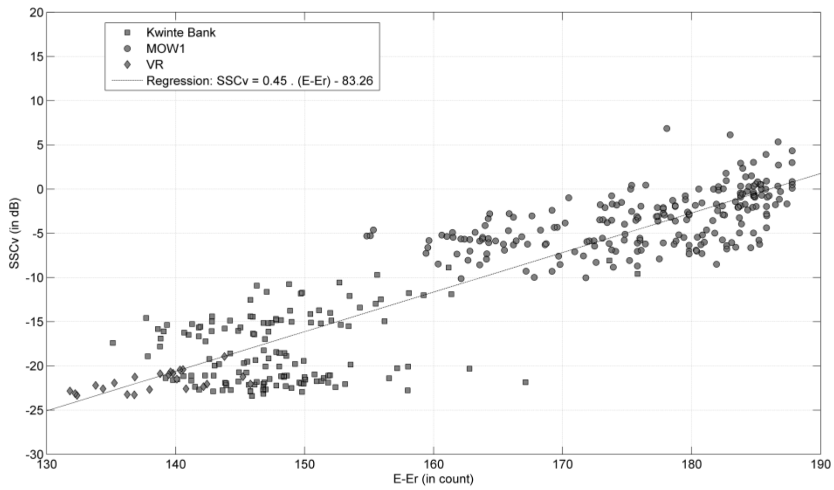


Figure A3-6. Scatter diagram of the corrected acoustic backscatter and in-situ SPM mass concentration.

Results

Effects on sedimentology

The Vlakte van de Raan area is composed primarily of fine sands (Figure A3-7). On the ebb tidal delta itself median grain-sizes are generally lower than 200 μm, though surficial sediments are most heterogeneous in Belgian waters, with grain-sizes of up to 500 μm. Sediments of the delta front are at the transition of fine to medium sands. Figure A3-7 shows a predominance of fine sands for the Belgian part, though recent samples ($>$2008) have shown sands of 400 to 500 μm, especially along the lower slope of the delta front. The origin of the coarser sediments is not clear, though the elevated values did also occur in the past. A more regional evaluation of sediment distributions along the Belgian coastal zone, revealed a **heterogeneous nature of sediment distributions in the vicinity of major human impacted areas, in combination with a poorer sorting (Figure 3.3-3, this report). This is also the case on the Vlakte van de Raan, where a mixture of sediments, causing habitat heterogeneity, is observed around the disposal grounds S1 and S2. This is likely due to the mixture of sediments that is disposed of in the long-term (clay to sand).**

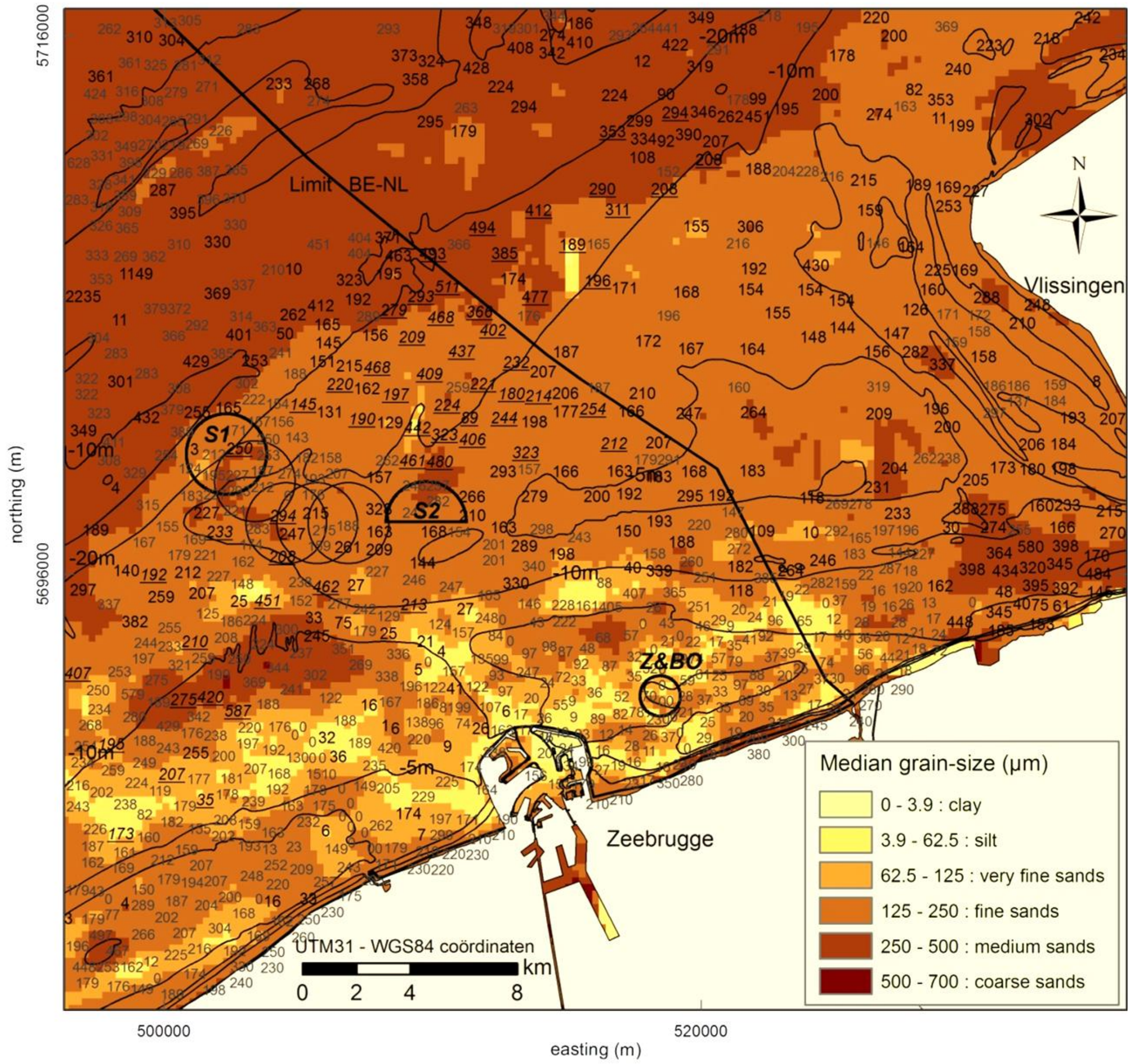


Figure A3-7. Map of median (d50) grain-size along the Vlakte van de Raan (1900-2005), together with the d50 value showing data spread and variability (SediCURVE database, Van Lancker, 2009). Grey values originate from non-standardized databases. Note that variability along the delta front at the Belgian-Dutch border is largest. Underlined values originate from samples later than 2008; they are remarkably coarser than the averaged value. S1 and S2 are present-day disposal grounds of dredged material. The location of former S1 grounds is also indicated.

Effects on morphology

Du Four and Van Lancker (2008) discussed the effects of disposal activities on the morphology and sedimentology around the disposal ground S1. Main conclusions were related to: (1) Formation of large-scale disposal mounds, as also small-scale depressions, formed by scouring events. These primarily constitute of sand, regardless the high mud content of the dredge spoil. (2) Disposal efficiency was estimated as 30–40%, which would lead to a yearly growth of 380,000 m³. A different sedimentation pattern was revealed according to the morphological setting (e.g. disposal on a shoal (former S1) or in a gully (new S1)). (3) After cessation of activities, a rapid physical recovery was revealed. Importantly, it was shown that bedload transport in the area was ebb-dominated and led to a more regional smothering of the dredge spoil, back to the navigation channels. This contrasted to previous findings suggesting an overall flood dominance of sediment processes.

In this paper, the effects of long-term disposal on the delta front are discussed. Firstly, the large-scale morphology of the Vlakte van de Raan as an ebb tidal delta of the Scheldt river was revisited (Figure A3-8). From a combination of bedform morphology and modelled residual currents, a complex of flood- and ebb-dominated channels was mapped: (1) at the foot of the delta front, residual currents are oriented to the northeast; a flood-dominated channel occurs; and (2) higher up the slope residual currents mainly point in a southwest direction. The western part of the Vlakte van de Raan is clearly offshore deflected; on this part disposal of dredged material has a history of 40 yrs (1970 till now) (sequence of disposal grounds on Figure A3-7).

From bathymetric charts, the evolution of this western part was studied in relation to disposal activities. Figure A3-9 shows the evolution of the 10 m contour line in the period 1979-2006. Expansion to the west mainly took place in the period 1979-1984 (~1.5 km). Afterwards, disposal gave rise to a sand pile extending northwards, attaining a maximum extent in 1999. A new disposal ground was designated; and the sand pile collapsed into the gully. In 2006, the 10 m contour had significantly retreated (more details in Du Four and Van Lancker, 2008). At present, a new sand pile is forming into the gully (Figure A3-9). **From the analyses, it is clear that long-term disposal activities lead to sedimentation (at least 1.5km) outside of the designated areas, though no relation could be established between the overall offshore deflection and long-term disposal. The present-day accretion in the tidal gully is forming a new habitat different in texture than originally. Contour lines are compressing and currents likely accelerate locally. This will impact on hydrographic conditions on the long-term. Whether this leads to habitat fragmentation needs further monitoring.**

To investigate recent erosion/sedimentation processes in relation to morpho-sedimentary dynamics, high resolution seabed mapping with multibeam was used. Figure A3-10 shows the main morphological entities, together with bedforms and their dominant asymmetry. Striking is the ebb dominancy of the bedforms in the shallower areas: in the vicinity of the disposal grounds and along the Akkaert Bank. This has important implications towards the recirculation of disposed material, hence back to the navigation channels.

Seabed evolution was studied based on 8 repetitive multibeam surveys (2006-2007; 2008-2010), along 4 representative profiles (Figure 3.2-5, this report and Figure A3-11). The following conclusions can be drawn: (1) there is no important bedform migration, except for the area north of the disposal ground where large dunes migrated in 2006-2007 and small dunes in 2008-2010; (2) bed evolution (i.e. depth changes) is dynamic, and depends on the morphological position of the profile. Most striking are the shallower depths measured in June 2009 (ST0917). Most accretion (~54cm max) occurred north of the disposal ground, whilst on the other profiles a maximum of 10-18 cm was observed, mostly in the troughs. Accretion was minimal along the central profile (P1); here it is assumed that bed shear stresses are highest, preventing important deposition of sediment. Noteworthy are the results of ST1029. On all measured profiles erosion had occurred, though accretion would be derived from the full-coverage multibeam imagery on the delta front (see further Figure A3-19, where the sand dunes are at least strongly reworked, showing no beam trawling activities, in contrast to previous imagery). Research on the linkages with hydro-meteorological forcing, and disposal activities, is underway, as also the estimation of potential sediment sources. The more pronounced bed evolution northward of the disposal ground is most likely due to the important sediment fluxes from the disposal activities.

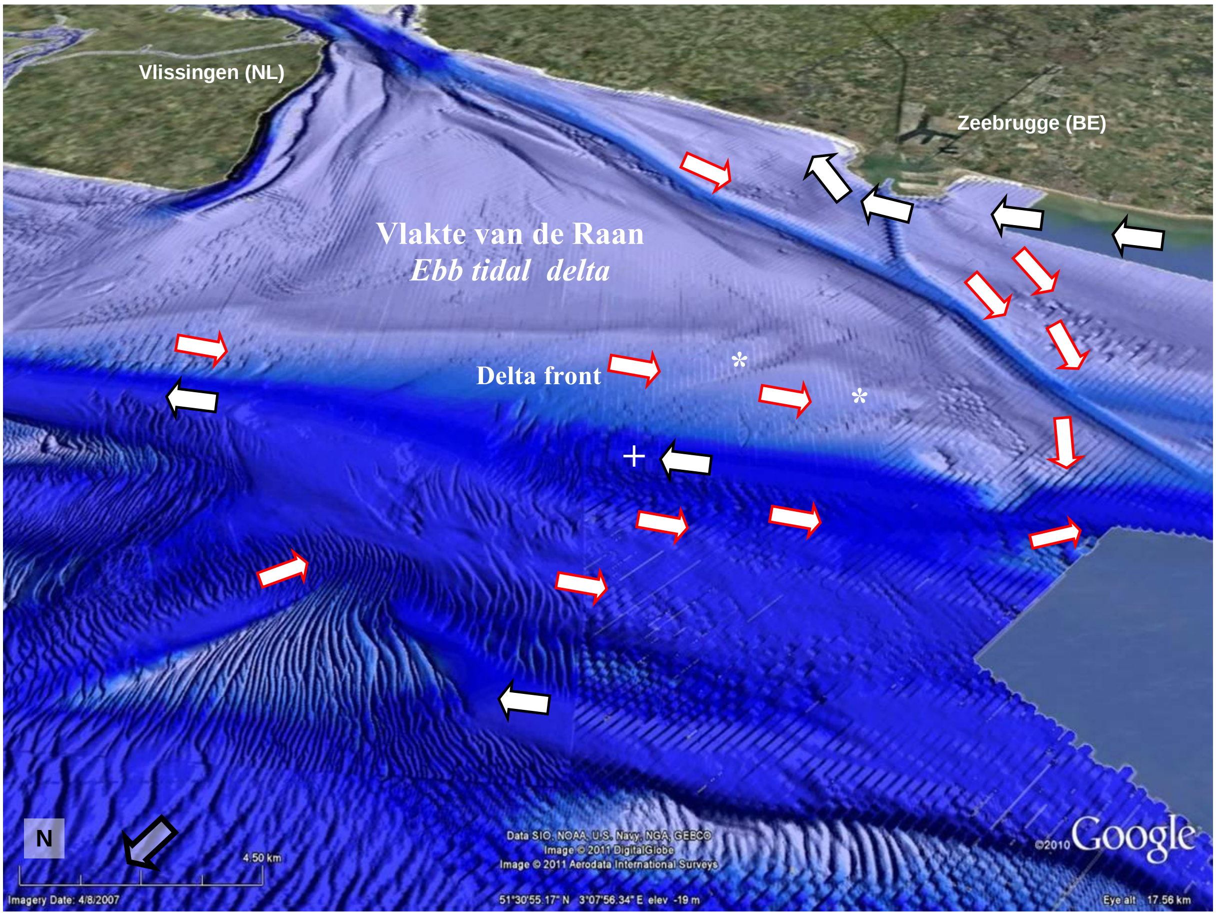


Figure A3-8. Morphology of the ebb tidal delta of the Vlakte van de Raan. Note the navigation channels towards the harbour of Zeebrugge and Antwerp. Arrows provide a synthesis of modelled residual currents (Van Lancker et al., 2007). Close to the coast the currents are clearly flood-dominated; more offshore a complex of flood- and ebb dominated channels occurs. On the upper slope of the delta front the morphology channelizes the ebb (*); offshore a flood-dominated channel reigns (+). Bathymetric data from Deltares 2011 (Nederlandse Hydrografische Dienst & Rijkswaterstaat Dienst Noordzee).

Impact on hydrographic conditions

(i) Effects on regional sedimentation patterns

Model results of a slack tide ratio, calculated over 2 tidal cycles, are shown in Figure A3-12 for both neap and spring tidal phases (see also Baeye et al., in press). Generally, a high sedimentation potential (high ratio) is calculated for the shallow waters in the coastal zone. Under neap conditions the entire delta front is prone to sedimentation, as also a large part of the shallow areas; under spring only the areas southwest and northeast of the western part of the Vlakte van de Raan are prone to sedimentation. **It is hypothesized that this natural sedimentation was further enhanced by the increased extension of this part of the ebb tidal delta** (see Figure A3-9). Further modelling, using former bathymetries (i.e. more retreated contour lines), is needed to confirm this hypothesis.

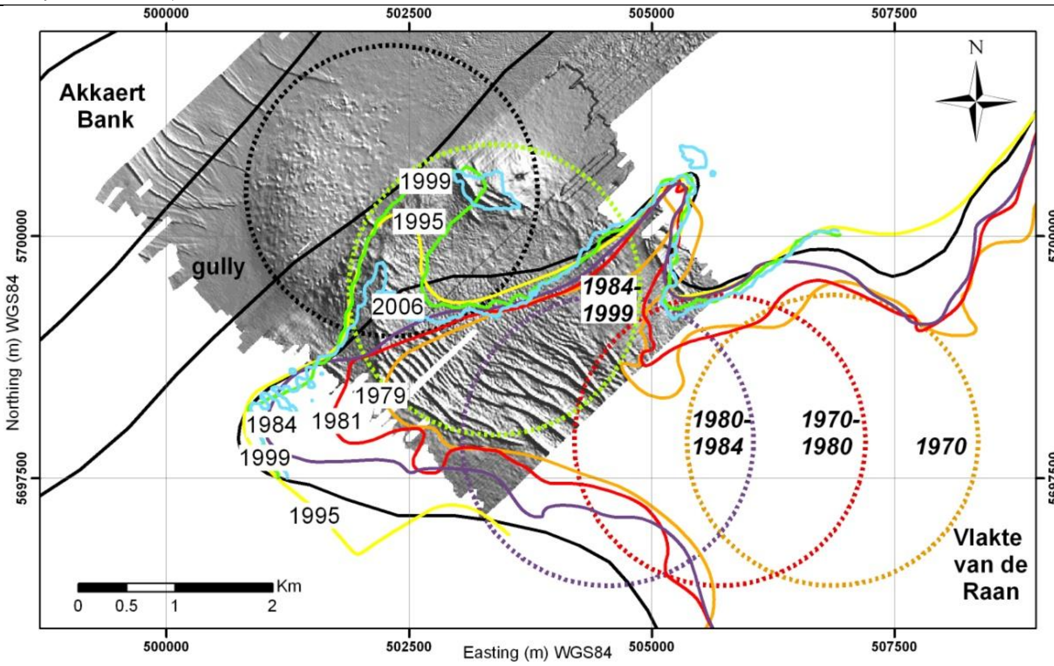


Figure A3-9. Disposal history at location S1 and morphological changes in the period '70 to 2006, superimposed on recent multibeam bathymetry (2006). The successive disposal circles of S1 are indicated, as also the displacement of the 10 m contour (Bathymetric data from Maritime Access, Flemish Authorities). The multibeam bathymetry provides insight into the morphological evolution: forming of a sand pile as a northward expanding habitat, but no longer present in 2006 (collapse and displacement of the sand into the gully; see also Figure A3-10).

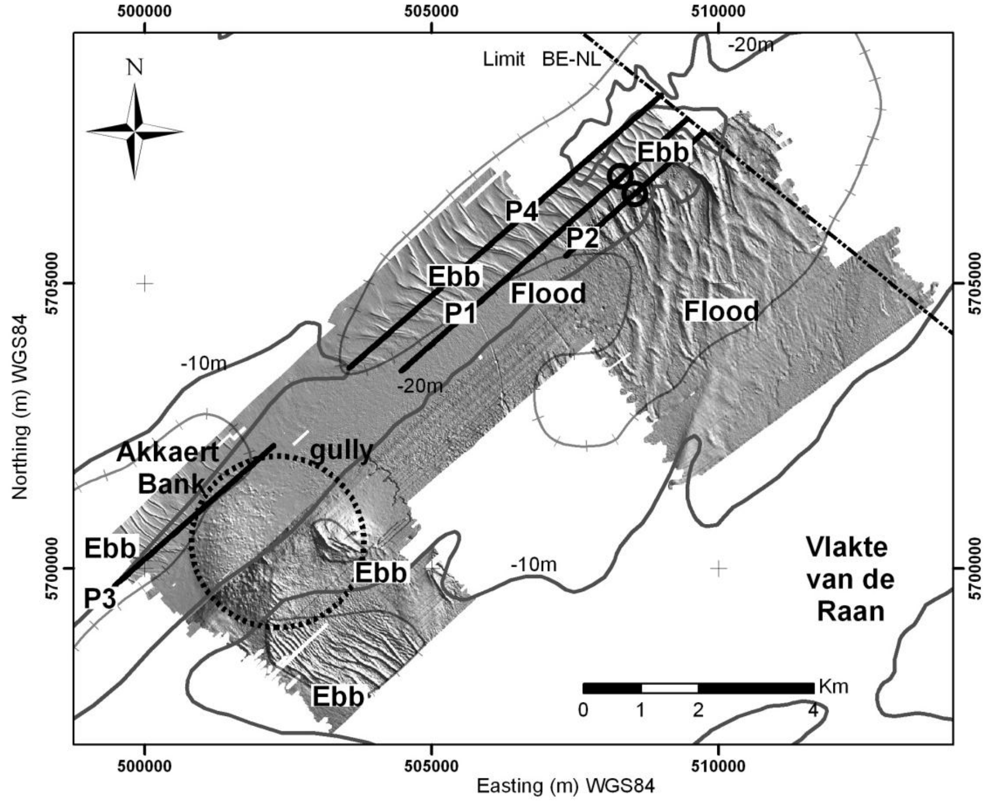


Figure A3-10. Seabed morphology from multibeam seabed mapping. Areas with large dunes are observed south and north of the disposal ground of dredged material (dashed circle). At the northeast extremity of the gully, a series of large complex dunes (up to 4m) are present. In the axis of the gully and 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 (circles on profile P1 and P2). Four profiles (P1 to P4) are indicated along which bedform evolution was followed (see Figure A3-11). The intersected line represents the maximum extent of the bedform area, as derived from broad-scale DTM's.

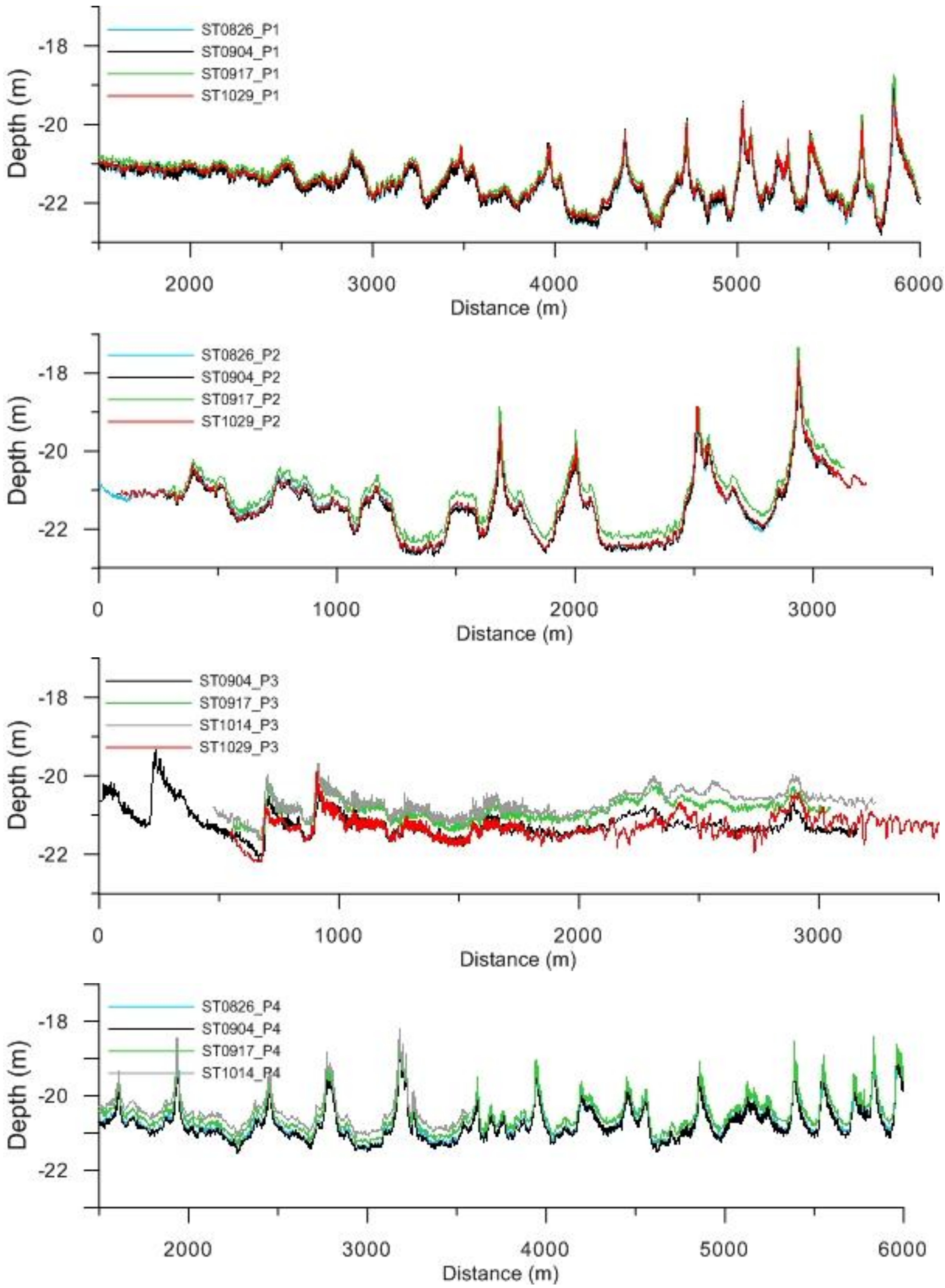
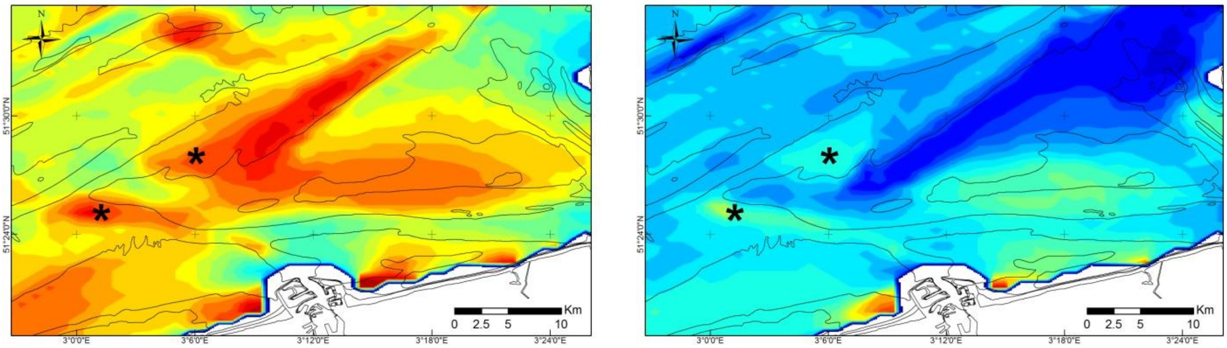


Figure A3-11. Seabed evolution along the delta front, based on time series of multibeam bathymetry. Location of the profiles, see Figure A3-10. All profiles are oriented W-E



A B

Figure A3-12. Blue, green to red: increasing time ratio of slack water (%), averaged over 2 tidal cycles. Neap (A) and spring (B) tidal conditions. (*) Area where increased sedimentation takes place, possibly enhanced by the extension of the western part of the Vlakte van de Raan, due to long-term disposal activities. Slack tide is here defined as when bottom shear stresses are less than 0.5 Pa.

(ii) Effects on local turbidity levels

ADCP profiling up- and downslope the delta front of the Vlakte van de Raan was performed to investigate variability in currents and turbidity levels. Figure A3-13 shows a current ellipse using all measurements. Current velocity is highest under flood conditions (NE directed) and reaches 0.8 m s^{-1}, *vs* 0.6 m s^{-1} during ebb (equinox conditions with >5m tidal amplitude), though the duration of the ebb is longer. The current ellipse is not fully developed during the flooding phase of the tide, probably constrained by the slope. Along the slope the current ellipses become gradually more rotary with decreasing current velocities (see also Figure A3-19).

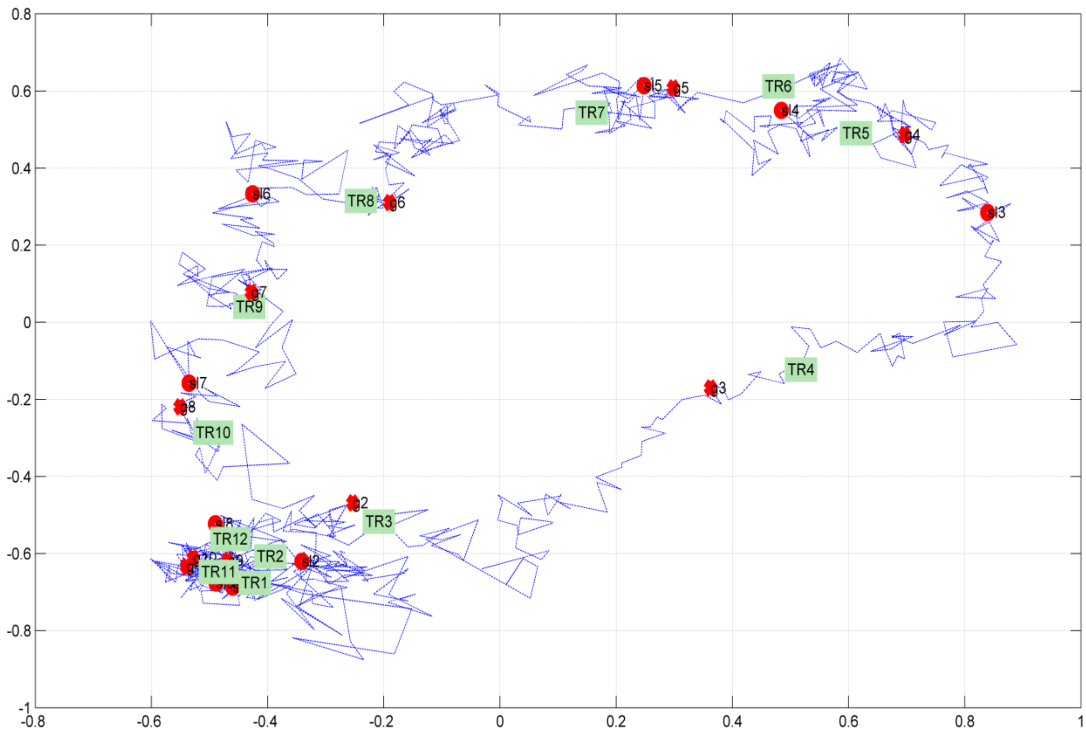


Figure A3-13. Current ellipse reconstructed from all ADCP current measurements (axes are in m s^{-1}). The transect numbers are indicated (TR), as also the positions of vertical profiling on the slope and gully (red bullets: 'g'; 'sl').

Figure A3-14 shows results of derived SPM concentrations during the transects. Especially, the SPM concentrations along the transects 7 to 10 are remarkable, as the built-up of a turbidity plume is shown moving downwards the slope. Turbidity levels are more than 0.1g l^{-1}. The timing of this plume development corresponds with the ebbing phase of the tide (from slack water to ebb) with maximum concentrations around slack water (TR8). Currents are offshore deflected and veer towards the southwest. At ebb, waters are less, but more turbid than at flood.

The timing of the turbidity plume was also compared to the periods of disposal of dredged material. During the 13-hrs cycle, disposal was restricted to the S2 disposal ground (location, see Figure A3-2). Four disposals of on average 1100 Tonnes Dry Matter took place, but also the day before, when 5 times material was disposed of. The spread of these consecutive disposals was modelled. The total extent of the influence area was about 18 km along-shore and 15 km cross-shore. Figure A3-15 represents the spread of the dredge spoil for the period of the ADCP transects (Figure A3-14). It is simulated that the dredge spoil is disposed of at the bottom, implying a lag between the disposal event and resuspension by currents and waves. Results show that tidal currents control clearly the movement of the centre of mass. Although the last disposal event before the observation of the turbidity plume was 6-h earlier, it was only during the ebbing phase of the tide that the centre of mass moved downwards the slope of the delta front. The simulations of the day before showed similar patterns with a circular movement of the centre of mass in the influence area, hence mostly restricted to the Belgian part of the Vlakte van de Raan.

The effect of the turbidity plume is likely also seen in the LISST profiles (Figure A3-16). Curve sl6, at the time that the turbidity plume is moving offshore, indicates the largest particle sizes. Most probably these correspond with flocs, indicative of the transport of fine-grained material. Overall, the shape of the particle size distributions (PSD) are similar in the gully, with a mean size varying from 65 μm (g5 on Figure A3-13 corresponding with slack water) to 100 μm (g10 on Figure A3-13; ebb). Along the slope, the PSD shapes show a higher variability with the most bimodal distributions in position sl6 and sl7 (see above), at the timing of the turbidity plume. Mean particle sizes range from $\sim 65\mu$m (sl9; ebb) to 100 μm (sl6 and sl7). At the max of ebb and flood, particles sizes are largest in the gully; finest along the slope. This points to more advection in the gully.

Bed shear stresses (Pa) versus SPM concentration were calculated, representative for the slope and for the gully, and to demonstrate along-gully (A) versus cross-gully variability (B) (Figure A3-17). Results indicate that maximum SPM concentrations are here reached under N to W-directed flow regimes, hence during the ebbing phase of the tide. In a cross-shore direction maximum values are offshore directed, correlating with the turbidity plume.

As a conclusion, it can be supported that during the ebbing phase of the tide, turbidity plumes from disposal activities or natural SPM fluxes on the shoal part of the Vlakte van de Raan move downwards the slope. With the longer duration of the ebb phase, and lower current velocities, the chance for sedimentation of fine-grained material is highest under these conditions. During the consecutive flood phase, the turbidity plume is likely desaggregated. Fines will be resuspended and washed away, enhanced by current concentration in the flood channel. The transient fluxes of high and low turbidity impose that benthic species need to be particularly resistant to strong variations in seabed erosion/deposition processes. This adds to the results of Figure A3-12, showing the natural tendency of deposition in this area. Hence, only mud-loving species will thrive. The effects of these hydrographic conditions on macrobenthic occurrences and composition are further discussed in the following sections.

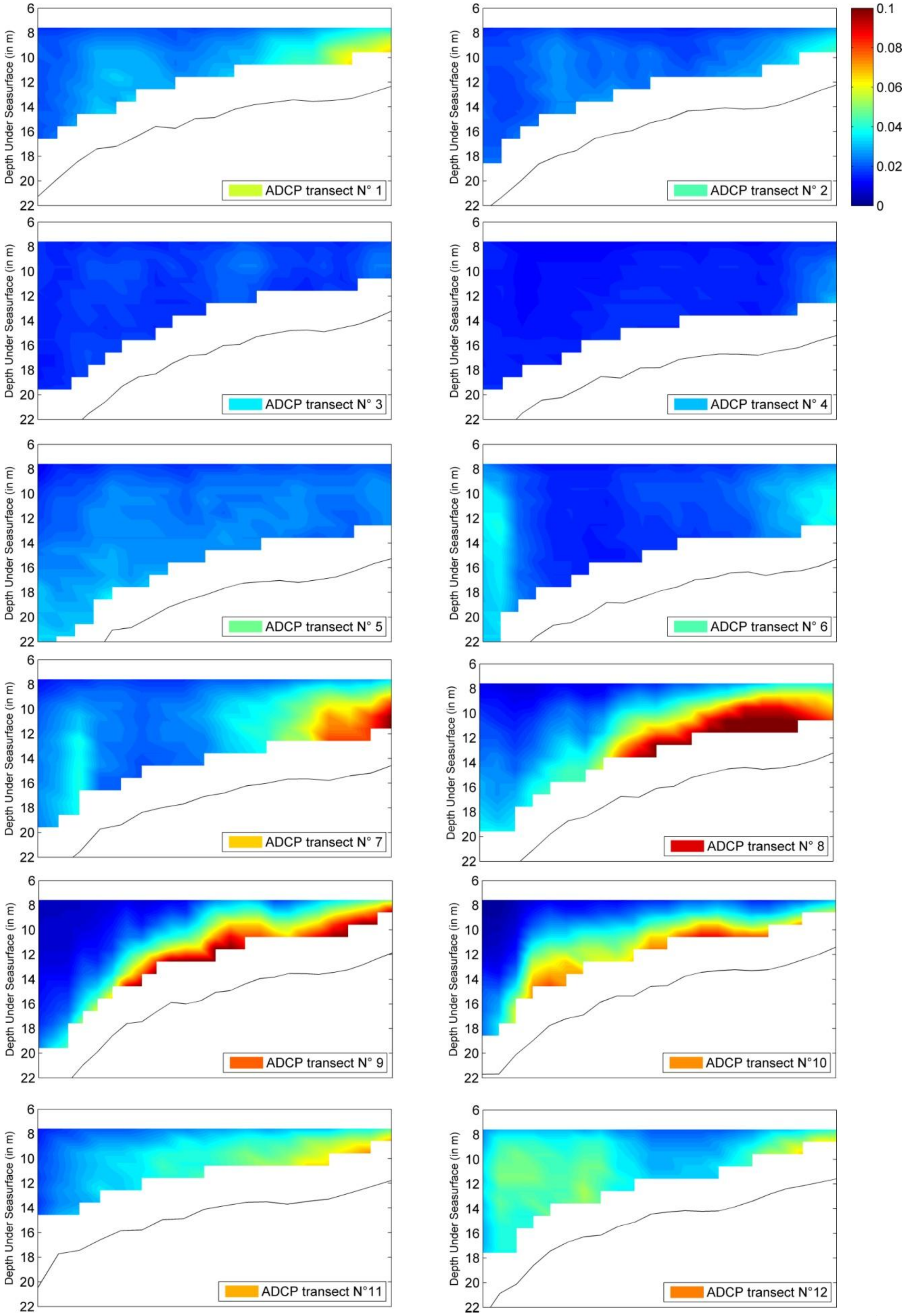


Figure A3-14. Cross-sectional ADCP transects (only downslope) of SPM concentration (g l^{-1}), with reference to the current ellipse of Figure A3-13. The high SPM concentrations in transects 7 to 10 correspond with a turbidity plume, and coincide with the ebbing phase of the tide (NW to SW veering current direction).

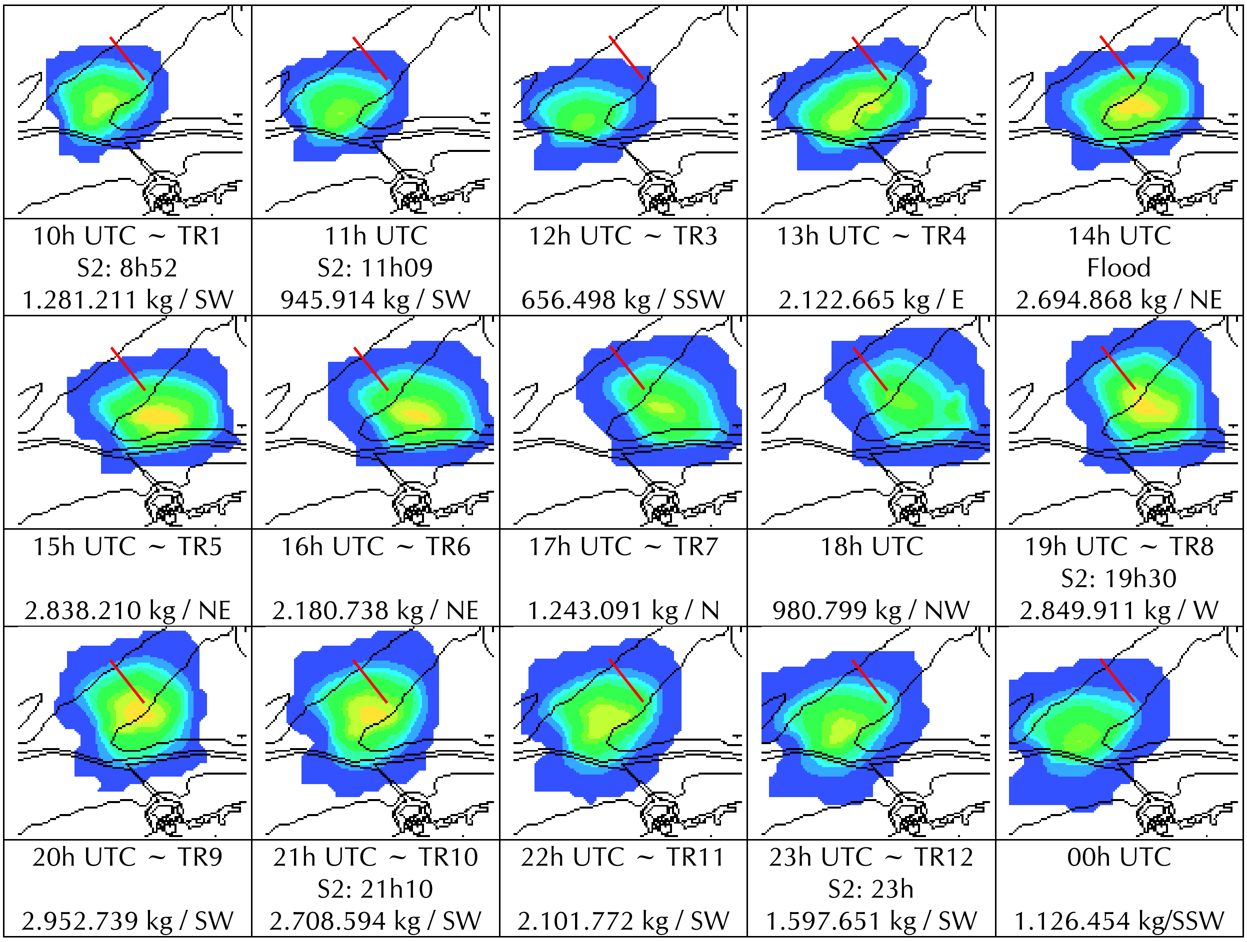


Figure A3-15. Modelled influence area of consecutive disposal of dredged material at the S2 disposal ground, period 22/3/11 10h to 23/3/11 00h. Eleven disposal activities were accounted for, starting on 21/3/11 8h32 and ending on 22/3/11 22h59. The timing of disposal events at the S2 location is given, as also the total mass (kg) and the direction of the current. Equinox conditions. On the ADCP transects (red line) a turbidity plume was observed from 17-21h UTC.

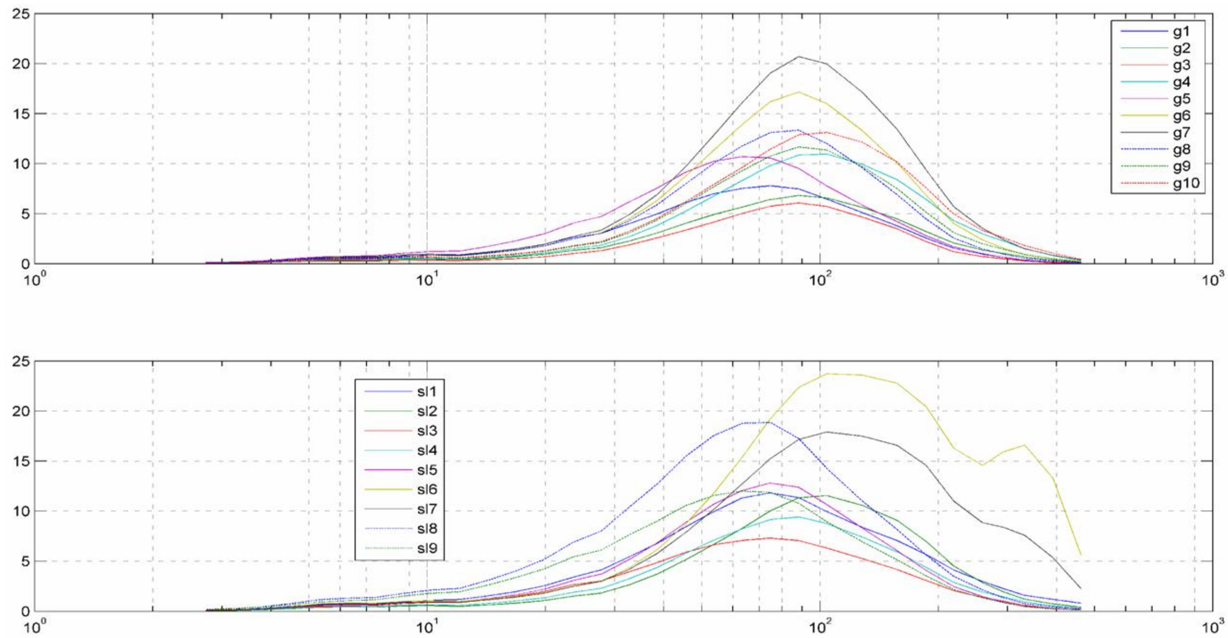


Figure A3-16. SPM particle size distributions (from LISST) with reference to current ellipse (Figure A3-13); g: gully (above) and s: slope position (under). X-axis: particle size (μm); Y-axis: volume concentration ($\mu l\ l^{-1}$).

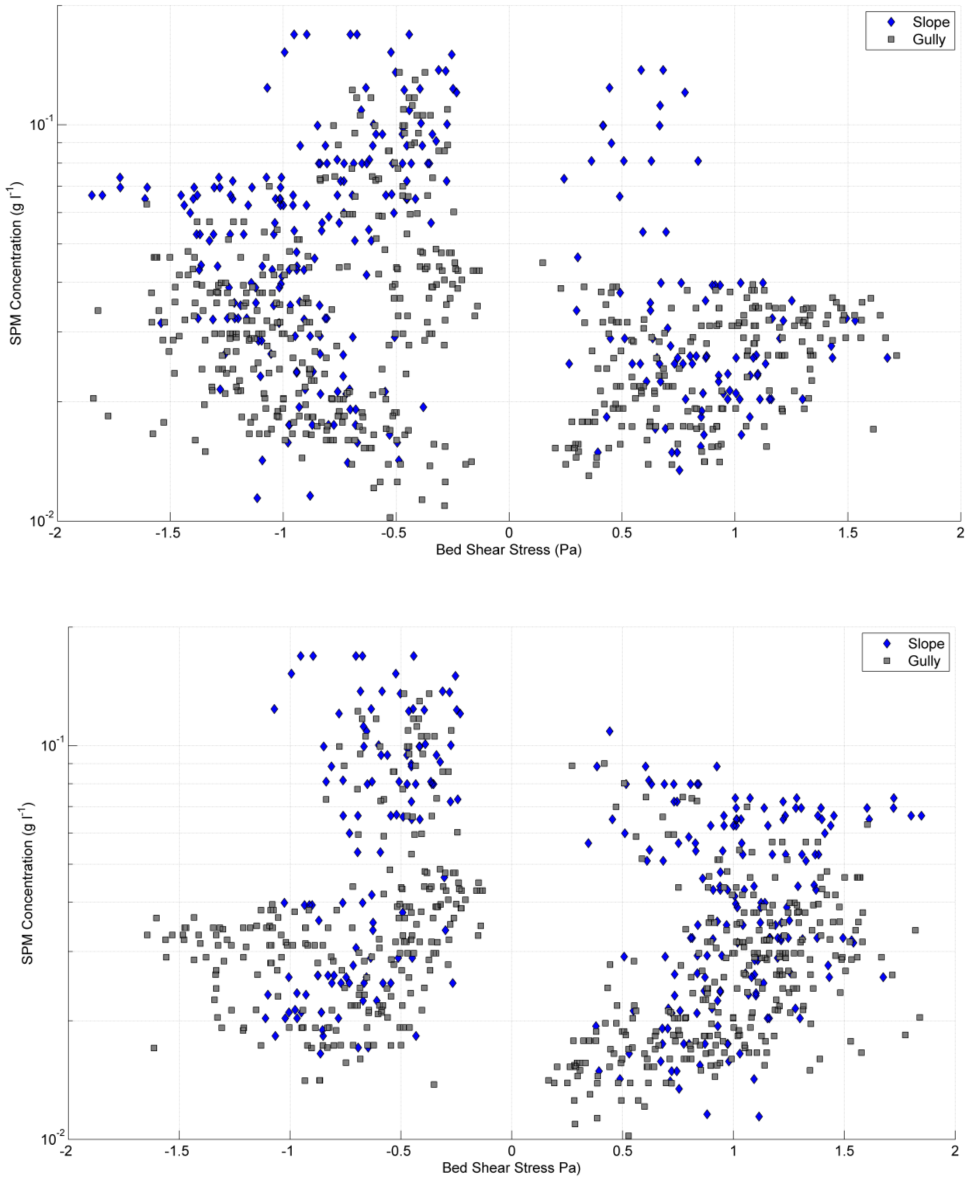


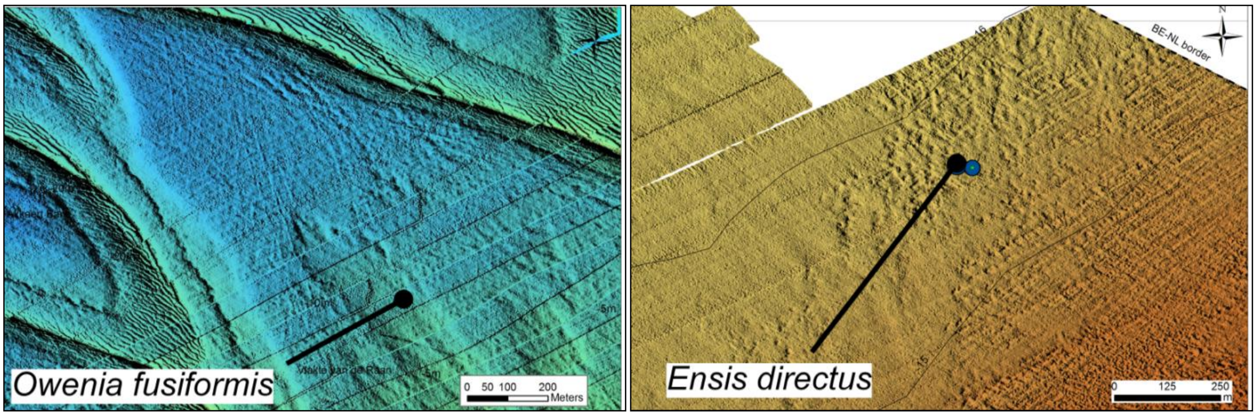
Figure A3-17. Bed shear stress (Pa) vs. SPM concentration (gl^{-1}): (A), with along-gully current direction; (B), with cross-gully current direction. In (A) positive bed shear stresses are generated by NE-directed flow; in (B), positive values are onshore directed. Under these conditions, SPM fluxes were clearly higher under the ebb tidal phase.

Effects on benthos

(i) Identification of dense aggregations of macrobenthos

Along the delta front of the Vlakte van de Raan, full-coverage multibeam observations (resolution 1 to 2 m) showed multiple circular to elongated small mounds with moderate reflectivity and a rougher texture. This acoustic signature could not be correlated with known bedform types, nor with marks of anthropogenic disturbance (MESH signature catalogue; http://www.rebent.org/mesh/signatures/). Still, varieties of these facies have been associated, previously, with the occurrences of dense aggregations of the tubeworms *L. conchilega* (Degraer et al., 2008; Van Lancker et al., 2012) and *O. fusiformis* (Van Lancker et al., 2012). Both species are ecosystem engineers and belong to the *Abra alba* community, having the highest biodiversity within the inter- and subtidal soft sediments of the North Sea (Van Hoey et al., 2004). When occurring in high densities ecosystem engineers structure the environment and attract more species, with a positive feedback on some fish species (Rabaut et al. 2007). Apart from structural effects they also have an important functional role (e.g. oxygen, carbon and nutrient recycling) (Braeckman 2011). As such, their mapping is crucial within an ecosystem-based approach to management.

Sampling in the small mound areas in the gully along the delta front revealed indeed high densities of *O. fusiformis* (Figure A3-18a). The mounds were 15-40 cm in height and occurred in the troughs of large dunes mainly; the patch size was 0.6-12 m². The repetitive multibeam imagery obtained in the area (2006-2010) will later be used to evaluate the stability of the presence and extent of the patches. Higher up the slope another characteristic acoustic facies was revealed (Figure A3-18b). Patchiness increased and formed part of an elongated band in the depth zone -16 to -12 m (Figure A3-20). Sampling revealed high densities of both *O. fusiformis* (up to 11.000 ind m^{-2}), as well as high densities of the American razor blade *Ensis directus*, the most important invasive species in the Belgian part of the North Sea (Houziaux et al., 2011). The dimensions of perceived individual patches were around 20 m in diameter, with a height of around 20-40 cm. Their extent could be depicted by slope calculations from digital terrain models; the mounds had characteristic values of >2°. The observations comply with those discussed in Van Lancker et al. (2012), and confirm the higher biodiversity patches on and near sandbank slopes. Still, video imagery would confirm the true biological nature of this acoustic facies.



A **B**

Figure A3-18. A. Dense aggregations of *O. fusiformis* in the troughs of large dunes in the bedload convergence zone. Their occurrence is likely related to the transient fluxes of fine-grained material, both along-gully and cross-gully. B. Part of the elongated band in which high densities of both *O. fusiformis* and *E. directus* were found along the upper slope. This area is mostly subdued to high levels of turbidity, both naturally- as anthropogenically-induced. From residual currents, fluxes in an ebb direction are dominant, hence trapping the fines. Seabed samples are here significantly finer. Locations: Figure A3-20.

Correlating the areas with small mounds and previously described hydrographic condtions shows that those areas occur 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.

(ii) Effects on the spatial distribution of dense aggregations of macrobenthos

Multibeam surveys were also conducted along the full extent of the Vlakte van de Raan, but restricted to the areas between -10 and -20 m, along the north and south slope. Reconnaissance lines were sailed with a spacing of 2 km (Figure A3-19). The imagery obtained was screened for patchiness, similar as those described above and in Van Lancker et al. (2012). Strikingly, the most prominent patches occurred in the Belgian sector of the delta front. **It is hypothesized that this is due to a natural convergence of fines, due to the mechanism of the flood and ebb channels, trapping fines, enhanced by regular deposition of fines through disposal activities**.

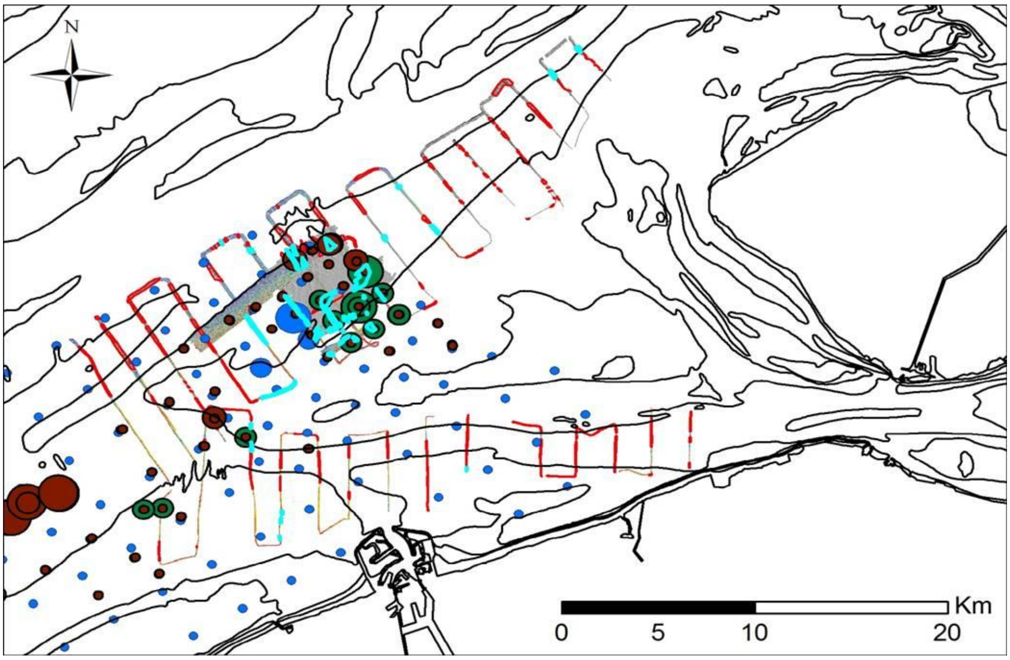


Figure A3-19. Vlakte van de Raan area and the sailed multibeam tracks along the north and south slope (RV Belgica ST1029, 16-19/11/10). The acoustic facies were interpreted: red is indicative of changing seabed properties (e.g. dunes, or important sediment changes); in cyan are those areas where small mounds were observed, likely reflecting dense aggregations of macrobenthos. The circles and their size reflect the abundance of Ensis directus, following Houziaux et al. (2011). Note that the cyan areas primarily concentrate on the Belgian part of the delta front.

(iii) Effects on benthos composition

The mechanism of flood and ebb channels and its relevance towards soft substrata benthos distribution on the slope of the delta front is shown in Figure A3-20. The distribution of *Ensis directus* revealed high densities of juveniles at the foot of the delta front (end of the flood channel), whilst adults were concentrated higher up the slope. This hypothesized the existence of biological zonation and was further investigated. Macrobenthos samples were taken along transects perpendicular to the slope (Figure A3-4), and spread along the delta front. From the biological analyzes, the slope could be subdivided into three areas (Figure A3-20) and corresponded well with a gradient in sediment dynamics: (1) the flood channel and lower slope with medium sands and higher dynamics, though mud in the troughs of the dunes: *O. fusiformis* thrives, as also *E. directus* juveniles; (2) the upper slope with finer sediments, more rotary currents, less in strength: mainly *O. fusiformis* (~11.000 ind m^{-2}) and *E. directus* (12-16 m MLLWS) (> 500 ind m^{-2}); and (3) an intermediate area (along the dashed line in Figure A3-20) with relatively poor species richness (Tafara Breine, 2011). Correlation with the acoustic backscatter, derived from ADCP and represented in Figure A3-14, shows that the upper slope area is most intensively influenced by turbidity plumes, hence the species *O. fusiformis* and *E. directus* must be resistant to varying stress levels, naturally and anthropogenically-induced.

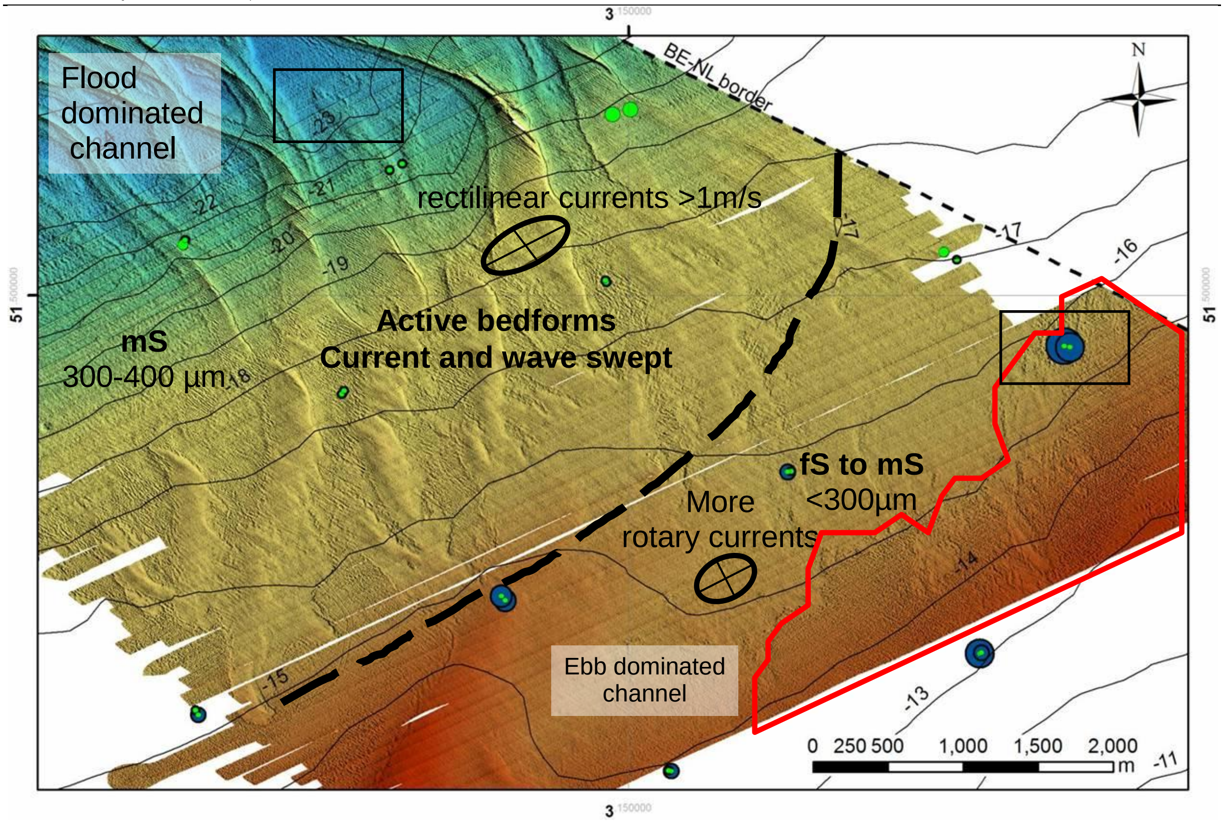


Figure A3-20. Synthesis figure of sediment dynamics, as derived from acoustic measurements (MBES ST1029; ADCP ST1108). Recently reworked sand dunes were observed (without major trawling traces, in contrast to earlier observations that mostly witnessed ripped-up seafloors). In this zone of active transport medium sands prevail. Higher up the slope sediments become finer and currents became more rotary and less in strength. The ebb current is here important. Highest densities and species richness occur in this upper slope area (e.g. *O. fusiformis* ~11.000 ind m^{-2} *E. directus* (blue circles) >500 ind m^{-2}). Green dots correspond with the occurrence of *E. directus* juveniles; they are most abundant near the end of the flood-dominant channel. The red delineated zone likely corresponds with an acoustic facies of biological origin. The upper slope area is most frequently subdued to transient turbidity plumes, naturally and anthropogenically-induced. Only, stress-resistant species can survive. Location: area near Belgian-Dutch border, see also Figure A3-10 for an overview. Rectangles indicate the positions of Figure A3-18A/B.

Discussion and conclusions

The following hypotheses were formulated: (1) Long-term disposal of dredged material causes regional sedimentation in the area; and (2) Increased biodiversity near the Belgian-Dutch border is due to increasing availability of fines due to disposal activities.

To test these hypotheses fine-scale seabed mapping (e.g. surficial sediments, morphology and benthos) was performed. Together with modelling results on hydrographic conditions (e.g. residual currents; sedimentation due to tidal forcing; suspended particulate matter), and current measurements, it was argued that variability in sediment processes are largest for the Belgian sector of the delta front of the Vlakte van de Raan. Finer sediments are naturally trapped, but this process is enhanced by changes in morphology due to long-term disposal of dredged material, as also to the higher availability of fines in the Belgian sector of the delta front. Disposal activities induced permanent modifications of hydrographic conditions, though whether or not this causes adverse effects on the ecosystem cannot be answered from the present datasets. Here only supplementary evidence is presented of high abundances of species, with highest densities where fine material actively deposits. The species must be stress resistant given the prevailing transient nature of sediment processes. Integration with longer-term biological and physical monitoring data is needed (e.g. Lauwaert et al., 2009), as also further clarification on the role of varying levels of suspended particulate matter on benthos (e.g. Rodriguez Palma et al., this report). The adversity of effects will link to issues on biodiversity, food webs and seafloor integrity. The latter may be altered by increasing sedimentation when important changes in oxygen, carbon, or nutrient cycling would occur (Rosenberg 2001; Rice et al. 2012).

The spatial scale of the effects of disposal will depend on the natural sediment dynamics. In suspension, fine-grained material may be dispersed over several kilometers (here up to 18 km), though the interplay of currents, in combination with availability of SPM, will determine the importance of smothering on the benthos. Around the disposal grounds, habitat creation or modification takes place. The extent depends on amount, frequency and duration of disposal activities, though in combination with sediment dynamics. For the disposal ground S1, the westward expansion of 1.5 km was reinforced by the ebb-dominancy of sediment transport pushing out the surplus of material that became available through disposal. The severity of the impact on the benthos will then further be determined whether or not a habitat change occurs (e.g. difference in sediment nature between disposed material and substrate type). This will be most likely the case for the S1 present-day disposal ground.

In any case, increased system knowledge (incl. morphological setting, substrate characteristics, sediment processes, sediment dynamics, habitat sensitivities and recovery potential) is needed to estimate final impacts.

Acknowledgement

This contribution forms part of the objectives of the Belgian Science Policy project QUEST4D (QUantification of Erosion and Sedimentation patterns to Trace naturally- versus anthropogenically-induced sediment dynamics; BelSPO SD/NS/06B). Flemish Authorities, Maritime Entrance, is thanked for providing data on bathymetry and disposal activities on the Vlakte van de Raan. Officers and crew of *RV Belgica* are warmly thanked, as also Reinhilde van den Branden, Rindert Janssens, Emiel Vereecken and many students during successive campaigns at sea. Ghent University, Renard Centre of Marine Geology is acknowledged for the use of the multibeam processing software Sonarscope (Ifremer). Flanders Marine Institute (VLIZ) is thanked for the use of the LISST instrumentation.

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Annex 4. Historic (1899-1914) and recent (1994-2008) distribution maps of 14 common endobenthic bivalves in the BPNS

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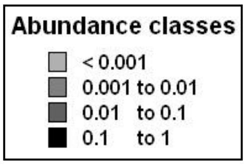
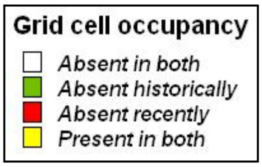
Abundance data were standardized at the sampling stations to the maximum amount of specimen collected for each species in each data-set. For the historical stations, a problem appeared for *Donax vittatus* with one very high abundance of juveniles (over 13,000 specimens), which can be attributed to an exceptional recruitment event. This value being two orders of magnitude higher than the second maximum abundance (400) and accounting for more than two third of all specimens collected, the latter value was used for this species generally collected in low numbers. Raw interpolation maps of relative abundances were created for all species in the two situations (interpolation method: Inverse Distance Weighing; search radius: 5 km) to identify areas with higher probability of occurrence.

Given the fact that the two data-sets display a very different geographic spreading of samples, the data were further processed relatively to 61 grid cells in which at least one historic dredge and two recent Van Veen samples were taken (see material and methods, section 2.3.1). Averaged abundance values were standardized to maximum abundance. Data were further reduced to presence or absence in both data-set to draw difference map of grid cell occupancy (see legend below).

<u>Map legends:</u>

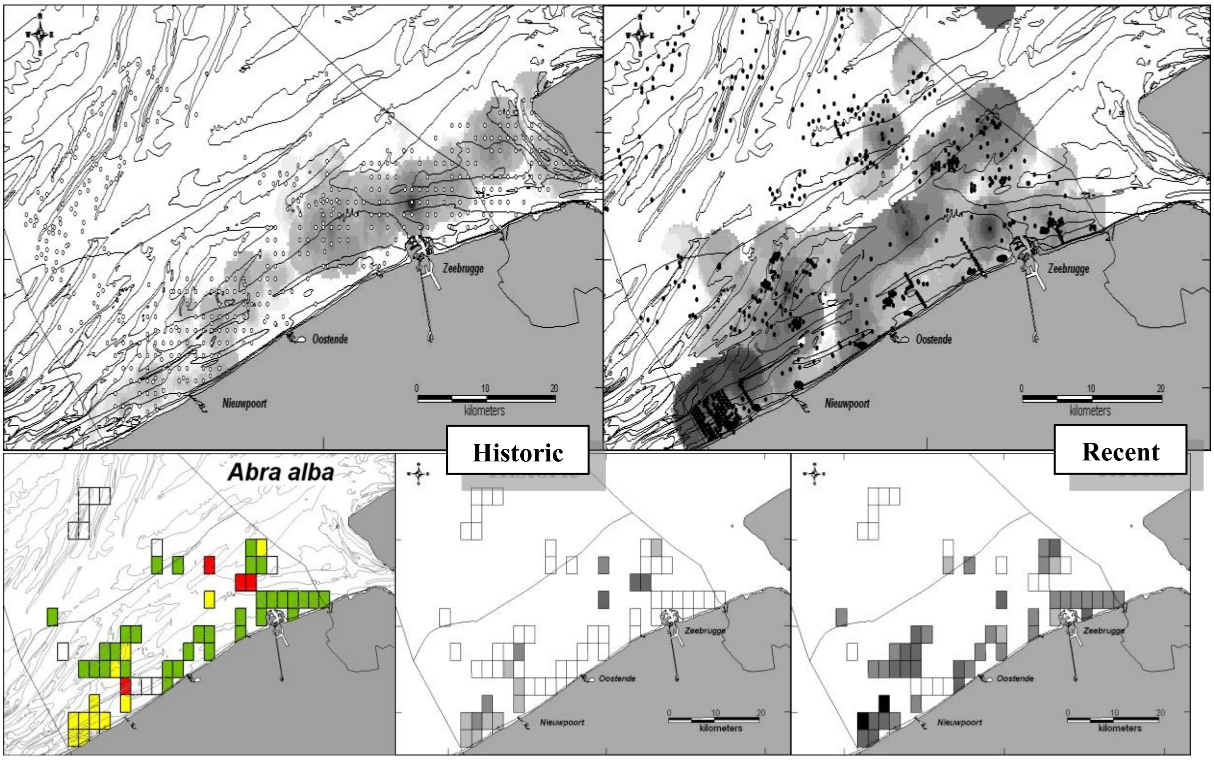


Station and grid cell data (n=61): relative abundance (abundance standardized to maximum observed abundance)

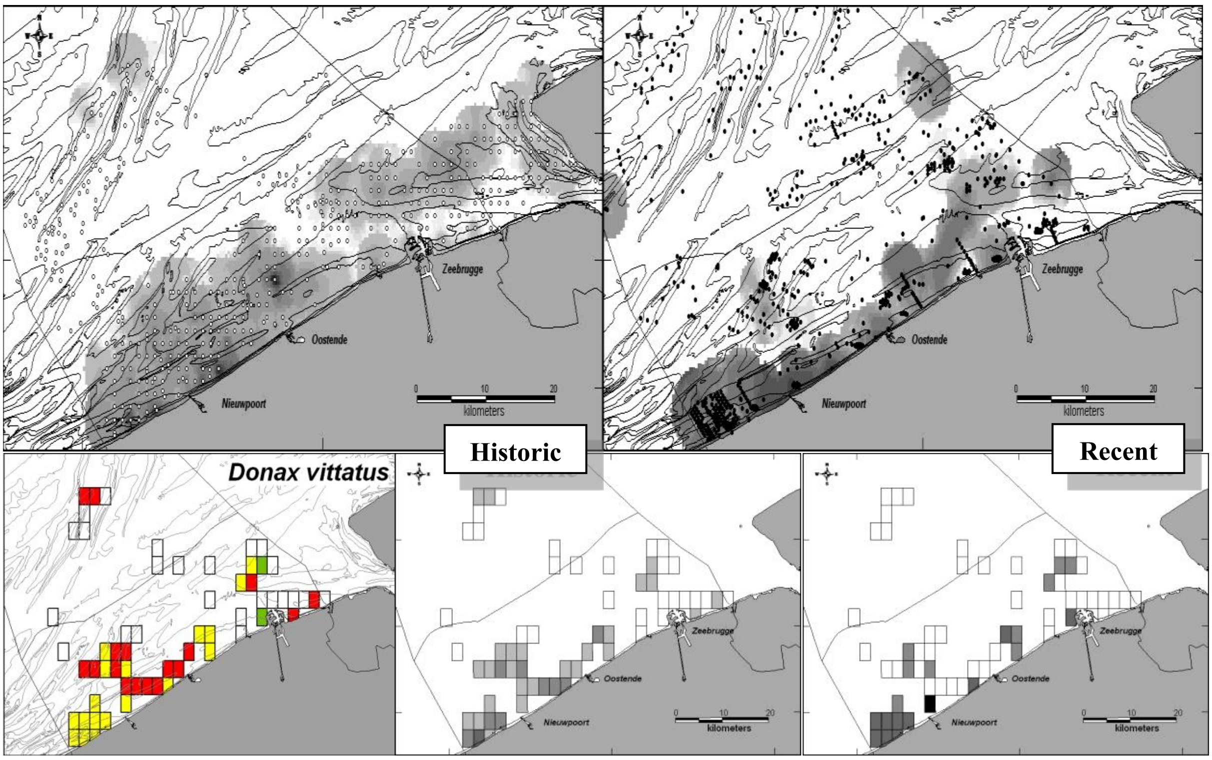


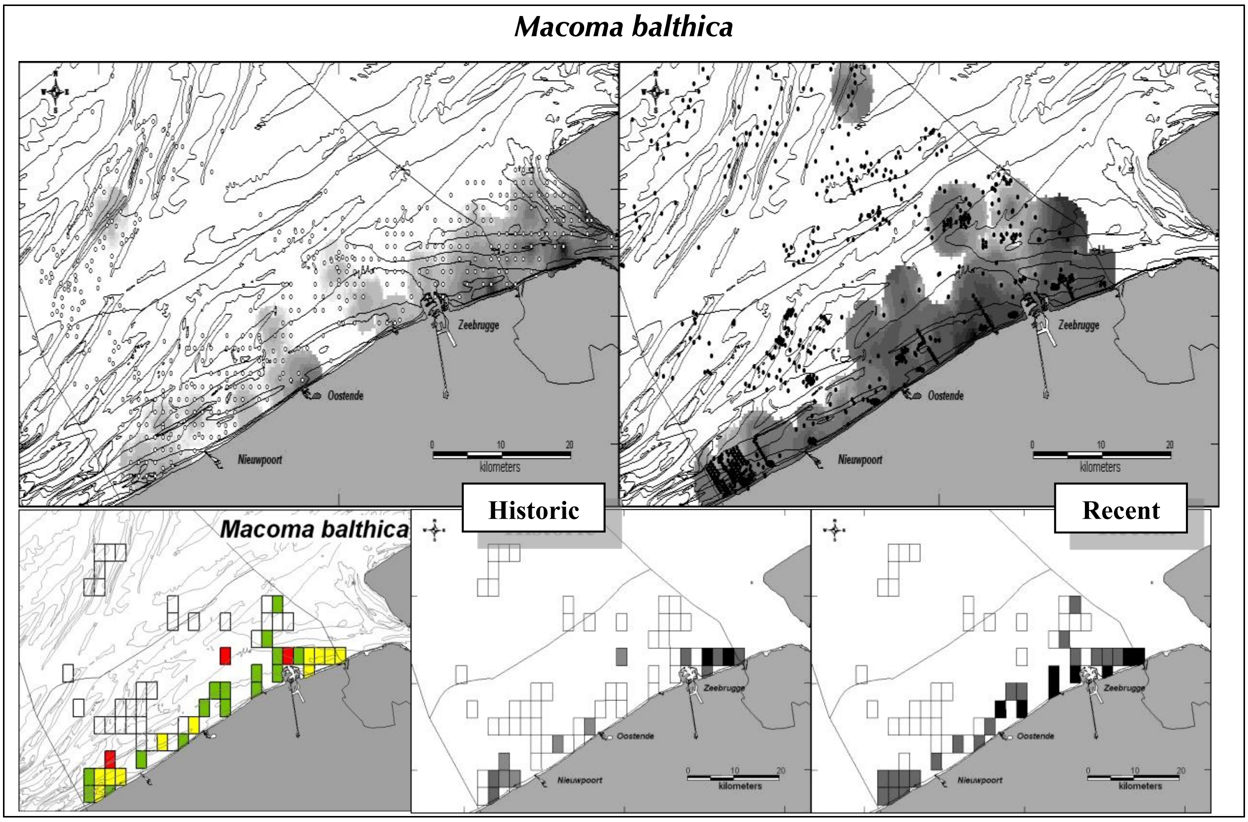
Grid cell data (n=61): presence state in historic and recent data-sets

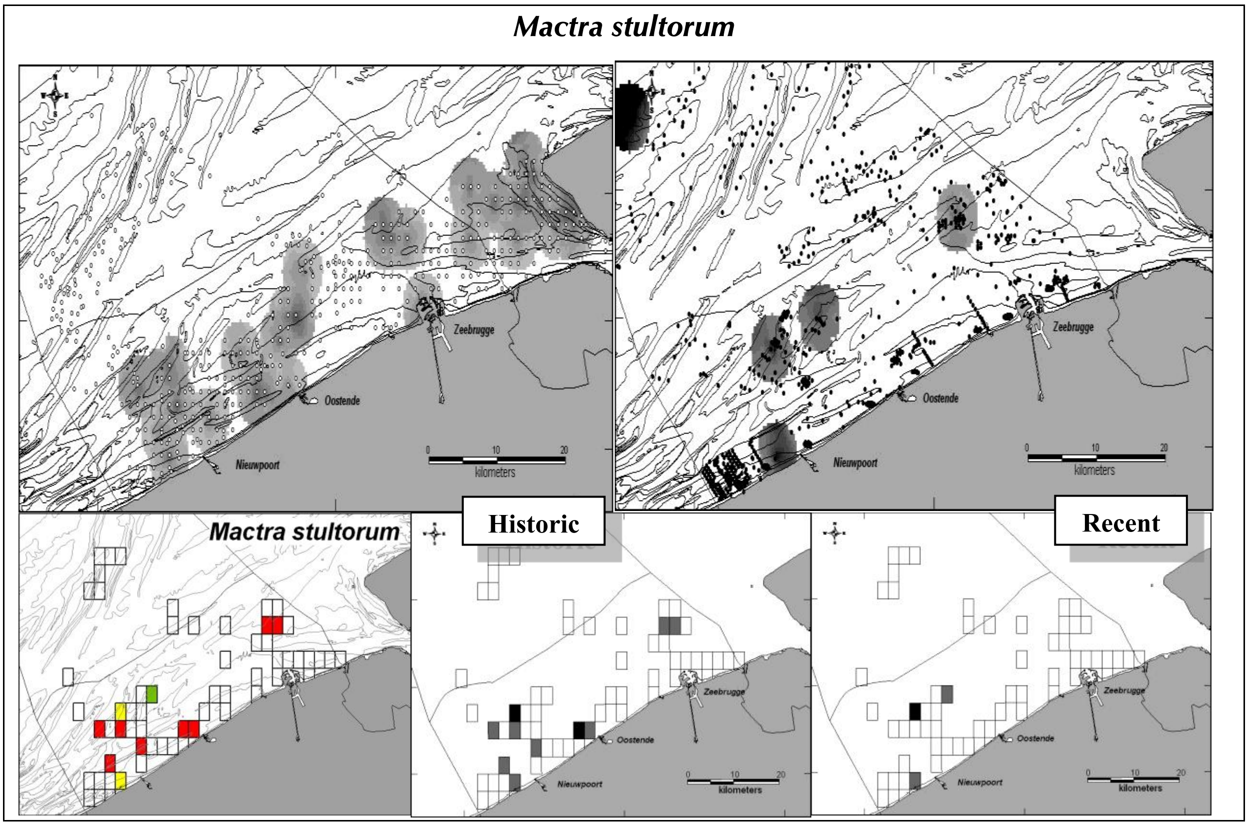
Abra alba

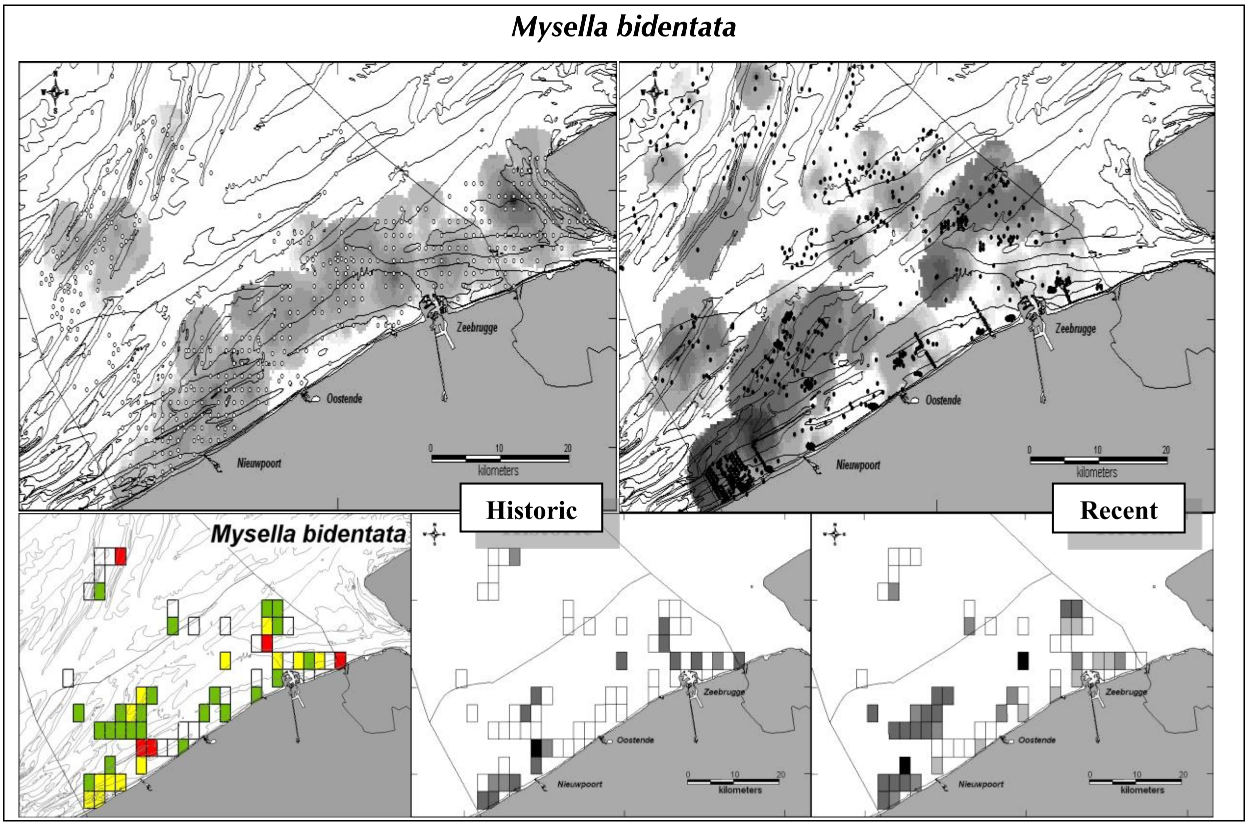


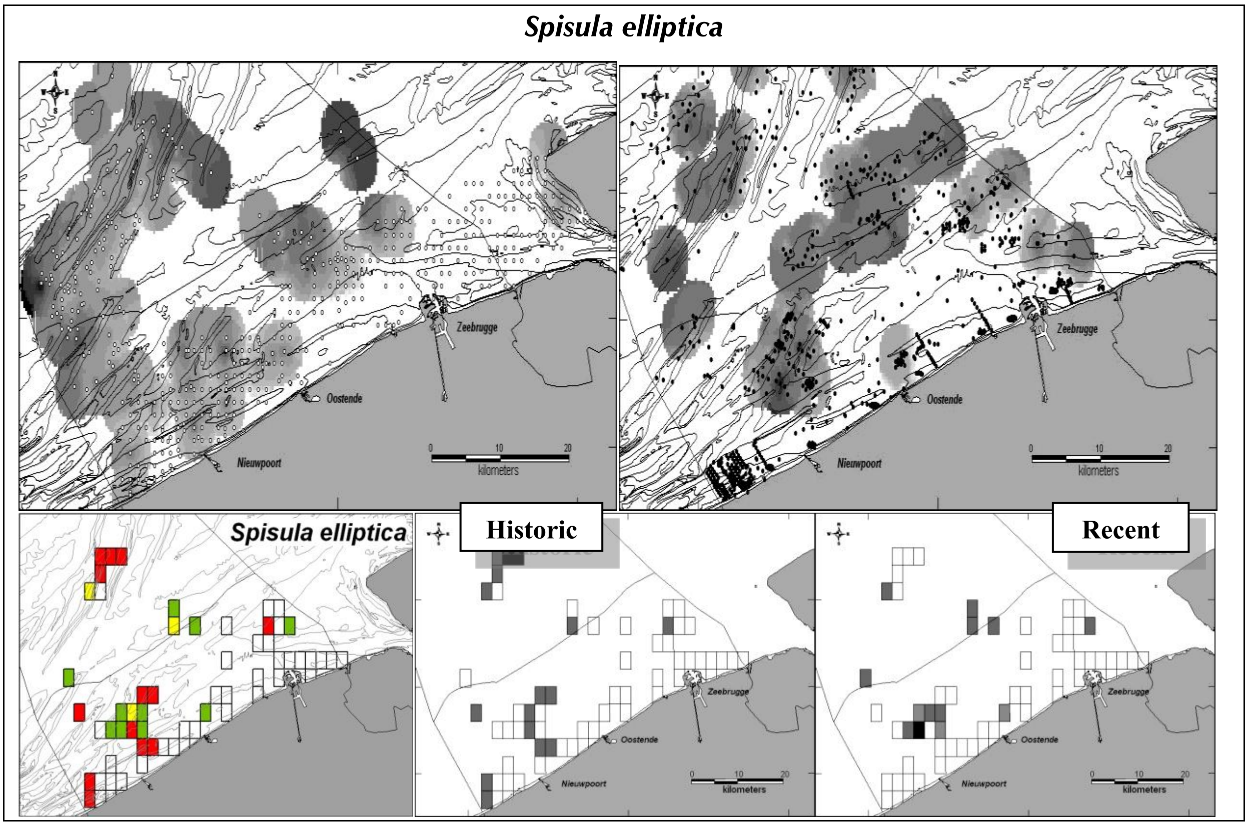
Donax vittatus




Macoma balthica
Zeebrugge
Oostende
Nieuwpoort
kilometers
Historic
Recent
Macoma balthica


Mactra stultorum
Zeebrugge
Oostende
Nieuwpoort
kilometers
Historic
Recent
Mactra stultorum


Mysella bidentata
Zeebrugge
Oostende
Nieuwpoort
kilometers
Historic
Recent
Mysella bidentata


Spisula elliptica
Zeebrugge
Oostende
Nieuwpoort
kilometers
Historic
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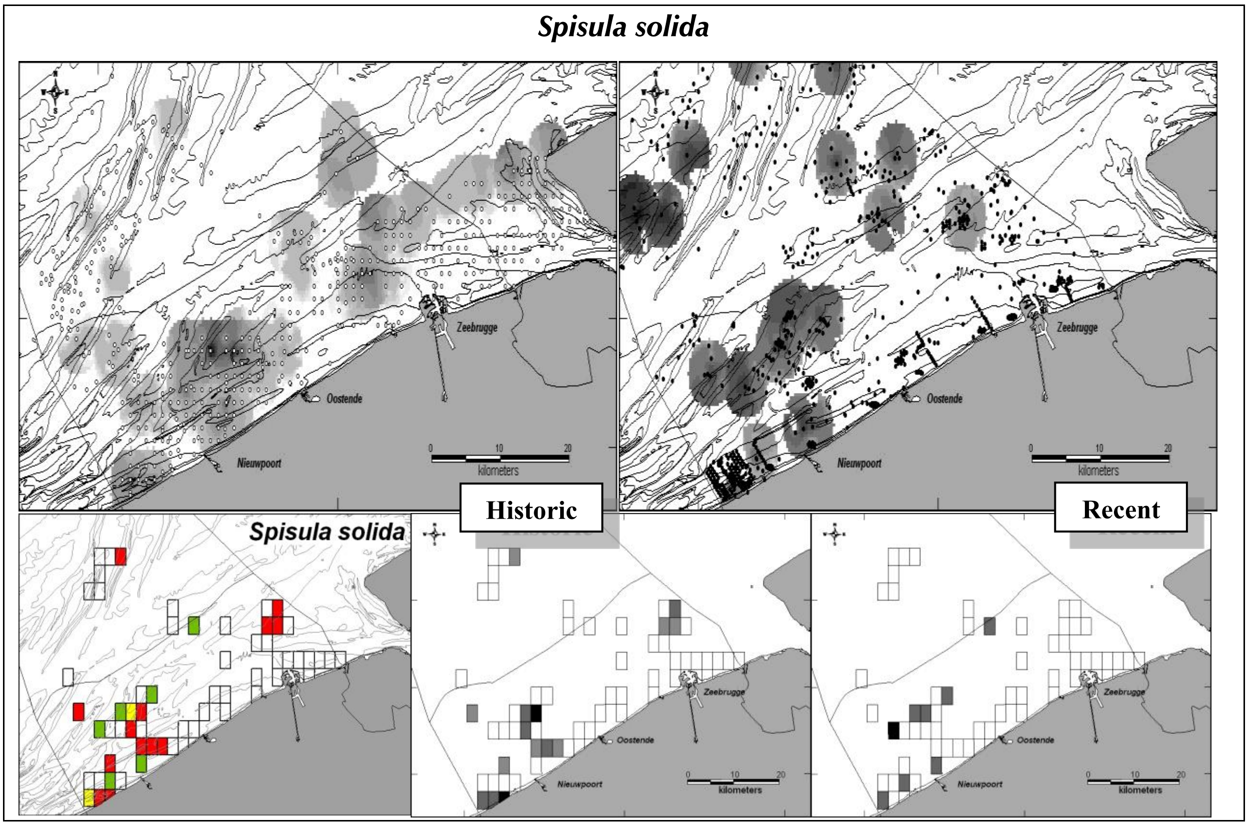
Spisula elliptica


Spisula solida
Zeebrugge
Oostende
Nieuwpoort
kilometers
Historic
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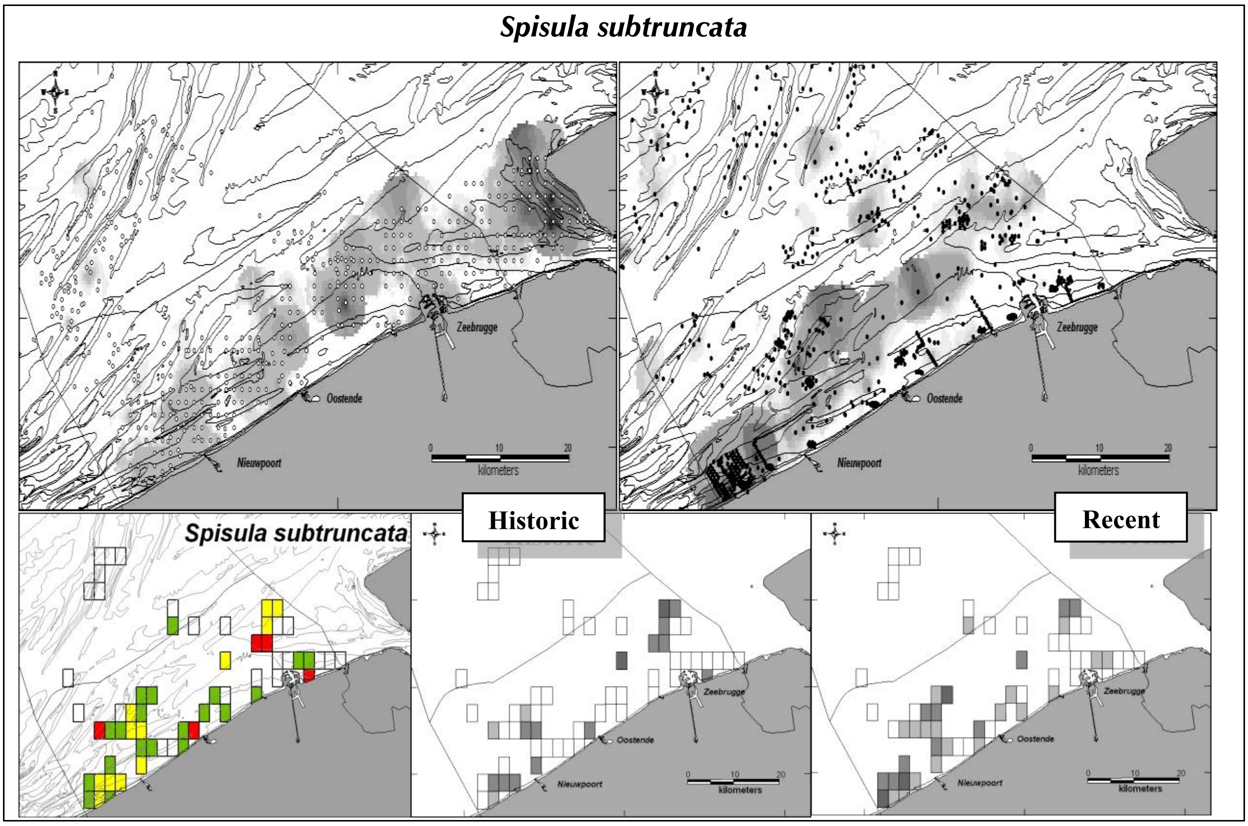
Spisula solida


Spisula subtruncata
Zeebrugge
Oostende
Nieuwpoort
kilometers
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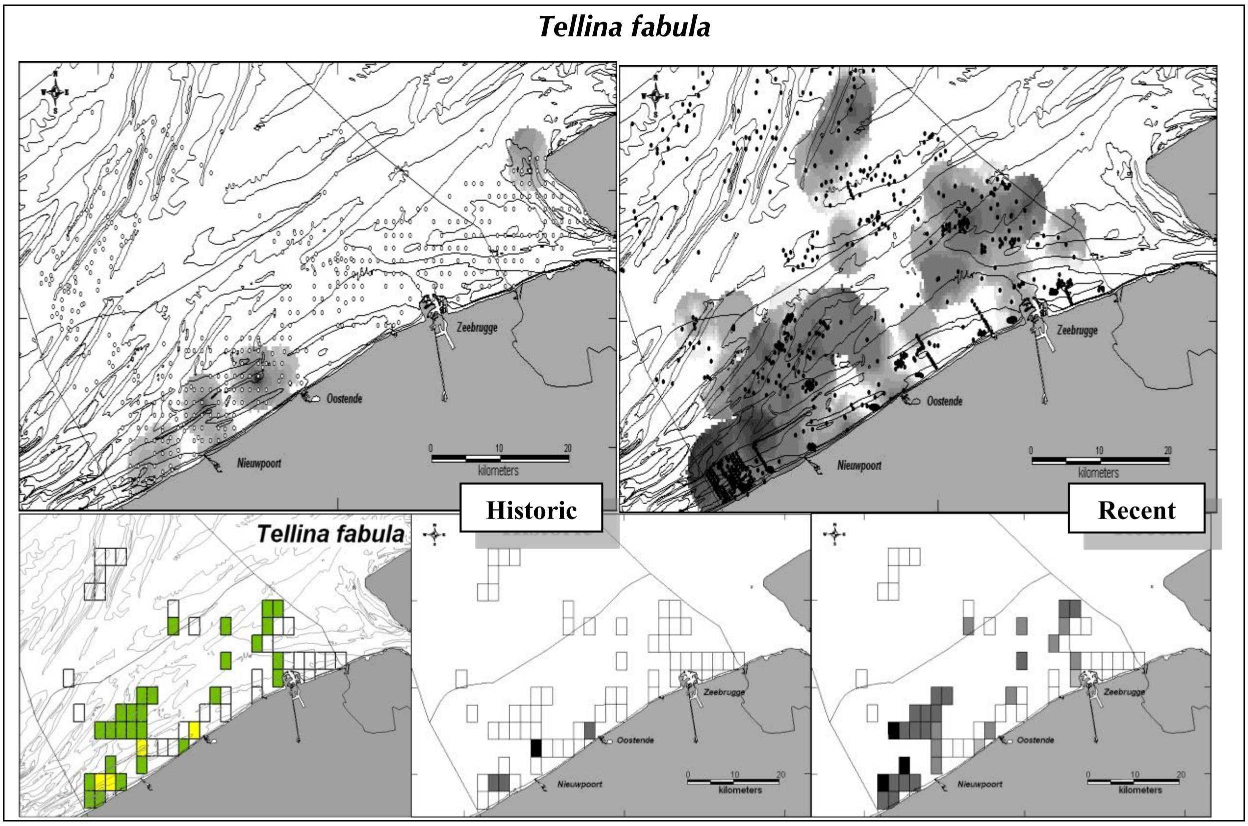
Recent
Spisula subtruncata


Tellina fabula
Zeebrugge
Oostende
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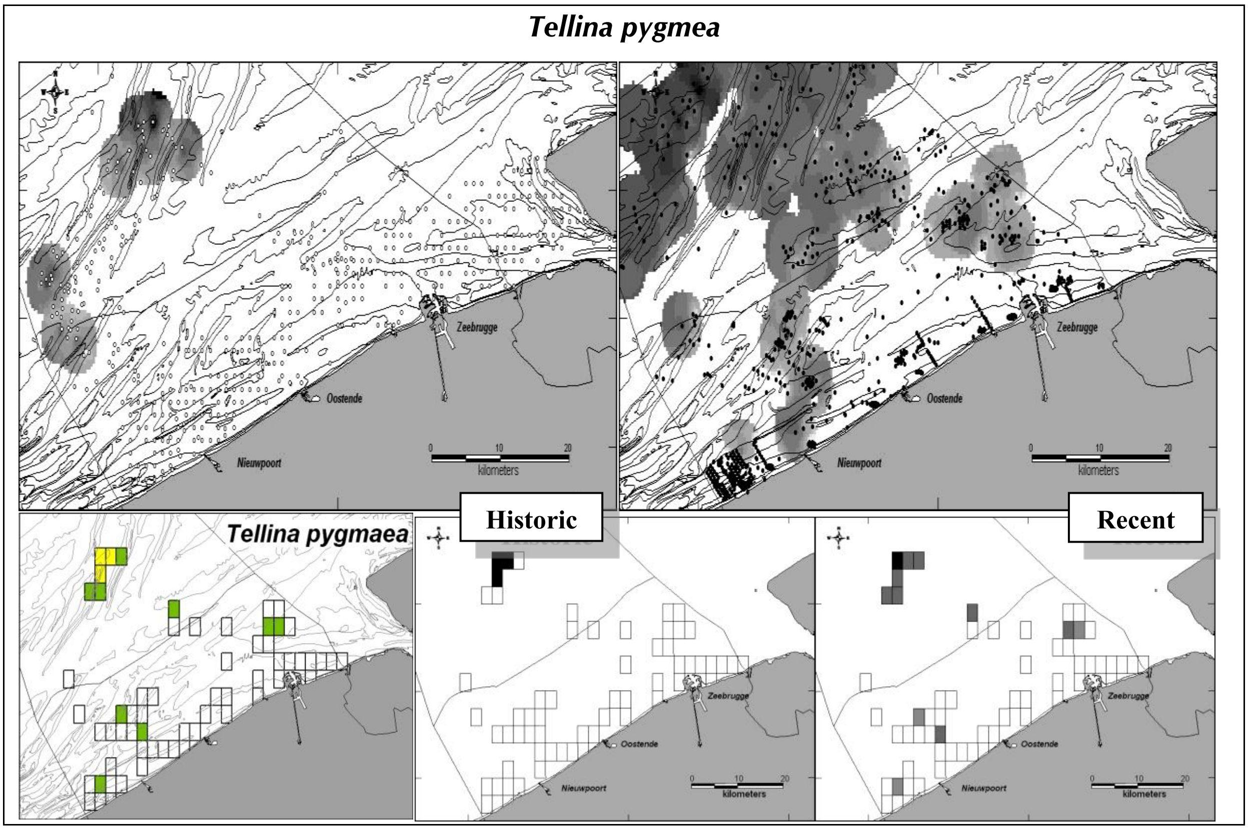
Tellina fabula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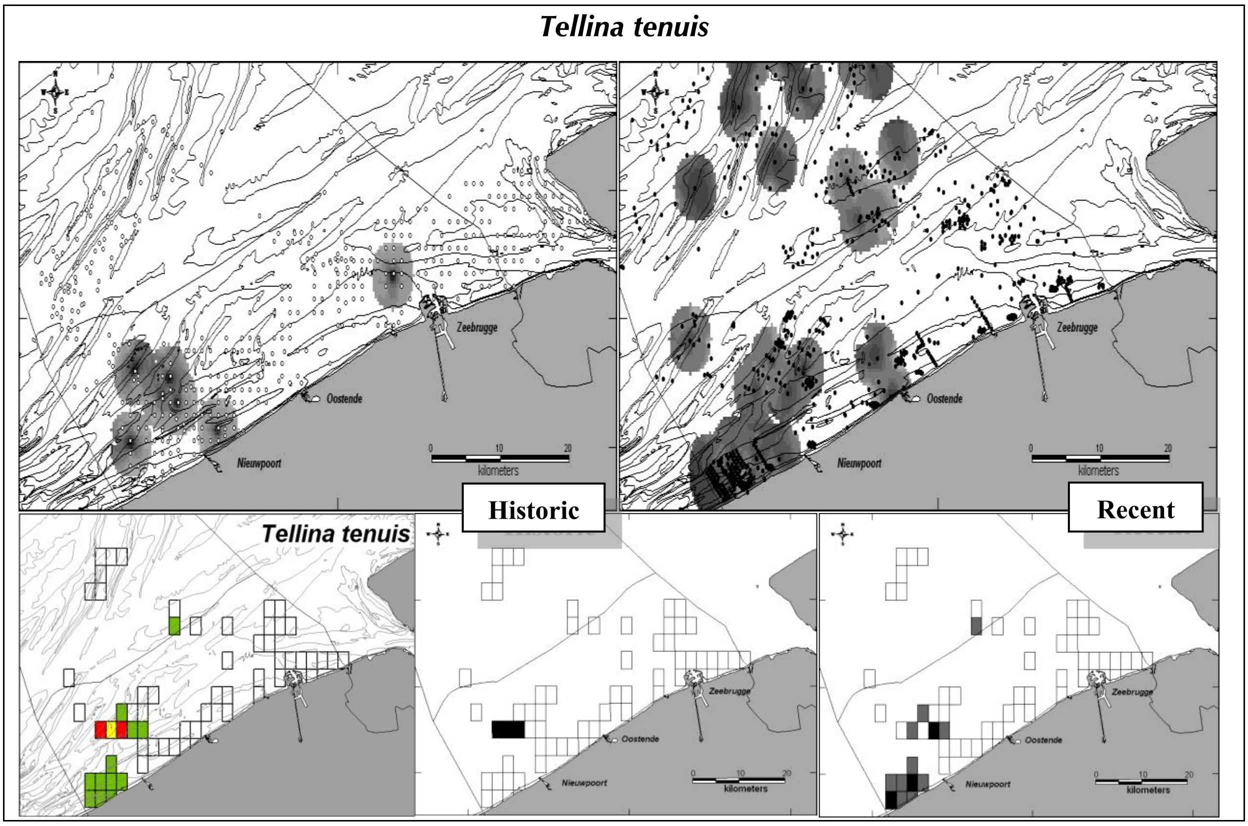
Tellina tenuis
Zeebrugge
Oostende
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Historic
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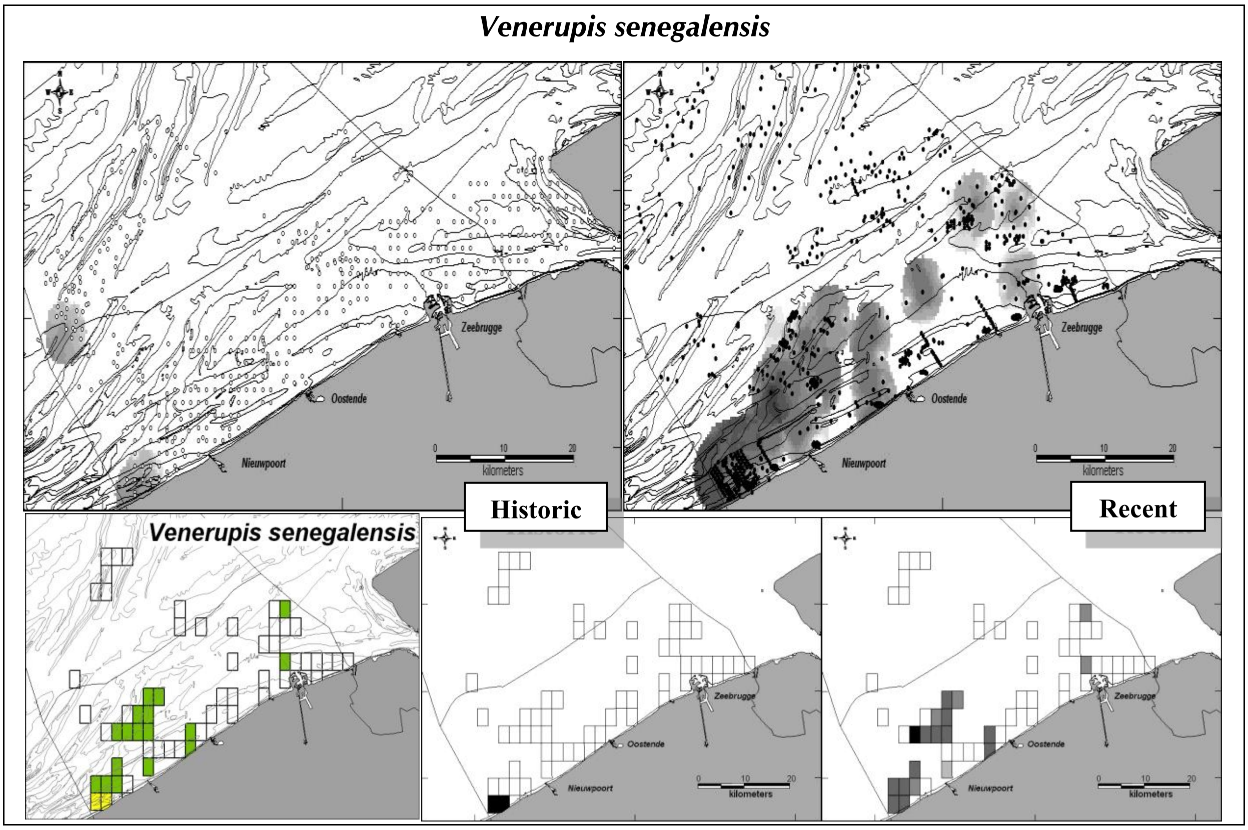
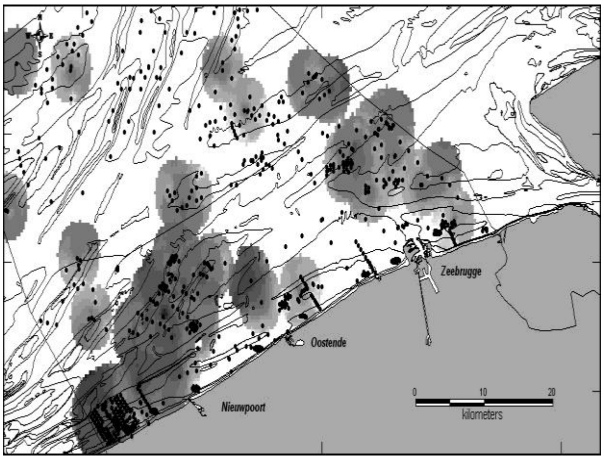
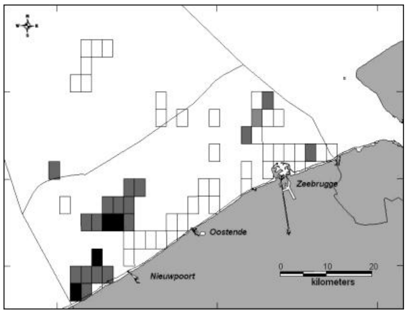
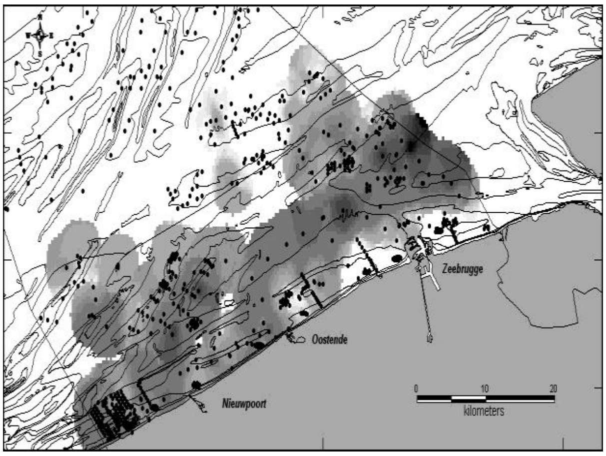

Venerupis senegalensis
Zeebrugge
Oostende
Nieuwpoort
0 10 20
kilometers
Historic
Recent

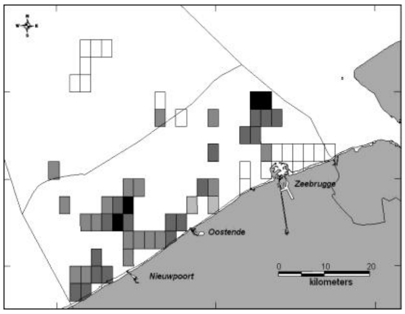
Tellimya ferruginosa, recent (no historic data)





Ensis directus, recent (no historic data)





Annex 5. Influence of European Directives on Monitoring

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Abstract

European legislation for marine monitoring has become increasingly complex. Overall, there is a demand to move towards a functional and ecosystem-based approach to management. This cannot be achieved by merely integrating present-day monitoring activities. New approaches are needed of which adaptive and risk-based monitoring are promising concepts, in the view of keeping monitoring manageable, and time-and cost-efficient.

EU Directives and Monitoring

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 good marine monitoring programme can quickly and reliably detect negative trends in the marine environment and trigger appropriate action. Monitoring data can often be used to show how specific human activities have specific impacts on the marine environment.

Monitoring is required under Articles 11 and 17 of the Habitats Directive (Directive 92/42/EEC) and Articles 10 and 12 of the Birds Directive (Directive 79/409/EEC). There are also detailed requirements for coastal and transitional waters under Articles 5, 8 and 15 of the Water Framework Directive (WFD, Directive 2000/60/EC). The reporting obligations under the Habitats Directive, in particular, call for comprehensive monitoring of the species and habitat types listed in the Directive's Annexes.

The OSPAR Convention for the North-East Atlantic also requires close monitoring of specific endangered and declining species, together with a set of ecological quality objectives (EcoQOs). Further requirements for marine biological monitoring are laid down by the Agreement on the Conservation of Small Cetaceans of the Baltic and North Seas (ASCOBANS).

The **Marine Strategy Framework Directive** (MSFD, Directive 2008/56/EC), adopted in June 2008 and implemented in the Belgian legislation in June 2010, is the environmental pillar of the EU's Integrated Maritime Policy aiming at achieving healthy marine waters by 2020 (for an overview, see Van Gaever, this volume). It applies an integrated approach to ecosystems and strives to contain the collective pressure of human activities within sustainable levels. It prescribes broad-based marine monitoring related to 11 descriptors, as a basis for assessing environmental status and for taking and measuring the success of any action needed. Table 1 lists the 11 descriptors enabling assessing good environmental status within the MSFD framework (Borja et al., 2010). Comparison is made to requirements of WFD and other Directives *w.r.t.* nutrients and eutrophication.

The MSFD includes a requirement to adopt specific and standardized methods for monitoring and assessment to ensure consistency to compare the achievements of good environmental status throughout European seas, with the same level of ambition in protection and restoration (Borja et al., 2010). MSFD requires an assessment of the marine habitat types (not directly required by WFD), with the additional issue that monitoring methods and indices of change may be habitat specific (Borja et al., 2010). WFD and MSFD should be integrated to give a land to open sea system of assessment and management (Borja et al., 2010).

Within Member States, marine monitoring programmes are being adapted to the needs of the EU Birds Directive, Habitats Directive and Water Framework Directive (WFD), as also preparations are being made to implement MSFD. This involves standardising monitoring programmes that are already in place and others that are yet to be developed to create efficient integrated programmes. However, MSFD requires new methods of assessing the status of the marine environment to be developed and coordinated with other EU states. Table 2 outlines the needs of MSFD compliant monitoring programmes (Annex V of the Directive). Apart from these needs assessments should be made on the basis of the indicative lists of elements (e.g. characteristics of marine ecosystems and the possible pressures and impacts on them) set out in Annex III (Table 3), and with reference to environmental targets, yet to be defined. The latter, and associated indicators to be defined, need establishment by 2012; establishment and implementation of monitoring programmes is due by 2014.

Overall, all of these EU Directives demand a move towards a functional and **ecosystem-based approach to management**. This means that all elements should be considered that make up the ecosystem[1] (physical, chemical and biological variables), as well as activities that take place, in order to ensure that biodiversity, health and integrity of the marine environment is maintained in the longer term. However, this relies on the ability and the will to modify and extend the present monitoring practices and to move from '**station-oriented monitoring' to 'basin or system-oriented monitoring**', in combination with specific 'cause–effect' studies for the often highly dynamic marine systems (de Jonge et al., 2006). As such, some authors plead for a radical rethinking of marine monitoring, if we want to achieve **marine sustainability** in EU waters, the common denominator of most EU objectives (Morris et al., 2011). Defining marine sustainability remains a challenge, but at least Rice et al. (in press) considers uses sustainable if: (1) pressures associated with the uses do not hinder the ecosystem components to retain their natural diversity, productivity and dynamic ecological processes; and (2) recovery from perturbations are rapid and secure, such that the attributes lie within their range of historical natural variation. As such, a significant restructuring of the system by which marine monitoring data are collected, collated, and interpreted is required. Ultimately, efficient monitoring programmes would show that our seas are clean, safe, healthy, productive (i.e. sustainable consumption and production) and diverse, and that management activities have succeeded (UKMMAS, 2007).

The goal of this presentation is to reflect on setting-up integrated monitoring programmes *w.r.t.* EU Directives. Based on a literature review on monitoring approaches in EU context, ways forward in monitoring are suggested in view of ensuring marine sustainability.

Present-day monitoring

Regarding EU Directives, present-day monitoring is mostly focused on WFD requirements, and on the human activities subdued to Environmental Impact Assessments (Directive 85/336/EC). These primarily include marine aggregate extraction, windmill farm implantation, and dredging and disposal of dredged material. However, to comply with EU Directives on an overall level, and MSFD in particular, data are unlikely to be generated, *directly*, from existing monitoring programmes (Morris et al., 2011). Many elements of the marine ecosystem are not dealt with, nor are their assessments integrated towards an ecosystem-based approach to management. Mostly key elements such as issues, questions, choices regarding monitoring are missing, and limited account is taken of reaching sustainability of resources.

[1] Marine ecosystem components can be grouped into 4 distinct, but interlinked systems: (1) water and sediment physico-chemical quality (incl. general conditions and contaminants); (2) planktonic system (phyto- and zooplankton); (3) mobile species system (e.g. fishes, sea mammals, seabirds); and (4) the benthic system (incl. species and habitats). Changes in the composition of these biological components can be related to changes of pressure parameters and those changes can be linked to normative definitions to further help with definitions to set critical boundaries or targets for desired ecosystem status (Borja et al. 2010).

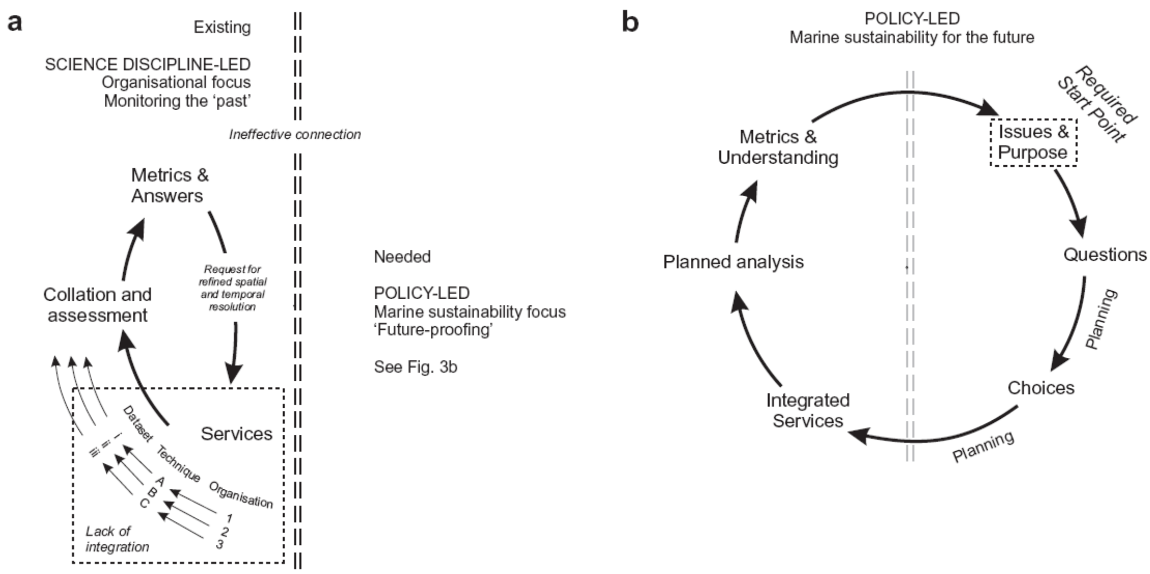

Figure A4-1. **Left** – View of the existing applied marine science framework. Services, (such as marine measurements and sample collection) drive the effort, and tend to work in parallel, not having been integrated by an initial structured design, but rather formed in part by those services currently available within established institutions. At present, these can produce requests for refined resolution of measurements. Overall, the services tend to measure elements of the present and past marine system, whilst the direct connection to the delivery of the marine sustainability policy is ineffective. **Right** – Key components of a future framework. The key elements of an integrated marine programme designed to help achieve marine sustainability. Integration starts with general and then specific questions, driving the integrated services (which include data gathering), and these form the basis for analysis and understanding of marine sustainability (Morris et al., 2011).

Table A4-1. Qualitative descriptors (1 to 11) for determining good environmental status, within the Marine Strategy Framework Directive (MSFD), compared with similar issues within the Water Framework Directive (WFD), and cross links related to a pressure (using nutrients and eutrophication as an example). BQE – biological quality elements (Borja et al., 2010).

Marine Strategy Framework Directive	Relation to nutrients/eutrophication	Links to Water Framework Directive	Links to other directives/legislation
(1) Biological diversity is maintained. The quality and occurrence of habitats and the distribution and abundance of species are in line with prevailing physiographic, geographic and climatic conditions	Avoid deterioration along organic loading gradient (Pearson–Rosenberg model on degradation along pressure gradients: see Gray and Elliott (2009)), minimize secondary eutrophication effects (i.e. impacts on submerged macrophyte and angiosperms and sublittoral benthic communities)	Included within all normative definitions on ecological quality status for BQE that includes composition and abundance of species	Habitats Directive 92/43/EEC Birds Directive 79/409/EEC and 2009/147/EC Convention on Biological Diversity (United Nations, 1993)
(2) Non-indigenous species introduced by human activities are at levels that do not adversely alter the ecosystems	Avoid influx of non-native Harmful Algal Blooms (HAB) species	Not mentioned in the WFD, but constitutes a pressure and should be included in the analysis of pressures and impacts. Assessing methods including alien species and their impacts on the ecosystems need to be developed included in some metrics, e.g. fish in transitional waters. Changes to all BQE	EU Strategy on Invasive Species (3 December 2008)
(3) Populations of all commercially exploited fish and shellfish are within safe biological limits, exhibiting a population age and size distribution that is indicative of a healthy stock	Avoid anoxic zones, fish kills and water quality barriers	As such, not taken into account within the WFD but included in some metrics, in transitional waters, e.g. fish guilds. Changes to epibenthos and fishes	Common Fisheries Policy and the new reform COM(2010)241 final
(4) All elements of the marine food webs, to the extent that they are known, occur at normal abundance and diversity and levels capable of ensuring the long-term abundance of the species and the retention of their full reproductive capacity	As (1) and (3)	As such, not taken into account within the WFD. However, at some extent, it is included implicitly within each of the BQE, as expression of the quality of structure and functioning of ecosystems. Requires all BQE to be merged	
(5) Human-induced eutrophication is minimised, especially adverse effects thereof, such as losses in biodiversity, ecosystem degradation, harmful algae blooms and oxygen deficiency in bottom waters	Avoid eutrophication	This pressure is related to physico-chemical and phytoplankton and other macroalgae, macrophytes elements, within the WFD, and then linked to benthos and fishes	Urban wastewater treatment directive (91/271/EEC; 98/15/EC), Nitrates Directive (91/676/EEC), Bathing Water Directive (76/160/EEC; 2006/7/EC)
(6) Sea-floor integrity is at a level that ensures that the structure and functions of the ecosystems are safeguarded and benthic ecosystems, in particular, are not adversely affected	Avoid biogeochemical changes due to excess organic inputs	This qualitative descriptor can be related explicitly to macroalgae, angiosperms and macroinvertebrates quality elements within the WFD. Relate also to hydro-morphological status	Habitats Directive 92/43/EEC Recommendation on Integrated Coastal Zone Management (2002/413/EC); also Environmental Impact Assessment and Strategic Environmental Assessment Directives
(7) Permanent alteration of hydrographical conditions does not adversely affect marine ecosystems	Avoid WQ barriers	This qualitative descriptor can be related explicitly to hydro-morphological elements within the WFD	
(8) Concentrations of contaminants are at levels not giving rise to pollution effects	Treat nutrients as all other contaminants and avoid inputs with respect to assimilative capacity	Related explicitly to chemical status within the WFD	Priority Substances Directive (2008/105/EC) and the new Environmental Standards Directive (2008/105/EC)
(9) Contaminants in fish and other seafood for human consumption do not exceed levels established by Community legislation or other relevant standards	Avoid levels of toxins resulting from ingestion of HABs	As such, not taken into account within the WFD. However, at some extent, it can be related implicitly to the chemical status within the WFD	Shellfish Harvesting Directive (2006/113/EC) Regulation 2007/333/EC (quality) and the new Environmental Standards Directive (2008/105/EC) and IPPC Directive
(10) Properties and quantities of marine litter do not cause harm to the coastal and marine environment	Not relevant	Not specifically mentioned in the WFD, but should be considered in the analysis of pressures and impacts at WFD	
(11) Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment	Not relevant	Not specifically mentioned in the WFD, but it is considered as a part of the analysis of pressures and impacts	Renewable Energy Directive (2009/28/EC), EU's Energy-Related Strategy

Table A4-2. Monitoring requirements under MSFD (After 2008/56/EC. Annex V. Monitoring Programmes)

Need to provide information for an **assessment of the environmental status** and for an estimate of the distance from, and progress towards, good environmental status in accordance with Annex III and with the criteria and methodological standards to be defined pursuant to Article 9(3)[2].

Need to ensure the generation of information enabling **the identification of suitable indicators for the environmental targets** provided for in Article 10[3].

Need to ensure the generation of information allowing the **assessment of the impact of the measures** referred to in Article 13.

Need to **include activities to identify the cause of the change** and hence the possible **corrective measures** that would need to be taken to restore the good environmental status, when deviations from the desired status range have been identified.

Need to provide information on **chemical contaminants in species for human consumption** from commercial fishing areas.

Need to include activities to confirm that the corrective measures deliver the desired changes and not any unwanted side effects.

Need to **aggregate the information on the basis of marine regions** (e.g. North-east Atlantic Ocean) **or subregions** (e.g. the Greater North Sea).

Need to ensure **comparability of assessment approaches and methods within and between marine regions and/or subregions**.

Need to **develop technical specifications and standardised methods for monitoring** at Community level, so as to allow comparability of information.

Need to ensure, as far as possible, **compatibility with existing programmes developed at regional and international level** with a view to fostering consistency between these programmes and avoiding duplication of effort, making use of those monitoring guidelines that are the most relevant for the marine region or subregion concerned.

Need to include, as part of the initial assessment provided for in Article 8, an **assessment of major changes in the environmental conditions** as well as, where necessary, **new and emerging issues**.

Need to address, as part of the initial assessment provided for in Article 8, the **relevant elements listed in Annex III[4] including their natural variability** and to evaluate the trends towards the achievement of the environmental targets laid down pursuant to Article 10(1), using, as appropriate, the indicators established and their limit or target reference points.

[2] Article 9(3): Criteria and methodological standards to be used by the Member States, which are designed to amend non-essential elements of this Directive by supplementing it, shall be laid down, on the basis of Annexes I and III, in accordance with the regulatory procedure with scrutiny referred to in Article 25(3) by 15 July 2010 in such a way as to ensure consistency and to allow for comparison between marine regions or subregions of the extent to which good environmental status is being achieved. Before proposing such criteria and standards the Commission shall consult all interested parties, including Regional Sea Conventions.

[3] Article 10: Establishment of environmental targets. When devising targets and indicators, Member States shall take into account the continuing application of relevant existing environmental targets laid down at national, Community or international level in respect of the same waters, ensuring that these targets are mutually compatible and that relevant transboundary impacts and transboundary features are also taken into account, to the extent possible.

[4] Annex III refers to (1) Characteristics, e.g. physical and chemical features; habitat types; biological features; and (2) Pressures and impacts, e.g. physical loss and damage; other physical disturbance; interference with hydrological processes; contamination by hazardous substances; release of substances; nutrient and organic enrichment; and biological disturbance. See Table 3.

Table A4-3. Framework to select parameters to be monitored under MSFD, related to the list of relevant characteristics (A) and pressures and impacts (B) (Annex III of the MSFD Directive). D1 to D11 refers to Descriptors for which good environmental status should be achieved. D1 Biological diversity; D2 Non-indigenous species; D3 Commercial fish; D4 Food webs; D5 Eutrophication; D6 Sea floor; D7 Hydrogeographical conditions; D8 Contaminants and pollution effects; D9 Contaminants in fish and other seafood; D10 Litter; D11 Energy/Noise. X = characteristic is an intrinsic part of the Descriptor; (X) = characteristics with an indirect relation, or a relation of secondary relevance with the Descriptor. For Table B, X = pressure is of primary importance for the descriptor; (X) = pressure is of secondary importance (Cardoso et al., 2010).

A

Annex III Characteristics*		D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11
Physico-chemical												
	Topography	X					X					
	Temperature	X			(X)		(X)	X				(X)
	Salinity	X			(X)		(X)	X				
	Nutrient	X			X	X	(X)					
	pH	X			(X)			X				
Habitat types												
	Predominant habitat types	X			X		X					
	Special habitat types	X			X		X					
	Habitat types meriting special reference	X			X		X					
Biological features												
	Phyto-zooplankton	X	(X)		X	X	(X)					
	Bottom fauna*	X	(X)	X	X		X					
	Fish	X	(X)	X	X		(X)					
	Mammals**	X	(X)		X							
	Seabirds**	X	(X)		X							
	Other species	X	(X)		X		(X)					
	Non-indigenous**	(X)	X		X		(X)					
Other features												
	Chemicals	(X)			X		(X)		X	X		
	Others	(X)			X		(X)				X	X

* Characteristics are specified in MSFD Annex III, Table 1, Indicative lists of characteristics

** for D1, also bottom flora, reptiles and genetically distinct forms of native species are treated. "Seabirds" should encompass all birds that use the marine environment and include species normally referred to as "waterbirds" such as waders, divers and ducks.

B

Annex III Pressures and Impacts*		D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11
Physical loss	Smothering	X			X		X					
	Sealing	X			X		X					
Physical damage	Siltation	X			X		X					
	Abrasion	X			X		X					
	Extraction	(X)			X		X					
Other physical disturbance	Noise	(X)			(X)							X
	Marine litter	(X)					(x)				X	
Interference with hydrology	Change in thermal regime	(X)			X		(X)	X				X**
	Changes in salinity	(X)			X		(X)	X				
Contamination	Synthetic substances	(X)			X		X		X	X		
	Non-synthetic substances	(X)			X		X		X	X		
	Radionuclides	(X)			X		(X)		X	X		
Systematic release of substances	Introduction of other substances	(X)			X		X		X			
Nutrient and organic matter enrichment	Input of fertilizer	(X)			X	X	X					
	Input of organic matter	(X)			X		X					
Biological disturbance	Microbial pathogens	X			X	X	(X)					
	Non-indigenous species	(X)	X	(X)	X		X					
	Selective extraction	(X)		X	X	X	(X)					

* Pressure and impacts are specified in MSFD Annex III, Table 2, Indicative list of pressures and impacts

** This is an energy input too and is described in TG11 report but no indicator is provided.

As such, it is very unlikely that existing datasets can be integrated to produce a comprehensive understanding of whether human activities in the marine environment are detrimental to marine sustainability or not (Morris et al. 2011). Data from fine- to coarse-scale sampling cannot be combined without the generation of misleading inferences. Rebuilding dependencies and links from disconnected data is difficult, and reduce the chance of gaining benefits. Still, significant progress is being made in understanding the various time-scales and magnitudes of marine environmental change. However, establishing such knowledge bases needs time (e.g. time series need further extension), but meanwhile policy questions need addressing. Setting-up adaptive monitoring programmes are hence needed, evolving and adapting as science and policy further develop (e.g. Laane et al., in press). Monitoring is indeed not about the actual achievement, but good and informative monitoring is about 'adjusting' policy and actions (Morris et al., 2011). Most present monitoring programmes do not allow us reaching sustainability. Above all, most Member States are subdued to budget-driven programme reductions, hence calling for creative thinking and re-adjusting monitoring programmes in a most time- and cost-efficient manner.

Future developments and improvements to monitoring

The development of a successful and economically viable monitoring plan, based on soundly formulated hypotheses, and containing appropriate verification instruments, would ideally have the following objectives (www.monae.org): (1) Provide an integrated approach to monitor all waters (transitional, coastal and marine waters); (2) Have the potential to address management issues, i.e. to be hypothesis-driven; (3) Establish the guidelines for monitoring throughout the next decades; (4) Integrate the monitoring requirements of EU Directives; (5) Define and apply a methodology for the definition of water bodies; (6) Possess internal flexibility, in order to accommodate new methodologies that may be developed and/or applied over its life-cycle; and (7) Use a hierarchical approach, allowing cost-optimisation with respect to information requirements.

Gray and Elliott (2009) provide details of different monitoring types and strategies for implementation (Table 4). Surveillance**,** operational and investigative monitoring are widely applied within WFD. The latter is per definition aimed at hypothesis testing to further understand key processes. It must be built on the basis of meaningful research questions and take the form of scientific research projects. Any combination, mostly in a hierarchical approach, would be instrumental within the MSFD framework, provided time- and cost efficiency is demonstrated. Well-designed surveillance and operational monitoring will be needed, setting the scene for more specific and detailed investigative programmes.

Adaptive monitoring

Ideally, MSFD is implemented following an adaptive management approach, reflecting the need for a continuous cycle of data generation through monitoring, assessment and management actions (Morris et al., 2011; Laane et al., in press). It contrasts to the precautionary principle that was defined and applied by OSPAR in the 1980's. In general, this approach is to stay on the very safe side and does not take into account new scientific developments and findings (in Laane et al., in press). Adaptive management has the attributes of being flexible, encouraging public input, and monitoring the results of actions for the purpose of adjusting plans and trying new or revised approaches. It is evidence-based and a learning process with the aim of reducing uncertainties, considering possibilities and calculating risks (Laane et al., in press).

Table A4-4. Types of monitoring (After Gray and Elliott, 2009; Ferreira et al., 2007)

Surveillance monitoring A posteriori detection of trends, with action then determined. Importance of spatial and temporal scales.	*Self-monitoring* Carried out by developer/industry.
Condition monitoring Determines the present status of an area, could be linked to biological valuation.	*Toxicity testing* Testing either in the field or laboratory.
Operational monitoring Carried out by industry and may be linked to management aims. Screening/verification of drivers-pressure-state-response relationships. At the interface of monitoring modelling – ecological modelling.	***Investigative monitoring*** Applied research (cause and effect), once any deviation from perceived or required quality is detected then aim to look for explanations. Importance of process studies to understand the change.
Compliance monitoring To determine compliancy with a set of conditions laid down by a licence.	*Diagnostic monitoring* Determining effects, but link to cause.
Check monitoring For a regulatory body to ensure that a developer is performing monitoring to best standards.	*Feedback monitoring* Real-time analysis, linked to predetermined actions. Ability to control, prevent or stop an activity if a deleterious change is observed.

Understanding patterns, scale and process

For implementing an ecosystem-based approach to management understanding patterns, scale and processes is important, for which new science is critical. The relationships between human activities and environmental conditions are context-dependent; temporal and spatial scales of impacts vary with different pressures and with system vulnerability, which, in turn, are dependent of the characteristics of the areas in question (Cardoso et al., 2010). In many cases, monitoring must be adapted to local conditions, and expanded for the seafloor, both in terms of area covered and types of attributes measured. The issue is faced that marine systems may be highly dynamic and variable in which the signal of change due to human actions is often difficult to detect against background variability (McLusky and Elliott, 2004), a remaining critical issue concerning monitoring programmes (de Jonge et al., 2006; Ferreira et al., 2007). Frequency of monitoring should ideally be related to seasonal dynamics and cover the natural variability within the habitats, though management actions or decision making may now require further adaptation of the plans. Generic guidance on number of samples is not appropriate, but merely setting minimum levels of confidence and uncertainty should be strived at (Carstensen, 2007). Furthermore, there may be mismatches between what can be meaningfully monitored and what EU Directives require (de Jonge et al., 2006). In any case, a better understanding of the relation between structure and functioning of marine ecosystems is needed. Therefore, adoption of tiered approaches to sampling and observations is needed covering (simultaneously) several scales, and resolutions, backed-up by ground truth information. Authors plead for collaborative work to bring unique or expensive technologies together to work on projects of mutual interests. A network of reference sites would be able to provide long-term environmental data, linked-up to spatially covering observations (platform/shipborne, airborne and from space).

Risk based approach to monitoring

In order to use resources wisely and maximize the information gathered, a pragmatic approach needs to be adopted for assessing the overall state of marine environments. Maximum use of ongoing monitoring programmes should be made, through combination and integration where possible. Still, management efforts should be targeted efficiently at the most serious environmental problems, while not losing sight of other environmental challenges that also need action (e.g. protection of areas that already have a good environmental status) and places where progress is being made (Cardoso et al., 2010). Overall monitoring schemes are best confined to ecosystem features that are particularly vulnerable and where pressures are most exerted on the seabed. Cardoso et al. (2010) prioritizes assessment of areas and indicators related to: (1) the distribution of the intensity or severity of the pressures across the region at large; (2) the spatial extent of the pressures relative to the ecosystem properties possibly being impacted; (3) the sensitivity/vulnerability or resilience of the ecosystem properties to the pressures; (4) the ability of the ecosystem properties to recover from impacts, and the rate of such recovery; (5) the extent to which ecosystem functions may be altered by the impacts; and (6) where relevant, the timing and duration of the impact relative to the spatial and temporal extent of particular ecosystem functions (e.g. shelter, feeding, etc).

The variation in scale of both environmental conditions and impacts of pressures means that assessments of good environmental status should begin with sub-areas of both greatest vulnerability and highest pressures. If the environmental status in these areas is good, then it can be assumed that the status over the larger area is 'good'. On the contrary, if the environmental status in the sub-areas is not 'good', then monitoring and assessments would be conducted stepwise at additional sites along the gradients of pressure or vulnerability (monitoring along gradients of degradation). The size of the appropriate steps along the gradient will depend on the nature of the gradient and the way the environmental conditions are being degraded. It may vary significantly with different cases. This risk-based approach will be particularly effective for Descriptors that are spatially patchy and where pressures are applied at specific locations. Pragmatic prioritization of monitoring strategies enables general statements to be made about environmental status at large scales, while keeping monitoring requirements manageable (Cardoso et al., 2010).

Need for integrative assessments of marine waters

With increasing monitoring demands, the need for coordination of assessments arises, together with multidisciplinary integration of approaches and data (Borja et al., 2010; Morris et al., 2011). Formulation of the science and policy context will need to be clear and systematic to allow such integrated approaches. MSFD requires assessment following a holistic functional approach, however, our knowledge of ecosystem functioning is much less developed and the methods and indices for their study are inherently more uncertain. A merged approach is needed, as also a harmonized, seamless transition from catchment through transitional waters and coast to an open marine system (Borja et al., 2010). MSFD will have to consider all habitats simultaneously, but being aware that tools are needed that are region specific. Within the integration exercise, comparisons can be made of changes against reference conditions, yet, especially in the developed countries, pristine, unchanged conditions rarely exist.

Data and information needs

Data collection is central to any observation programme. Facilitation and sharing of best available knowledge and data is crucial to efficient monitoring programmes. A data framework is needed, as well as methodological standards and quality assessment procedures of the monitoring programmes (e.g. appropriateness of time series and sampling station density; consistency of the programme). Apart from acquisition, standards are needed for collection analysis, storage and sharing of data and information. This is currently taken place in a number of European projects: **Emodnet** or European Maritime Observatory Data NETwork (EU DG MARE) which is now in its prototype phase (2008-2013) and comprising preparatory actions (often with data portals) related to hydrography, geology, biology, chemistry and habitats. An operational phase is foreseen from 2014 onwards. Other relevant projects, delivering data following European standards and harmonized data products are the EU FP7 Infrastructure projects **SeaDataNet** (www.seadatanet.org/) and **Geo-Seas** (www.geo-seas.eu), respectively *w.r.t.* oceanographic data and geological/geophysical data. Most of these initiatives strive at compliancy towards the INSPIRE Directive. Other dedicated portals for seabed (habitat) maps were provided by the EU Interreg IIIb projects **MESH**, Mapping European Seabed Habitats; www.searchmesh.net; **MESH-Atlantic** (www.meshatlantic.eu), and **OneGeology** (Applying Geoscience for Society) (www.onegeology.org), with tools for visualisation and downloading. For a data portal (and references to others) related to Marine Biodiversity and Ecosystem

Functioning, reference is made to **MarBEF** (http://www.marbef.org/). From a partnership between the European Commission (DG Environment, Joint Research Centre and Eurostat) and the European Environment Agency, a Water Information System for Europe (**WISE**) (http://water.europa.eu/) has been established.

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Annex 6. Suspended Particulate Matter structuring Macrobenthic Communities

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KEYWORDS

Suspended particulate matter, macrobenthos, community structure, Belgian part of the North Sea

ABSTRACT

Although suspended particulate matter (SPM) carries a major part of the food resources for the macrobenthos, it might turn into an environmental stressor for the macrobenthos when the concentrations are high enough to interfere with the species' filtering and respiratory systems. This study therefore investigated the structuring role of SPM on the macrobenthic community structure, hypothesizing the optimal condition to be at intermediate SPM concentration levels. The relationships between SPM and benthic communities have been investigated in the Belgian part of the North Sea (BPNS), for which a vast amount of spatially-explicit information on the macrobenthos, surface SPM and sediment composition is available. 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 class) were used as co-variables throughout the whole study. Within the five median grain size classes and the Folk class, a generally higher species richness and macrobenthic density was found in the intermediate SPM class compared to both lower and higher SPM concentration classes, supporting the central hypothesis of this paper. However, 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 in hydrodynamically benign conditions. Although the expected unimodal relationship between suspension feeding and SPM concentration could not be found from our 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.

INTRODUCTION

Macrobenthic communities are known to live in the sediment-water interface. The composition and distribution of these communities is correlated with sediment characteristics, such as mud content and median grain size (Degraer *et al.*, 2008), as also to water column features (e.g. temperature, physical disturbances, primary production) (Raffaelli *et al.*, 2003; Snelgrove, 1998). This association of macrobenthos with the surrounding environment suggests that there is a two-way exchange or flux of matter between the benthos and the water column in the sediment-water interface (Raffaelli *et al.*, 2003).

Suspended particulate matter (SPM) comprises a wide variety of substances and can be divided into particulate organic matter (POM) and particulate inorganic matter (PIM) (Suzumura *et al.*, 2004). SPM that is deposited onto the sediment increases the POM available to feed the macrobenthic communities and (often) results in an increasing number of species, abundance and biomass, compared to those areas where food is limited (Pearson and Rosenberg, 1978). The input of SPM in the sediment-water interface involves different macrobenthic responses, among which at the level of the trophic structure. Suspension and deposit feeders are both dependent directly on SPM as a food resource. Next to being a food resource to benthic organisms (POM), SPM might also have negative effects on macrobenthic communities, especially when SPM concentrations and the content of fine-grained sediment (PIM) become very high. As an example, suspension feeders have been identified to be potentially negatively affected by high SPM concentrations (Akoumianaki and Nicolaidou, 2007; Essink, 1999), as their filter-feeding structures may be clogged by drifting sediment and abrasion (Fauchald and Jumars, 1979; Nicholls *et al.*, 2003).

In the last decades, the effects of intensive pressure on coastal zones have resulted in higher nutrient influxes to the seas coming from rivers and sewages, causing coastal eutrophication adding more POM to the water column (Diaz and Rosenberg, 2008; Stephens *et al.*, 1967). Furthermore, also bottom-disturbing human activities, such as trawling, will stimulate the resuspension of fines from the sediment and thus contribute to the increase of SPM in the water column, especially at the sediment-water interface (Churchill, 1989). This urges the need for a proper understanding of the relationship between SPM and benthic communities.

This paper hypothesizes a unimodal response of the macrobenthos along an SPM gradient, with (1) suboptimal conditions at lower SPM concentrations, due to the lower food availability; and (2) suboptimal conditions at higher SPM concentrations, due to negative interactions through clogging and abrasion. Optimal conditions for the macrobenthos are hence expected at intermediate SPM concentrations.

MATERIALS AND METHODS

CASE STUDY: BELGIAN PART OF THE NORTH SEA

Relationships between SPM and benthic communities have been investigated in the Belgian part of the North Sea (BPNS), for which 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) is available.

RESEARCH STRATEGY

Explanatory variables were multivariate SPM concentration probability distribution classes (further called SPM classes) and the univariate SPM characteristic D_{90}, indicative for the possible excess of SPM in the water column. The response of the macrobenthos was investigated through the analysis of the relationships between macrobenthic species richness, density and detrital feeding mode allocation on the response variable side, and the SPM classes on the explanatory variable side. This analysis rendered insight into the macrobenthos response to the multivariate SPM classes, but did not allow assessing the weight of (univariate) SPM characteristics in this relationship. An analysis of the relationships between the univariate SPM characteristic and the macrobenthos response variables, species richness and density, was hence performed. To exclude that part of the variation explained by sediment composition, granulometry was treated as a co-variable throughout this study.

DATA AVAILABILITY AND SELECTION

Data on the spatial distribution of the macrobenthos were taken from Degraer *et al*. (2008) (Figure A5-1). To investigate whether different feeding modes would be impacted differentially, the macrobenthic species were classified into 3 groups: suspension feeders (SF), interface feeders, facultative suspension feeders, surface deposit feeders (IF.FSF.SDF) or subsurface deposit feeders and grazers (SSDF.Gr): 66 species were classified as such.

As 90% of the macrobenthos samples were collected in September-October (i.e. autumn), only SPM data collected between April and October (i.e. period of recruitment, prior to sampling) were considered in this study. SPM data were collected only for those grid cells, for which macrobenthos data were available: 52 to 600 satellite SPM observations were available per macrobenthos sampling point. SPM classes were statistically defined using entropy analysis (Johnston and Semple, 1983). Five SPM classes were considered here, matching a general onshore - offshore gradient of decreasing SPM concentrations: from very high SPM concentrations (VH, average: 17.8 mg l^{-1}) over high (H, 7.3 mg l^{-1}), intermediate (I, 4.0 mg l^{-1}), low (L, 2.3 mg l^{-1}) to very low (VL, 1.7 mg l^{-1}) SPM concentrations (Figure A5-1).

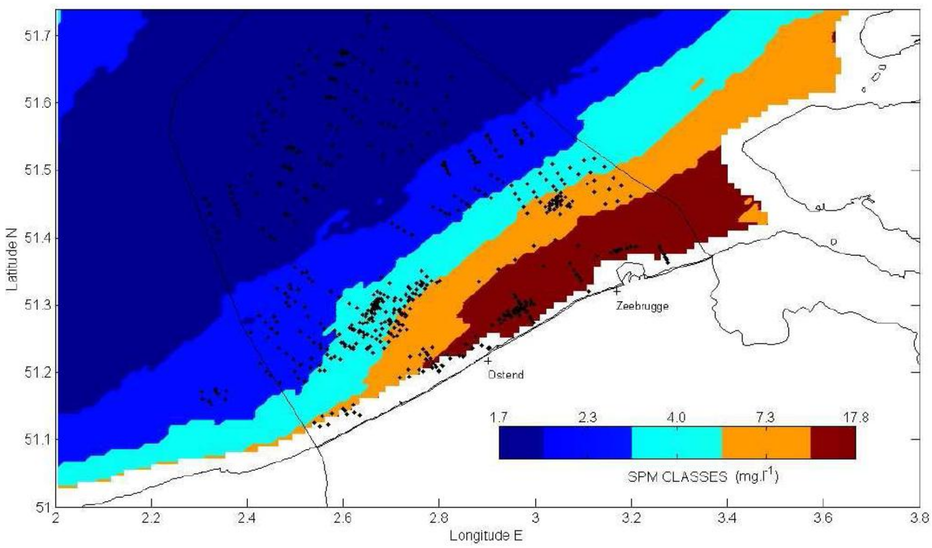

Figure A5-1. Geographic distribution of the macrobenthos samples (●) in relation to SPM classes.

Granulometry was determined directly from the macrobenthos samples based on an LS Coulter Counter laser diffraction methodology: median grain size (D_{50}) and mud content (%) were used in this study. Macrobenthos samples were allocated to 50 μm D_{50} range classes (further referred to as median grain size classes). Given the unequal spread of macrobenthos data over the median grain size classes, only the median grain size classes between 200 and 450 μm were considered here; these complied with the *a priori* criterion of a minimum of 50 macrobenthos samples per median grain size class. In addition, information on the Folk sediment classes were retrieved from the Emodnet-Geology Substrate map (Kaskela *et al*., 2010), using the geographic coordinates of each macrobenthos sampling point. Only Folk class 2 (i.e. sand to muddy sands) revealed a representatively high number of observations (> 50 observations). 577 sampling points, for which we had information on macrobenthos, SPM and sediment composition, were found appropriate for further analysis.

Differences in response variables, exposed to different SPM concentrations (i.e. explanatory variables) within the various (co-variate) sediment classes were statistically explored with the non-parametric Kruskall-Wallis test. If these were statistically different, pair-wise comparisons

(Mann-Whitney U-test) were performed. Statistical significancy was kept at 5 %. The significance levels for the pair-wise comparisons were adapted using the Bonferroni correction, in which the level of significance is lowered as a function of the number of pair-wise comparisons (as such compensating for the inflation of the Type I error risk).

More detailed information on data availability, research strategy and methodology is provided in Rodriguez Palma (2011).

RESULTS

Statistically significant differences (Kruskal-Wallis tests: $p \leq 0.002$) in macrobenthic species richness and densities between the five SPM classes were detected for the 200-250 μm, 250-300 μm and 300-350 μm median grain size classes, as well as for the Folk class 2. Within these grain size classes a generally higher species richness and macrobenthic density was found in the intermediate SPM class, compared to both lower and higher SPM concentration classes (Figure A5-2; Table A5-1). This response of highest values within the intermediate SPM tended to weaken from fine-grained to coarser-grained sediment classes. Similarly, the highest species richness and density within Folk class 2 were detected within the intermediate SPM class (paired Mann-Whitney U-tests, $p \leq 0.001$), except for the high SPM class (paired Mann-Whitney U-tests: $p \geq 0.016$) (Figure A5-3; Table A5-1).

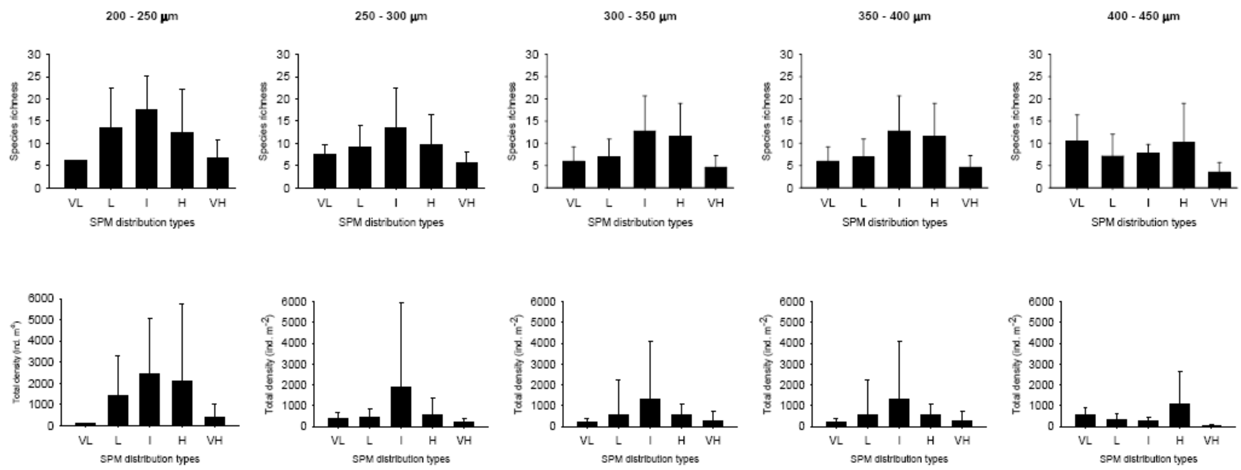

Figure A5-2. Macrobenthic response to SPM classes (VL, very low SPM concentration; L, low; I, intermediate; H, high; VH, very high) within the five selected median grain size classes. Species richness, ind. 0.1 m^{-2}; total density, ind. m^{-2}. Whiskers, standard deviation.

We further investigated the macrobenthic response to the univariate SPM descriptor D_{90}, indicative for the possible excess of SPM in the water column. This analysis was done only for the median grain size class 200-250 μm and the Folk class 2, for which we found the strongest statistical signal in the previous analysis. In both classes, the observed unimodal response was found to show a log-normal distribution pattern. The macrobenthic community structure had highest species richness and densities at D_{90} SPM concentrations of 5-15 mg l^{-1}. Below this concentration both species richness and density steeply decreased, whereas a more gentle decrease was observed towards higher concentrations (Figure A5-4).

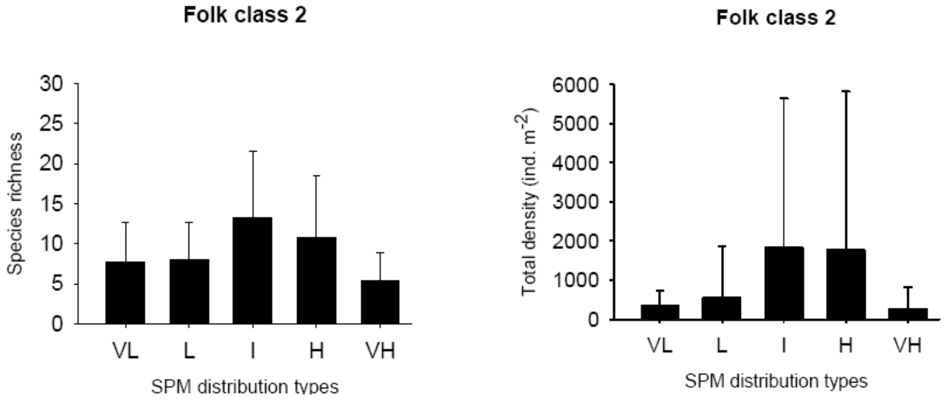

Figure A5-3. Macrobenthic response to SPM classes (VL, very low SPM concentration; L, low; I, intermediate; H, high; VH, very high) within Folk class 2 (sand to muddy sands). Species richness, ind. 0.1 m^{-2}; total density, ind. m^{-2}. Whiskers, standard deviation.

Table A5-1. Mann-Whitney U-test results (p-values) of the paired comparison of macrobenthic species richness and density between the five SPM classes over the different median grain size classes. 200-250, 250-300 and 300-350. 1.7, very low; 2.3, low; 4.0, intermediate; 7.3, high; 17.8, very high SPM concentration classes. Statistically significant difference adjusted with Bonferroni method: $p < 0.005$ (*).

		Sp.richness				Density			
	SPM	1.7	2.3	4.0	7.3	1.7	2.3	4.0	7.3
200-250	2.3	0.245				0.121			
	4.0	0.144	0.177			0.106	0.249		
	7.3	0.547	0.445	0.013		0.232	0.402	0.035	
	17.8	0.633	0.013	0.000*	0.014	0.693	0.007	0.000*	0.025
250-300	2.3	0.545				0.821			
	4.0	0.381	0.067			0.430	0.128		
	7.3	0.707	0.953	0.141		0.941	0.535	0.59	
	17.8	0.228	0.008	0.000*	0.023	0.206	0.003*	0.000*	0.028
300-350	2.3	0.399				0.030			
	4.0	0.001*	0.004*			0.001*	0.056		
	7.3	0.098	0.144	0.738		0.358	0.590	0.549	
	17.8	0.331	0.191	0.005	0.095	0.082	0.011	0.004*	0.445
Folk 2	2.3	0.514				0.007			
	4.0	0.000*	0.000*			0.000*	0.000*		
	7.3	0.017	0.061	0.016		0.009	0.122	0.096	
	17.8	0.047	0.001*	0.000*	0.000*	0.031	0.000*	0.000*	0.001*

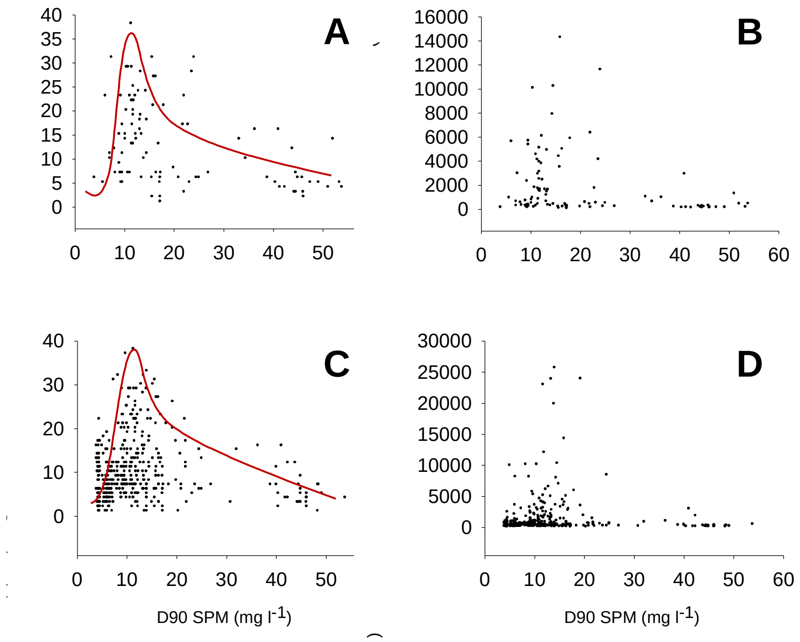

Figure A5-4. Macrobenthic species richness (plots A and C; spp. 0.1 m^{-2}) and density (plots C and D; ind. m^{-2}) responses to the SPM D_{90} value. Median grain size class 200-250 μm, A and B; Folk class 2, C and D.

Interface, facultative suspension and surface deposit feeders (IF.FSF.SDF) and subsurface deposit feeders and grazers (SSDF.Gr) dominated within all median grain size and Folk classes (60% and ± 30% of the macrobenthic abundances, respectively) (Figure A5-5). Within the fine-grained sediments (D_{50} < 300 μm) feeding mode prevalence did not differ significantly between SPM classes. Compared to the very low SPM class, significantly higher (Mann-Whitney U-test: $p < 0.001$) relative abundances in suspension feeders (SF) were found in intermediate SPM concentrations within median grain size class 300-350 mm. Within the coarser median grain size classes (D_{50} > 350 μm) an increase in dominance of SSDF.Gr with increasing SPM concentration, at the expense of IF.FSF.SDF was detected. No clear patterns in SF prevalence were found here.

DISCUSSION

Our study clearly illustrated a macrobenthic dependency on SPM in the water column. The macrobenthos response to SPM concentration could further be described as a unimodal function, with highest values in both species richness and density at intermediate SPM concentrations. These findings hence confirm our hypothesis of an optimal condition for the macrobenthos at intermediate SPM concentrations and suboptimal condition at either lower or higher SPM concentrations. Macrobenthic communities are indeed known to be affected by SPM: the organic fraction of SPM is representing the food availability to detritus feeders, and is as such considered the primary factor for regulating the structure of benthic communities (Akoumianaki & Nicolaidou, 2007, Norkko *et al.*, 2002; Rosenberg, 2001; Turner *et al.*, 1997). In case there is a lack of food a lower species richness and density might be expected, as shown in this study. SPM might however also become an environmental stressor, especially when the concentrations in the water are high enough to clog filtering and respiratory systems (Fauchald & Jumars, 1979) or when the excess of SPM results in an enhanced sedimentation with a consequently increased macrobenthos burial risk (Rhoads *et al.*, 1985). The lower values in species richness and density at higher SPM concentration in our study again confirm this aspect of the macrobenthic SPM dependency.

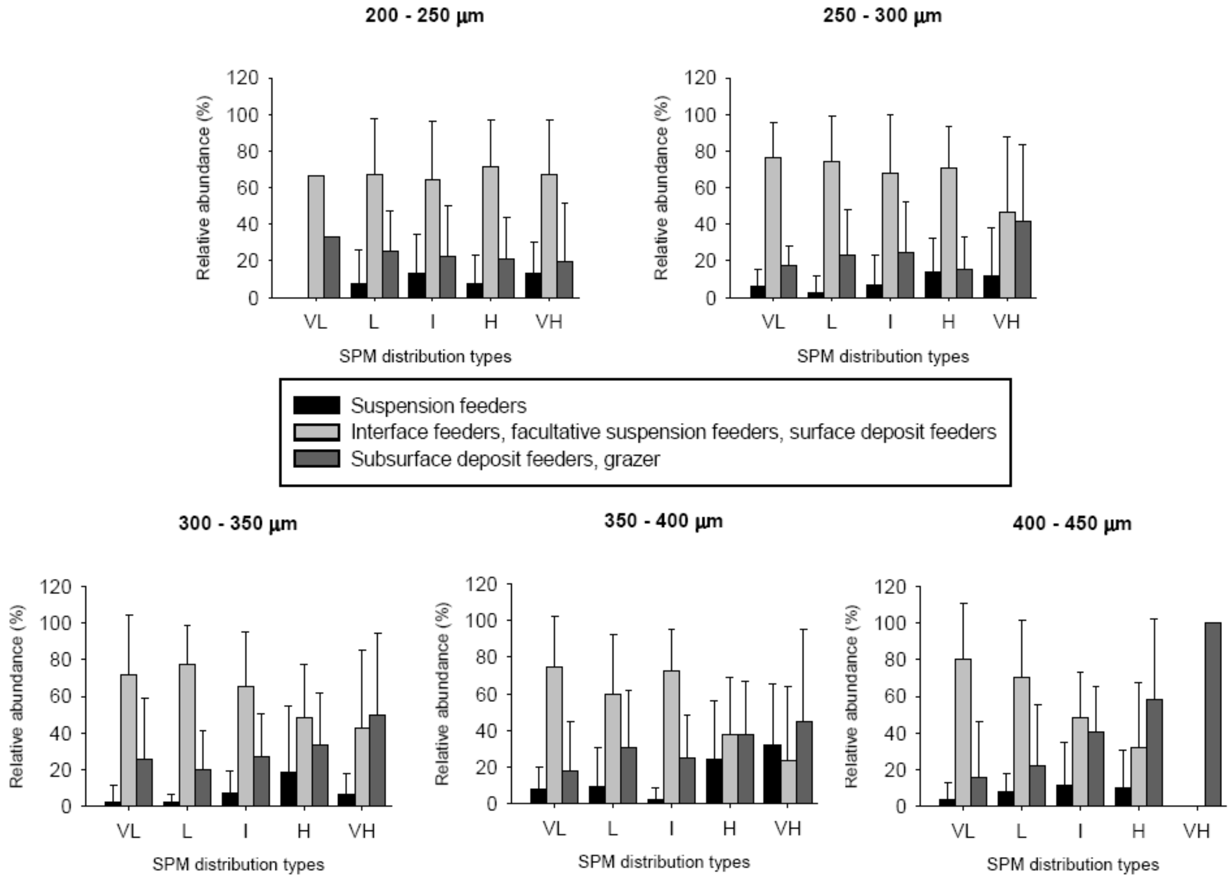

Figure A5-5. Relative abundance (standard deviation) of the three macrobenthic feeding modes in relation to the five SPM classes (VL, very low SPM concentration; L, low; I, intermediate; H, high; VH, very high) in the five selected median grain size classes. Whiskers, standard deviation.

The unimodal pattern of optimal conditions at intermediate SPM concentrations was not a normal, but a log-normal one, since below the optimal D_{90} SPM concentration of 5-15 mg l^{-1} we detected a steeper decrease of both species richness and density compared to higher concentrations. The actual causes behind this relationship are yet unknown, but the relationship itself could already be used when assessing benthic ecosystem quality in relation to SPM concentration. One should however be cautious about direct extrapolations as the SPM concentration values, used in this study, all refer to surface water concentrations. Although this value is known to be a good proxy for bottom water concentrations, a much higher concentration can be found at the bottom (Fettweis and Nechad, 2011). As the relationship between surface and bottom water concentrations is dependent on e.g. water column mixing (e.g. currents and wave action) and depth, a direct extrapolation to bottom water SPM concentration is yet impossible.

Whether or not the suboptimal condition at higher SPM concentration could be allocated to its negative impact primarily on filter feeding macrobenthic species could not be demonstrated in our study. Filter feeders were relatively rare in our study, which might have blurred the detection of such trend. Focusing on the more abundantly present interface, facultative suspension and surface deposit feeders (IF.FSF.SDF) and subsurface deposit feeders and grazers (SSDF.Gr), a response to SPM concentration was found, with a generally increasing dominance of SSDF.Gr at the expense of IF.FSF.SDF from lower to higher SPM concentrations. This pattern could possibly be explained by a higher subsurface food availability at higher SPM concentrations, due to the passive (e.g. hydrographic pumping) or active (e.g. bioturbation) burial of the excess of particulate matter at the sediment-water interface. Such mechanism might indeed be expected to promote the presence of SSDF.Gr organisms.

Even though a general pattern of optimal conditions at intermediate SPM concentrations was demonstrated, such response was not always as clear and depended on the median grain size or Folk classes under consideration. The response of macrobenthic communities to SPM should indeed not be expected to be exactly the same everywhere as a result of differences in the characteristics of e.g. receiving habitat, community composition, depth or sediment type (Smith and Rule, 2001). In our study, the highest values of species richness and density were found at intermediate SPM concentrations, but this pattern became less obvious with increasing grain size. This pattern could be explained through the the differential weight of environmental variables in structuring the benthos in different habitats. In hydrodynamically harsh conditions, characteristic for coarser sediments, the macrobenthos is expected to be determined in the first place by the hydrodynamic regime, while all the relative importance structuring importance of other environmental variables, among which SPM concentration, is considered low. As fine sediments are restricted to hydrodynamically benign conditions, other stressors, such as excess SPM concentrations, might start taking a prominent role in structuring the macrobenthos.

Also the pattern of an increased dominance of SSDF.Gr with increasing SPM concentration depended on the median grain size and Folk classes under consideration, with a more obvious pattern in coarser sediments. If indeed higher SPM concentrations support SSDF.Gr organisms through the burial of the excess of particulate matter (see above), then this dependency could be explained by the permeability of coarser sediments. In highly permeable sediments water and its SPM is efficiently pumped through the sediment surface layers (Vanaverbeke et al., 2011), allowing for a flourishing SSDF.Gr feeding mode.

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Annex 7. Natural variability assessment in support of environmental monitoring, a sediment transport modelling approach

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Abstract

Long-term (1999-2010), hydro-meteorological modelling data have been compiled into relational databases to evaluate seafloor mobility along the Belgian part of the North Sea. Modelling results are based on coupled current-wave, and sediment transport models running on a 750m grid resolution. Parameters relate to significant wave height/period/direction and mean current velocity/direction. For sediment transport, bottom stresses, total load, and bed evolution are incorporated at a half hourly time step. Evaluation is performed in function of natural variability assessment, of use in environmental monitoring. A case study is presented for the Buiten Ratel, a tidal sandbank in the Belgian part of the North Sea, where intensive marine aggregate extraction is executed in 20m of water depth.

Results show the spatial and temporal variability of seabed responses. According to the location of the extraction area, bed evolution may be depositional or erosional under varying hydro-meteorological conditions, and/or extraction 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.

Future perspectives include a progressive use of numerical modelling results as a spatial planning tool, in support of environmental monitoring.

Key words: Natural variability assessment; monitoring; sediment transport; decadal scale

Introduction

Evaluation of effects of human activity on seabed nature and processes has always been rather difficult. Time series in depth evolution are mostly complex and show a variability that cannot always be explained from varying intensities in human activities alone. The seabed is subdued to natural forcing too, though quantification is not straightforward, and often prone to large uncertainties. Our goal is to calculate multi-year time series of sediment transport parameters and develop statistics to describe the strength, spatial distribution, temporal variability, and relative importance of various causes of natural variability over the Belgian part of the North Sea. Since these variables affect the use of the seafloor, and in part define the benthic environment, they play an important role in influencing ecosystems and habitats.

A case study is presented for the Buiten Ratel, a tidal sandbank located in the Belgian part of the North Sea, in water depths of -8 to -27 m MLLWS (mean lowest low water at spring tides). The Buiten Ratel is a linear sandbank, though towards the North, its main body evolves into a broad head. Current interaction in the transition zone between both main morphological entities created a 'bottle neck' and kink feature: current velocities are enhanced in that zone, and grain-size is coarser than in its surrounding environment. Large to vary large dunes are present in the area. Figures 1 and 2 show an overview of the spatial variability of grain-size and dune asymmetries, together with variations in maximum current velocities and sand transport (Baeye, 2006).

Selected locations along the Buiten Ratel are extensively exploited for marine aggregates. FPS Economy, SME's, Self-Employed and Energy, Marine Sand Fund monitored seabed evolution in three areas of exploitation (see Roche et al., this volume); whilst the Institute of Sea Fisheries (ILVO) carried out biological sampling along locations, spread over the sandbank's morphological entities (see Debacker et al., this volume). In this contribution, natural variability in sediment transport has been evaluated for 9 locations.

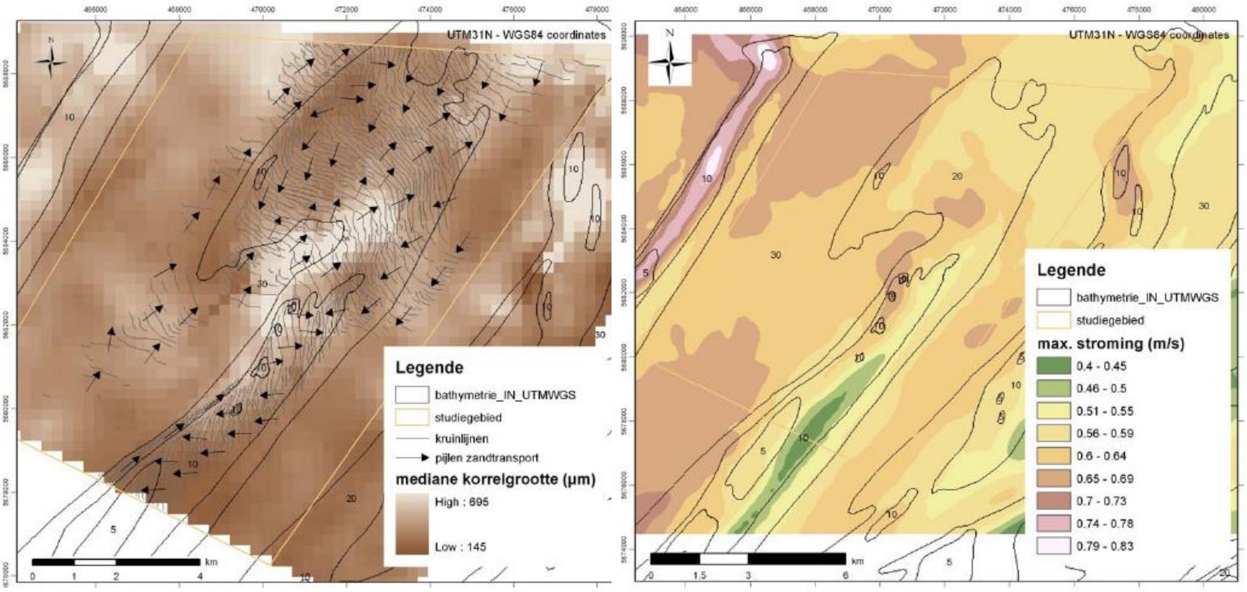

Figure A6-1. A. Bathymetry and median grain-size. Arrows indicate the directions of the large to very large dunes in the area. Note the coarser grain-size in the bottle neck and kink area (Baeye 2006). B. Maximum current velocity, based on the 750*750m hydrodynamic model.

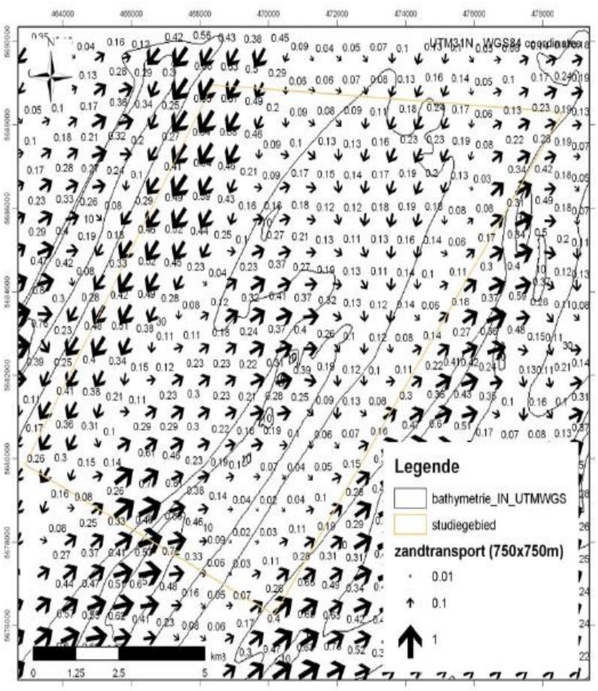

Figure A6-3. Sand transport magnitude and direction (750*750m) along the Buiten Ratel. Note higher sand transport along the western part of the linear sandbank (Baeye 2006).

Material and Methods

1. Numerical modelling databases

Results from long-term modelling have been used for the evaluation of hydrodynamics and sediment transport along the Buiten Ratel. A numerical wave database was used, set-up for the entire Belgian shelf (see Fernández et al., 2011, for a detailed description) and covering the period 1999-2010. Wave information is available every 3 hours, with a spatial resolution of the order of $1x1km^2$. Model results have been validated using buoy data from the Monitoring Network Flemish Banks (Flemish Hydrography, VLIZ Interface). The model used varying current and water levels that were obtained from the Coherens OPTOS BCZ model, a three-dimensional multi-purpose numerical model for coastal and shelf seas (Luyten, 2011). Output parameters related to the wave and current regime (mainly significant wave height, period, wave direction and mean current velocity, direction). Model output was further used for sediment transport calculations (bottom stresses, total load (Ackers-White formulae) (bedload and suspension load), and bed evolution) (see Van den Eynde, 2010, for a detailed description). Bathymetry data originated from the Flemish Hydrography (Maritime Services). For grain-size parameterization, the surficial sediment grid of Van Lancker et al. (2007) was used. Final model output was generated at a 0.5hr interval over the period 1999-2010; resolution 750m.

2. Evaluation

In this contribution, model results are presented for 9 locations along the Buiten Ratel. Positions have been chosen in the vicinity of the ILVO biological monitoring stations (see Debacker et al., this volume), in combination with the multibeam monitoring areas (MBES areas) (see Roche et al., this volume). It was aimed at evaluating differences along the linear part of the sandbank (west and east flank), and along the head of the Buiten Ratel. Modelling data were compiled into relational databases and further queried.

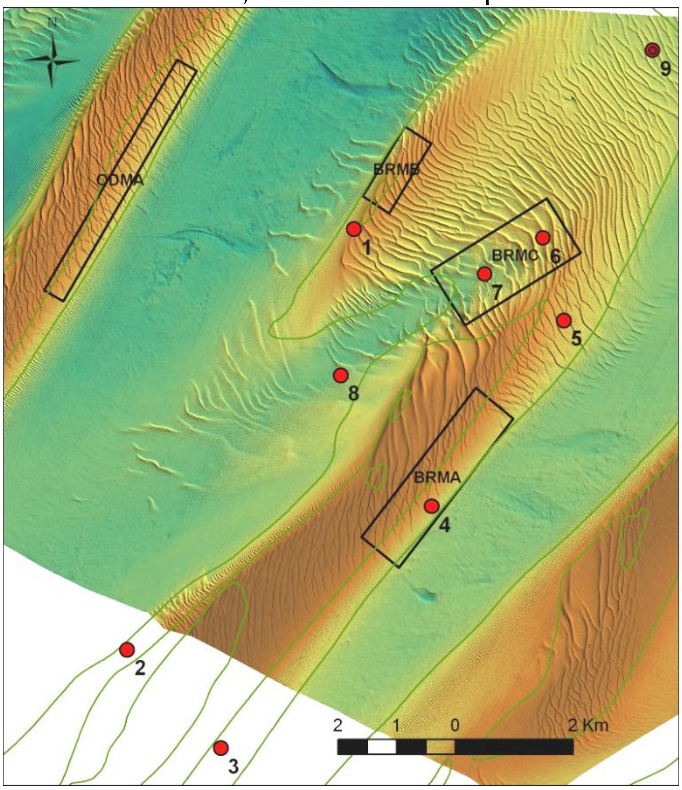

Figure A6-4. Buiten Ratel locations for sediment transport evaluation. Multibeam bathymetry from FPS Economy, SME's, Self-Employed and Energy, Marine Sand Fund. The black boxes indicate the monitoring areas (BRMA, BRMB, BRMC).

Table A6-1. Selected locations along the Buiten Ratel. Depth is recalculated from bathymetry data from the Flemish Hydrography; surficial sediments are derived from the sedisurf@sea database (Van Lancker et al., 2007). Note that depths range between 15 and 25m Mean sea-level (msl).

ID	Latitude	Longitude	Morphological Entity	MSL (m)	d50 (μm)	MBES area	ILVO sample
1	51.314850	2.562589	Head NW	19	276	BRMB	BRN03
2	51.250340	2.507864	Linear part W	15	247		BRZR08
3	51.235363	2.530833	Linear part E_s	16	246		BRZR04
4	51.272510	2.581962	Linear part E_m	16	264	BRMA	BRC10
5	51.301071	2.613918	Linear part E_n	17	291		BRC09
6	51.313652	2.608725	Head kink_n	19	383	BRMC	BRN10
7	51.308060	2.594544	Head kink_s	24	409	BRMC	BRN15
8	51.292484	2.559593	Channel kink	25	290		BRN18
9	51.342414	2.635288	Head N	22	279		BRNR01

Results

1. Evaluation of seabed mobility

    a. Tidal cycle variation

Current velocities amount up to 1 m/s, with highest current velocities along the head of the Buiten Ratel. Within the same depth zone, velocities were lower along the linear part of the bank. However, shallower locations (such as location 2) witnessed higher velocities. Overall, the flood current was dominant, except for the eastern flank of the sandbank. Still, the ratio flood/ebb varied around 1, hence both forces are highly competitive. Tidal ellipses were semi-circular, with eccentricity values (axis of slack water current direction *vs* axis maximum current direction during flood/ebb) varies around 0.25. Higher up the bank, the ellipses would become more circular. Residual currents were northwards directed for the western part of the sandbank, as also along its head part. In the locations along the eastern flank, residual currents were SSW directed. Evaluating seabed mobility, results showed that the bed was mobile for 50 to 60% of the time under Spring conditions, whilst less than 25% during Neap tide. Natural bed evolution varied according to location; most locations were stable (less than 1 cm difference), except for location 2 and 4 that showed erosion, respectively along the western and eastern flank of the linear part of the sandbank. Deposition was calculated along the kink or bottle neck part of the head (location 6). Similar tendencies were retained during neap tide, though along the bottle neck deposition is calculated. Table 1 provides a synthesis of seabed variability discussed in the previous section.

Table A6-2. Seafloor mobility assessment for 9 locations along the Buiten Ratel sandbank. Current characteristics and tidal cycle variability under a Spring and Neap tidal cycle.

Location	Head NW	Linear part W	Linear part E_s	Linear part E_m	Linear part E_n	Head kink_n	Head kink_s	Channel kink	Head N
Station	1	2	3	4	5	6	7	8	9
Current (m/s) Tides alone									
Max flood	0.82	0.93	0.76	0.8	0.82	**0.98**	0.97	0.88	0.79
Max ebb	0.78	0.56	0.89	**0.94**	0.91	0.85	0.8	0.82	0.83
Slack High Water	0.09	0	0.15	0.14	0.14	0.13	0.12	0.08	**0.16**
Slack Low Water	**0.37**	0.29	0.22	0.33	0.35	0.36	**0.37**	0.32	0.33
flood/ebb ratio	1.05	**1.65**	0.85	0.84	0.9	1.15	1.21	1.07	0.95
Eccentricity tidal ellipse	0.29	0.19	0.22	0.27	0.28	0.27	0.28	0.23	0.3
Residual current	0.09	**0.17**	0.05	0.06	0.04	0.09	0.1	0.1	0.05
Residual current dir	353	29	241	271	276	20	14	13	9
Seabed mobility tidal cycle									
Time (%) (ST)	**65**	43	48	56	58	58	53	60	62
Sed.Tr. (kg/m/s) (ST)	0.12489	**0.20093**	0.03283	0.06262	0.03185	0.13169	0.11467	0.07316	0.02782
Sed.Tr. dir (°) (ST)	47	55	220	225	216	60	60	54	64
Bed evolution (m) (ST)	0.00785	**-0.06792**	0.01713	-0.01807	-0.00417	0.01066	-0.00173	-0.00574	-0.00017
Time (%) (NT)	27	21	18	22	22	25	19	24	22
Sed.Tr. (kg/m/s) (NT)	0.00563	0.00548	0.00452	**0.01239**	0.01017	0.00047	0.00516	0.00039	0.00442
Sed.Tr. dir (°) (NT)	37	48	225	228	226	19	43	11	224
Bed evolution (m) (NT)	0.00118	**-0.10657**	0.0239	-0.01239	-0.00141	0.00506	-0.00258	0.02244	0.00158
Long-term evolution									
1999-2010	stable to deposition	erosion>>	deposition	erosion	stable	stable to deposition	stable	stable to deposition	stable

b. Medium-term natural variability – comparison with seabed monitoring

Table A6-3. provides the results of the measurement campaigns, as reported in detail in Roche et al. (this volume), together with the extracted hydro-meteorological and sediment transport modelling results for the respective periods. From averaged conditions, no obvious quantitative correlations could be found between the natural variation and the variation imposed by the extraction. More in-depth analyses are underway. The following figure shows a potential relation between measured seabed erosion and modelled negative bed evolution, due to hydro-meteorological forcing. Overall, natural variability would be low compared to the extraction-induced depth fluctuations, though hydro-meteorological forcing may reinforce erosive seabed responses. The influence of subsequent current-wave forcing on seabed evolution is shown in Figure 7. This period corresponds with the highest measured negative depth values in the BRMA monitoring area. Modelling output is shown for location 4.

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Table A6-3. Natural seabed evolution in-between multibeam measurement campaigns. **A**. Period between successive multibeam campaigns with variation in mean depth and depth difference. Mean depth differences derived from Black Box (BB) data are also provided (see Roche et al., this volume). **B**. Hydro-meteo (HM) extracted, matching as close as possible the inter campaign periods. Velocities are given in m/s; Hs (m) is significant wave height, both are averaged conditions. For total load sediment transport (kg/m/s) and bed evolution, the sum of the values was taken. Bed evolution is here represented as a trend.

Campaigns	Inter campaign period		Mean corrected depth	Mean corrected depth difference	Mean depth difference from BB
BRMA0723	2003-01-01	2007-10-08	-12.75	-0.13	-0.24
BRMB0816	2003-01-01	2008-07-02	-13.43	-0.01	-0.10
BRMC1005	2003-01-01	2010-02-25	-19.74	-19.99	-0.53
BRMA0816	2007-10-08	2008-07-01	-12.91	-0.16	-0.03
BRMA0820	2008-07-01	2008-09-08	-12.96	-0.05	0.00
BRMB0820	2008-07-02	2008-09-09	-13.52	-0.09	0.00
BRMA0830*	2008-09-08	2008-12-08	-12.91	0.05	-0.01
BRMB0830*	2008-09-09	2008-12-09	-13.43	0.09	0.00
BRMA0911	2008-12-08	2009-04-15	-12.85	0.06	-0.01
BRMB0911	2008-12-09	2009-04-15	-13.45	-0.02	0.00
BRMA0926	2009-04-15	2009-10-06	-12.96	-0.11	-0.02
BRMB0926	2009-04-15	2009-10-06	-13.50	-0.05	0.00
BRMA1005	2009-10-06	2010-02-23	-12.87	0.09	-0.01
BRMB1005	2009-10-06	2010-02-23	-13.45	0.05	0.00
BRMA1022	2010-02-23	2010-09-07	-13.07	-0.20	-0.04
BRMB1022	2010-02-23	2010-09-07	-13.50	-0.05	0.00
BRMC1015	2010-02-25	2010-05-26	-19.75	-0.01	-0.10
BRMC1022	2010-05-26	2010-09-06	-20.12	-0.37	-0.10
BRMA1030	2010-09-07	2010-11-25	-12.97	0.10	-0.01
BRMB1030	2010-09-07	2010-11-24	-13.41	0.09	0.00
BRMC1030	2010-09-06	2010-11-24	-20.00	0.12	-0.07

Campaigns	HM extracted		Wind velocity	Wind direction	Hs	Residual current velocity	Residual current direction	Total load	Total load direction	Trend bed evolution
BRMA0723	*2007-08-01*	2007-10-08	7.54	SSW	0.68	0.05	SSW	6.723	SW	*erosion*
BRMB0816	*2008-04-01*	2008-07-02	7.34	SSE	0.67	0.01	NE	3.048	NE	*erosion*
BRMC1005	*2009-10-07*	2010-02-25	9.54	S	1.10	0.02	NNW	4.512	ENE	*erosion*
BRMA0816	*2008-04-01*	2008-07-02	7.34	SSE	0.65	0.02	ENE	0.234	E	*deposition*
BRMA0820	2008-07-02	2008-09-08	8.69	SSW	0.75	0.02	ENE	0.296	SSW	*deposition*
BRMB0820	2008-07-02	2008-09-09	8.69	SSW	0.79	0.01	NE	2.756	NE	*stable*
BRMA0830*	*2008-10-01*	2008-12-08	9.12	SSW	0.95	0.02	ENE	0.436	SSW	*deposition*
BRMB0830*	*2008-10-01*	2008-12-09	9.12	SSW	1.00	0.01	NE	2.350	NE	*deposition*
BRMA0911	2008-12-12	2009-04-15	8.06	SSW	0.76	0.09	SSW	2.576	SW	*deposition*
BRMB0911	2008-12-12	2009-04-15	8.06	SSW	0.79	0.05	WSW	4.062	NE	*erosion*
BRMA0926	*2009-09-02*	2009-10-06	8.42	S	0.92	0.04	WSW	0.977	SW	*erosion*
BRMB0926	*2009-09-02*	2009-10-06	8.42	S	0.97	0.04	NNW	0.887	NE	*deposition*
BRMA1005	2009-10-07	2010-02-23	9.54	S	1.03	0.04	WSW	3.492	SW	*erosion*
BRMB1005	2009-10-07	2010-02-23	9.54	S	1.09	0.04	NNW	8.513	NE	*deposition*
BRMA1022	*2010-05-27*	2010-09-07	7.16	SSW	0.87	0.04	WSW	0.934	SSW	*erosion*
BRMB1022	*2010-05-27*	2010-09-07	7.16	SSW	0.92	0.04	NNW	21.054	NE	*erosion*
BRMC1015	2010-02-25	2010-05-26	7.61	SE	0.94	0.02	NNW	3.656	ENE	*erosion*
BRMC1022	2010-05-27	2010-09-06	7.16	SSW	0.92	0.02	NNW	6.208	ENE	*erosion*
BRMA1030	2010-09-09	2010-11-25	9.37	SSW	1.15	0.04	WSW	3.943	SW	*erosion*
BRMB1030	2010-09-09	2010-11-24	9.37	SSW	1.22	0.04	NNW	5.297	NNE	*deposition*
BRMC1030	2010-09-09	2010-11-24	9.37	SSW	1.23	0.02	NNW	2.789	ENE	*deposition*

Italic: major deviation from inter campaign period, due to data gaps or erroneous values

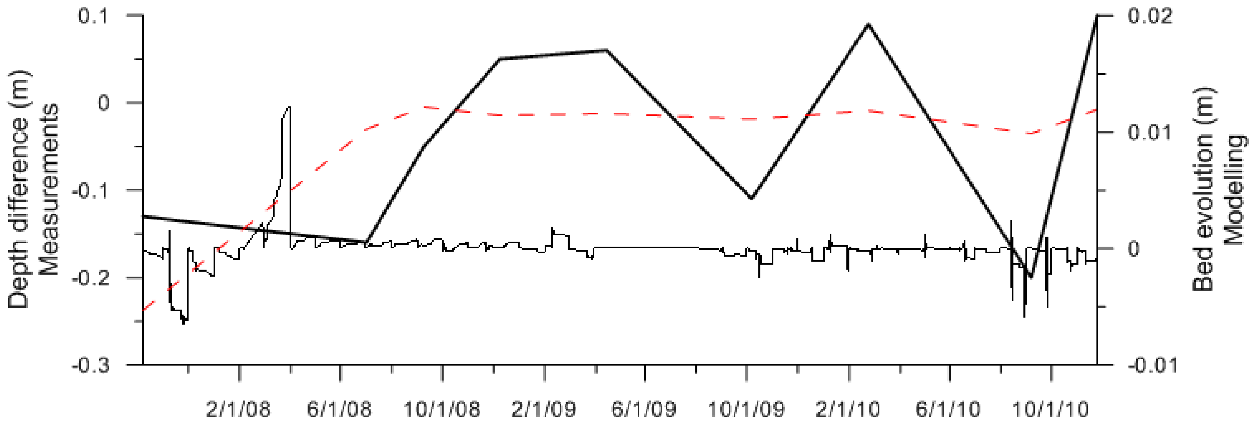

Figure A6-5. Combined plot of the evolution of derived depth differences (black line) from multibeam and black box data (dashed red line) (left axis) and bed evolution (m) from modelling results (right axis) (Data from Roche et al., this volume). Although the variations differ in an order of magnitude, most measured seabed erosion tends to correspond with periods of elevated negative bed evolution, due to hydro-meteorological forcing. Area BRMA, modelling results at location 4; east flank of the linear part of the sandbank. The negative bed evolution around 09/10 is shown in detail in the following figure.

c. Long-term seabed evolution

Seabed mobility or bed evolution on the long-term (1999-2010; 2003-2010; 2006-2010) showed similar tendencies as the evolution under a tidal cycle: (1) stable for most locations; (2) erosion along the linear part of the bank, west and east; and (3) deposition along the kink or bottle neck part and locally along the head of the bank. Figure 6 shows the bed evolution pattern for the monitoring areas.

All model results (currents, waves, bottom shear stresses, total load transport, bed evolution), and hydro-meteo conditions have been compiled into 1 database for each of the locations over the period 1999-2010. However, model data are available along the entire Belgian part of the North Sea for this period, enabling ad hoc calculations at any location and over any chosen time period or event. The latter were chosen, based on wind characteristics, extracted for the Westhinder measuring pile (Hydro—meteo network 'Flemish Banks', Flemish Hydrography).

To compare natural and anthropogenically-induced sediment dynamics, natural variability was studied within the periods that depths were measured, using multibeam technology. Dates were matched as close as possible, though periods with data gaps or erroneous data were filtered. Depth differences, derived from Black Box data, are also provided. See Roche et al. (this volume) for results on depth differences in the marine extraction areas, and their correlation with extraction intensities.

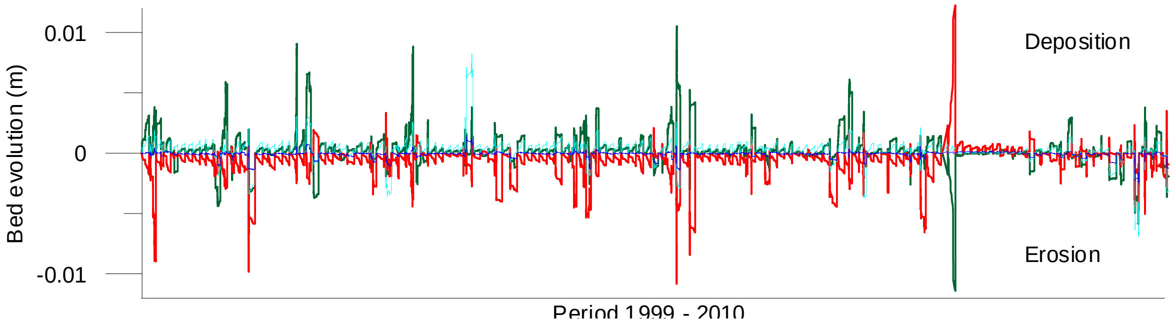

Figure A6-6. Modelled decadal bed evolution along 4 locations: green: location 1, along the NW flank of the Buiten Ratel Head, tendency to long-term deposition (BRMB); red: location 4, along the eastern flank of the linear part of the sandbank (BRMA), mostly erosive; cyan: location 6, in the kink part of the head (north) (BRMC) with a tendency to deposition; and blue: location 7, also in the kink part of the head (south) (BRMC) showing a rather stable trend.

Conclusions

Some results are shown from a study on the long-term evaluation of natural variability along the Belgian part of the North Sea. Together with data from human activities, and monitoring results of seabed changes, it becomes possible to assess natural versus anthropogenically-induced sediment dynamics. Spatial and temporal variability of natural processes are important to further assess the recovery potential after human activities have ceased. Future perspectives include integration of numerical models in geographic databases. 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.

Acknowledgements

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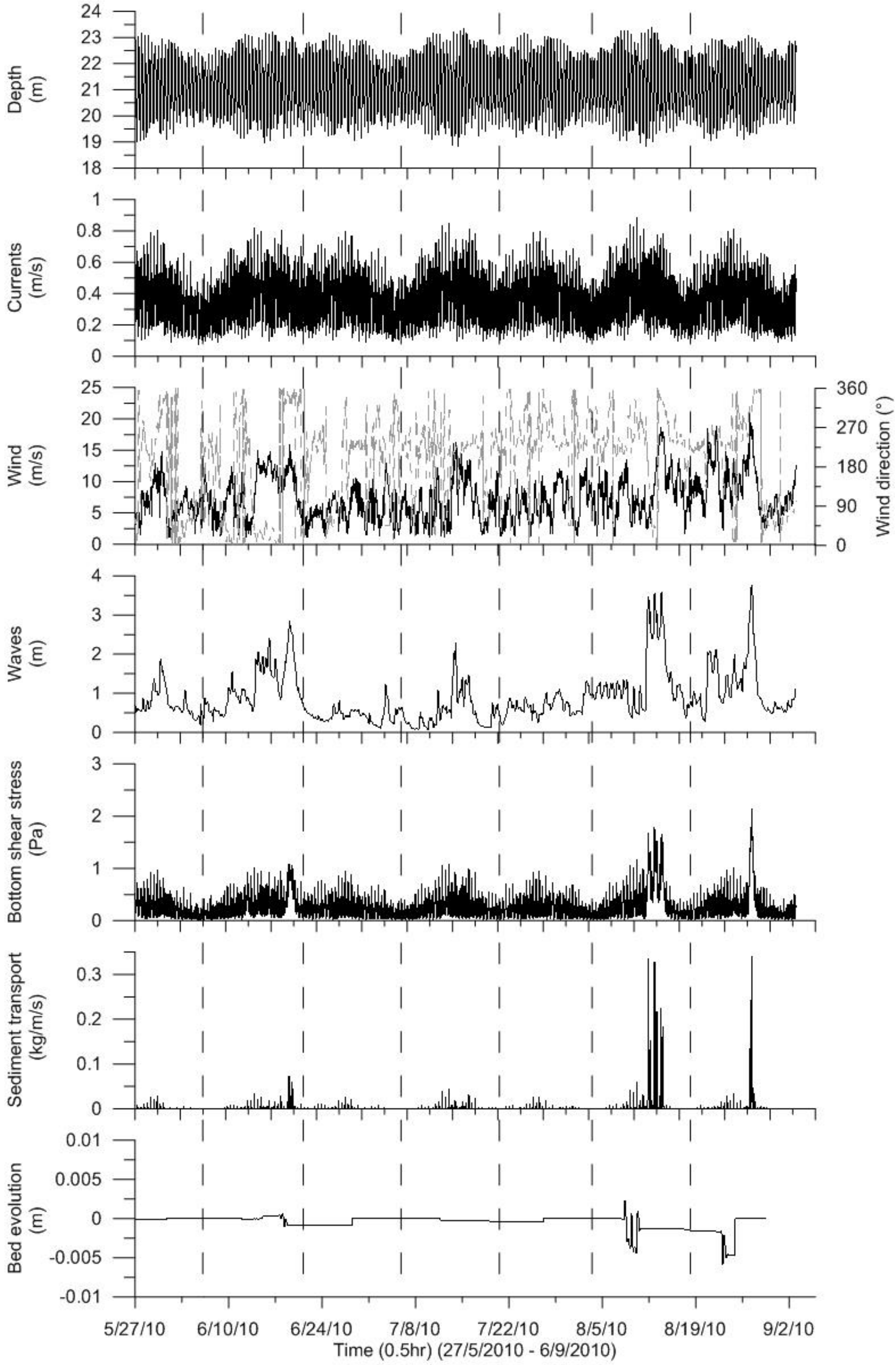

Figure A6-7. Location 4 within the BRMA monitoring area. Hydro-meteorological and modelled sediment transport parameters for the period May – September 2010. This period corresponds to the most negative measured seabed response, as show in Figure 6. Note a fairly consistent wind direction from the SW; significant wave heights more than 3m and highest during Spring tide conditions. Bed shear stresses reached nearly 2 Pa, resulting in significant sediment transport and subsequently negative seabed responses. Dashed lines indicate successive Spring-Neap cycles.

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