First scientific support plan for a sustainable development policy (SPSD I)

Programme "Sustainable management of the North Sea"

Research on natural sand transports on the Belgian continental shelf

BUDGET (Beneficial usage of data and geo-environmental techniques)

Summary of the research

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SYNTHESIS

Characterisation of the Belgian continental shelf (BCS)

The Belgian continental shelf (BCS) is characterised by a number of sandbanks that can be grouped as Coastal Banks, Flemish Banks, Hinder Banks and the Zeeland Ridges. The Coastal Banks and the Zeeland Ridges are quasi parallel to the coastline, whilst the Flemish and Hinder Banks have a clear offset in relation to the coast.

From a geological point of view, it has been shown that at least some sandbanks are not merely an up-piling of sand, but a result of different well-distinct evolutionary phases. Subsequently, the sediments involved can be very diverse in nature and vary from clay to coarse sands and gravel. However, only the upper sediment cover is representative of the present hydrodynamic regime. It was deduced that the thickness of the Quaternary is less than 2.5 m in most of the swales of the BCS with locally erosion of Tertiary clay deposits can occur.

The morpho-sedimentological characterisation of the BCS included the compilation of morphological and sedimentological data in order to give evidence of areas with a high sediment transport potential. To accomplish this aim emphasis was put on the occurrence of larger bedforms as they are formed under a higher current regime and are usually associated with areas having a significant sediment input. In this framework it was also important to know the sediments involved and hence a compilation of sedimentological data was a necessity.

To present a global overview of the presence and characteristics of the bedforms on the BCS, the occurrence of large dunes (sandwaves) were mapped based on information from publications, side-scan sonar surveys and single- and multibeam registrations. If sufficient dimensional data was available, fields of height classes were visualised.

Generally, the highest dunes are observed at the northern extremity of the Flemish Banks (up to 8 m) and in the northern part of the Hinder Banks region. Higher dunes are also observed at kinks that are often observed along sandbanks. Fields of large dunes also occur at the western extremity of the Goote Bank and in the northern part of the Hinder Banks region where they were abundantly observed in the swales. Closer to the coast their occurrence is merely restricted and the sandbanks are generally devoid of bedforms. Remarkably, the highest dunes are sometimes found in the shallowest areas.

On a sedimentological level, the nature and differentiation of the surficial sediments is mostly related to the unique configuration of the sandbank-swale systems whereby the interaction of the current with the large-scale morphology is responsible of a hydraulic sorting of the sediments. The sand fraction (0.063 to 2 mm) preferentially takes part in the up-building process of the sandbanks whilst the coarser sands, gravel (> 2mm) and the silt-clay fraction (< 0.063 mm) are merely found in the swales. The general coarseness of the steep slope of the sandbanks is due to the erosive action of the flood tidal current along this slope. The gravely deposits in the swales are merely relict sediments that are hardly moved by the present hydrodynamic regime and therefore it should be evaluated whether they are a renewable sediment source or not. Generally, the finest sediments can only deposit in the deeper swales, but studies in the near coastal area showed that muddy deposits can occur up to a depth of – 6 m MLLWS if a high availability of fine suspended matter exists. Shallower, this fraction is washed out by an interplay of currents and waves. On the scale of the BCS, the surficial sediments generally coarsen in an offshore direction. A literature overview is given of the existing sedimentological studies and this on as well a large- as on a small-scale basis.

The availability of current and other hydrodynamic measurements carried out on the BCS is discussed. However, most hydrodynamical measurements are rather short-term and are related to specific research questions. The model relevant for the understanding of the current propagation on the scale of the whole BCS is implemented on a rectilinear grid and has a resolution of about 750 m x 750 m. Along the open boundaries, the model uses the output from the mu-STORM model, a 2D operational hydrodynamic model covering the North Sea and the English Channel. At the mouth of the Westerschelde, the model is coupled to a 1D hydrodynamic model of the Schelde estuary.

On a synthesis map the above mentioned information has been compiled. A selection is made of current ellipses typically for a spring tide calculated from the 2D hydrodynamic numerical model mu-BCZ. Noteworthy, are the strongly rectilinear ellipses in the near coastal zone and in the mouth of the Westerschelde. Offshore and on the Vlakte van de Raan, the ellipses are more rotary in nature with a veering towards the sandbanks. At the northern limit of the BCS, the current ellipses are again more rectilinear.

Overview of sediment transport studies related to the BCS

An inventory was made of all sediment transport studies related to the BCS both related to bed-load as to suspension load transport. For each study a summary is presented including information on (i) the method used to derive the sediment transport information, (ii) the principal results and (iii) the directions and quantities of the sediment transport that were deduced. The studies were classified according to the principal technique that was applied.

Critical anlysis of the data and the methods used

All results related to sediment transport were compiled and analysed per method.

Residual transport directions based on the asymmetry of bedforms.
The asymmetry of flow-transverse bedforms can be used to derive the residual sediment transport directions. Both small to medium dunes (megaripples) and large to very large dunes (sandwaves) have been used as transport indicators on the BCS. The asymmetry of the bedforms is in the first place defined by the dominant tidal current as the overall shape represents a state of quasi-equilibrium to the relative strength of the opposing flows. On a large number of sandbanks such as the Flemish Banks and the Hinder Banks the residual flood current shapes the bedforms on the western bank flank and the eastern part of the swale whilst residual ebb currents are responsible for the ebb-asymmetry of the bedforms on the eastern bank flank and the western part of the swales. This mechanism is responsible for a convergence of sand streams towards the bank's crest resulting in sand up piling on the bank's summit.

- The direction of the steep side of bedforms remains recommended to derive sediment transport directions. The results that were compiled from different studies are consistent and coincide with results derived from other methods. However the results of a single moment do not always show the residual transport directions on a large time scale as time-series of measurements have shown that nearly all large and small dunes can change their asymmetry and present an ebb-asymmetry or a flood-asymmetry. This alteration of asymmetry is caused by the effect of hydro-meteorological conditions whereby dominant wind and swell from a particular direction can amplify the flood or the ebb current. The speed of this adaptation to the net transport direction is function of the size of the bedform. Once the storm is over, the bedforms will return to their original tidal-induced asymmetry, but again the speed of this change will depend on their size. This means that bedforms can be used to derive the residual transport directions on a large time scale but in this case the effects of external factors have to be filtered out. The asymmetry of very large dunes (with heights of more than 8 m) can be considered as permanent and could therefore be used to deduce residual transport on a time scale of several years. Small dunes can also be used as transport indicators, however their vulnerability should be evaluated to the ruling hydro-meteorological conditions.

Residual transport directions based on tracer experiments.
A number of tracer experiments were carried out on the BCS and adjacent beaches. Three techniques have been used to study the residual bedload sediment transport.

- Radioactive tracers were used in the vicinity of the harbour of Zeebrugge and most results reflected the dominance of the flood current in the direction of the Dutch border. Coastward transport was mainly the result of wave action coupled to stormy weather conditions. North of Zeebrugge, a small residual transport was found in the ebb direction. A tracer experiment carried out on the Westdyck sandbank (France) indicated a NE residual bedload transport towards the Flemish Banks.

- Fluorescent tracer experiments were carried out on the beaches, eastward of Zeebrugge and of Nieuwpoort and indicated an eastward-directed residual transport. Only one fluorescent tracer experiment was carried out offshore. During this experiment, 2 deployments of fluorescent sand were made on both bank flanks of the Middelkerke Bank. The results, although biased and hampered by unfavourable weather conditions, showed that the sediment was moved residually in a NE direction on the western flank and in a SW direction on the eastern flank. Sediment movement around the bank in a clockwise direction could as well be deduced.

- Only one experiment with magnetically enhanced sand was carried out on the beach of Nieuwpoort. The results showed that the majority of the mobilised tracer material was transported in a SW direction.

A number of tracer experiments were carried out to assess the suspension load transport.

- Six injections of radioactive tracers were carried out. The results pointed to a re-circulation towards the coastal area where the sediment seemed to be trapped though with a slight dominance of a residual transport in a NE direction. Still, care is needed as a number of factors biased the conclusions.

- A number of natural tracers can be used to trace large-scale and long-term residual water movements. Measurements of salinity carried out on the Dutch shelf showed that the water travels residually in a NNE direction and that the movement increased from almost zero near the Belgian coast to about 6 cm/s near the Isle of Texel. Residual sediment movement can as well be deduced from the displacement of a suspended matter minimum and from the superficial water temperature detected on thermal infrared imagery.

The results of the tracer experiments carried out on the BCS have revealed useful information on the residual transport directions. The technique is however not always successful as certain factors can prevent a normal dispersion of the tracer particles. If the area in which the experiments takes place is subject to a sediment accretion the tracer substance can be covered with sediment which makes it unavailable for transport. Fluorescent tracer experiments in the offshore have to rely on extensive sampling operations making the method rather expensive. In this case other tracer methods, in which the detection of the marked particles can take place directly on the seabed by using a detection unit mounted on a sledge, should be favoured. As radioactive tracers are no longer in use due their environmental-unfriendly image, magnetic tracers could be considered for this type of research.

<u>Residual transport directions based on sediment differentiation.</u>
Variations in the areal pattern of grain-size parameters have been used in different ways to determine the residual sediment transport directions. Two techniques have been used on the BCS: Sediment Trend Analysis (STA) and fraction analysis.

- In the STA technique the coarseness, sorting and skewness of a sample is compared with its neighbours. Residual transport takes place if a specific transport trend can be defined between the two samples. Most studies carried out on the BCS agree that the most reliable results are obtained if a combination of the transport trends FB- (Finer, Better sorted, and more negative skewness) and CB+ (Coarser, Better sorted and more positive skewness) is used. Trends in which the sorting is worsening along the considered transport paths have little similarity with the transport trends from other methods.

- The STA technique was used on the entire southern North Sea, along the western and eastern near coastal area and on sections of the Kwinte Bank, Middelkerke Bank, Goote Bank, Ravelingen and east of Zeebrugge. An STA carried out on the whole southern North Sea showed that a distinction could be made between a coastal area in which transport vectors were pointed towards the coast and an offshore area in which a NE transport was dominant. The results of a STA carried out on the scale of a coastal system and on sections of sandbanks comply with the directions derived from bedform analysis. The sediment dynamic model deduced from the bedform asymmetry in which sand is moved residually on both bank flanks by the effect of flood and ebb currents, was in agreement with the results of the STA.

- From the results, it can be deduced that STA is suitable to gain insight into sediment transport directions. However to deduce *residual* transport directions, it should be compared and integrated with complementary techniques and some prior knowledge of the hydrodynamic environment will greatly help to understand the obtained results. It remains highly advisable to carry out an STA in an environment where hydrodynamical agents equally influence the surficial sediments as otherwise time constraints might strongly bias the results. Moreover, the most reliable results are expected if only one depositional environment is taken into account.

- The study of the distribution of the different grain-size classes individually can provide a better insight into the processes governing the physical functioning of a coastal system. This technique was applied in the western near coastal area where processes of coarsening, fining and winnowing of specific grain-size fractions could be observed and related to differing hydro-meteorological conditions. Relatively, the coarsest sediments were found under calm weather conditions whilst under rougher conditions finer sandy sediments can be brought into the system and deposited.

Residual transport directions based on current and suspended sediment concentration measurements

- A large number of current measurements and sediment concentration measurements were carried out on the BCS mainly in the framework of the construction of the new outer walls of Zeebrugge harbour. These short-term observations provide an insight in the order of magnitude of the suspended sediment, but they are subject to important fluctuations in time.

- Data on current speed and sediment concentrations over a long time (spring-neap cycle) are preferentially obtained through continuous measurements with the help of sensors such as Optical Backscatter Sensors (OBS) or Acoustic Doppler current Profiling sensors (ADP). Measurements can be made from a ship or by using bottom frames. A small number of these measurements have been carried out in the past. Measurements on the relocation grounds Zeebrugge East and S1 made it possible to assess accurately residual suspension transport rates and directions during spring (up to 15 tonnes/m/day), middle and neap tide (up to 4 tonnes/m/day).

- Sediment concentration measurements in combination with aeroplane multispectral scanner recordings and a 2D hydrodynamic model have been used to calculate the suspended sediment transport in the entire Belgian coastal zone. The residual transport was parallel to the coast and flood-dominated for nearly the entire coast. Residual transport values varied between 0.6 and 5 tonnes/m/day.

Residual transport directions based on sediment transport models

The numerical sediment transport models, which have been applied to the BCS can be divided in suspended load and in total load models.

- The cohesive sediment transport models of the BCS are regional ‘engineering’ type models containing many simplifications (due to the limited knowledge of the physical environment). The turbulence fields, parameterised as subscale phenomena, the bed composition and the boundary conditions are poorly known, due to a lack of field data bed dynamics (erosion and deposition as a function of sediment composition, transport, consolidation) are simulated using simplified relations, biological processes are ignored.

- The processes responsible for the high turbidity formation are the currents and the import of suspended particulate matter (SPM) through the Strait of Dover. Due to mainly the decreasing magnitude of residual transport, which is NE directed and the shallowness of the area, the SPM is concentrated in the Belgian-Dutch coastal waters and is forming a turbidity maximum in front of Zeebrugge. The occurrence of a high turbidity zone can best be compared to a kind of sediment congestion; it is an open sediment system. The erosion of Tertiary clay, Holocene mud and peat layers is partly responsible for the increase of the SPM concentration in the considered area.

- Fine grained sediments are continuously deposited and re-suspended showing variations during tidal cycles, neap-spring cycles and during changing meteorological conditions. Deposition, re-suspension and transport of mud during a tidal cycle are basic processes and are responsible for the magnitude of the SPM concentration in the turbidity maximum area.

- The difference in magnitude between spring and neap tidal currents is partly responsible for the fact that the mud deposits are permanent. Especially, during neap tide, the mud has a higher probability to build up a structure, to consolidate and to increase its erosion resistance. More mud is thus found on the bottom and the SPM concentration is relatively low. During spring tide the opposite happens and part of these deposits are again re-suspended.

- A recent total load model uses hydrodynamic and wave information to calculate the sediment transport. The results show a sediment transport on the sandbanks in a clockwise direction: to the NE on the W flank of the banks and SW directed on the E flank of the bank. In the coastal zone (20 km) the transport direction is towards the NE. In the Scheur the direction is towards the W. In open sea (north of the sand banks) the sediment transport direction is towards the SW.

Evaluation criteria

Time and spatial scales of the residual transport results obtained with different methods can be quite different so care is needed comparing results obtained with different techniques. All techniques applied on the BCS were classified according to the corresponding time and spatial scale. Four different categories were defined for both time (micro scale: hours to days; meso scale: days to weeks; macro scale: weeks to months; mega scale: years to decades) and spatial scale (micro scale: 0.1 to 1 m; meso scale: 1 to 100 m; macro scale: 100 m to 1 km; mega scale: 1 to 100 km).

Sediment budgeting

Using the existing data it is difficult to set up a quantitative sediment balance (sand fraction) of the BCS. Quantitative data exist however for the human activities on the BCS, such as the dredging works, the study of the dumping place B&W S1 and data on sand extraction and beach nourishment.

- Yearly about $1.4x10^6$ t dry matter (TDM) of sand is dredged in the navigation channels
- Measurements indicate that 80-90% of the dumped sand stays on the dumping place. The results of a Sediment Trend Analysis (STA) suggest that the remaining 10-20% are transported back to the navigation channels. This corresponds to replenishment for the dredging year 1997 of 0.08-0.16 TDM (15-30%) from B&W S1. The same STA results indicate that the most important replenishment of the navigation channels is from sand transport from the west (Wenduine Bank, Wandelaar).
- Erosion occurs along some parts of the Belgian coast. During the nineties about $1.1x10^6$ TDM/yr of sand have been extracted for beach nourishment works.
- Every year $2.5x10^6$ TDM of sand is extracted (90% on the Kwinte Bank).
- From national and international investigations, a global transit of 5 $x10^6$ to $10x10^6$ TDM/yr is estimated as being transported along the French, Belgian and Dutch coast in a NE direction. Recently, an estimate of $20x10^6$ TDM/yr is reported for suspended matter, still this needs further investigation.

On the basis of a 40 days measuring period of suspended sand profiles and current meter data on the Middelkerke sandbank, the following sand transport rates were obtained:

- 0.9 tonnes/m/day (up to 0.3 m above the bed) along the steep slope; this was 10 times that of the southern end of the bank (0.05 tonnes/m/day); sand transport was up-slope at 25 degrees to the bank axis, in the direction of the major axis of the tidal ellipse;
- The transport on the steep slope was mainly in the size range of 100-140 µm which did not occur in any significant proportion in samples of the sea bed at that site leading to the conclusion that this fraction is likely advected from deeper water (SE);
- Excluding the finer component, the transport rates of coarser sand (> 200 µm) at the two sites were similar over the 40 days period;
- The transport rates are consistent with a time-scale of 100-1000 yr for the formation of the bank.

Recommendations

Emphasis is put on an efficient mapping of the seabed as such data is highly relevant for as well the research community as end-users and this as well for small- as large-scale applications. Two mapping techniques are recommended: multibeam and side-scan sonar. Both techniques are complementary and in combination a very-high resolution quantitative mapping of the seafloor including its the intrinsic nature can be obtained. Furthermore, both allow to quantitatively process the backscatter data and through the set-up of automated classification schemes a tools is provided for an efficient mapping of seabed sediments. Still, other techniques exist and deserve further investigation and exploration.

Groundtruthing remains a necessity especially since more research is needed regarding the true correlation of acoustic means and sediment characteristics. Stratified sampling based on the different acoustic facies could allow to set-up groundtruthed seabed classes that ideally comprise the variety of aggregates found on the BCS. However, according to the sediments involved, appropriate sampling tools should be chosen, preferentially integrated with video imagery. This will also open up perspectives towards biodiversity studies.

Sampling operations should be efficiently planned and take into account the larger scale sedimentary environment. Especially towards monitoring studies and the study of temporal variations, it is highly advisable to select areas that are at least homogeneous over an area confined within the positioning error radius around sampling locations.

Hydrodynamical and sediment transport measurements remain of vital importance for any sediment transport study. Although, a mathematical model may be the most suitable technique for calculating the effect of long-term and large-scale sediment transport processes, it is a necessity to feed the models with realistic data on current speed and sediment concentration data. Moreover, quantification of sediment transport and its translation towards sediment budgets are important towards a sustainable management of the seabed.

Especially, towards sand transport studies, multi-sensor bottom-mounted frames should be used that are deployed over at least a sping-neap tidal cycle. These allow to obtain data related to bedload and suspended load processes whereby the height of the sensors above the seafloor is adjusted according to the objectives. Although, this configuration allows obtaining detailed information on seabed dynamics, they remain point observations and extrapolation to a larger scale is often difficult.

The use of an acoustic doppler current profiling combined with data from optical backscatter sensors (well-calibrated) allows to calculate sediment fluxes over the vertical water column and in profile mode whilst sailing. The disadvantage is that often those measurements do not reach the seafloor itself although knowledge on this layer is vital for sand transport studies. ADP's can also operate from a bottom-mounted frame.

An instrument that offers the capability to study the particle size of the suspended matter and with potential towards sediment transport quantification is a laser in-situ scattering and transmissometer (LISST). This type of instrument is relatively new and promising and has up to now not been used for research purposes on the BCS. The instrument can also be mounted on a frame and deployed for longer time periods.

The sediment dynamic related field measurements can be used as input, calibration and validation of numerical modelling. Nowadays software allows 2D depth-average or fine-grid 3D hydrodynamical modelling of the current and water transport as well due to tidal as to different hydro-meteo conditions. Moreover, the propagation and transformation of waves can be simulated including the evolution of waves for a variety of wind stresses, current velocities and water depths. In combination with sediment transport modelling (bedload, suspended and total load transport) the morphological evolution of the seafloor can be simulated over time-scales of days to years.

An example of the application of an integrated research strategy is a seabed mobility study. The compilation of newly gathered and existing data in combination with existing numerical modelling allows to evaluate the sediment transport capacity in an area and sheds new light on sediment provenance areas.

To enhance the efficiency and practical use of seabed data, the set-up of an overall *Geographical Information System* (GIS) on the available marine aggregates becomes timely and would enable to select data according to end-users' needs. However, caution is needed if contour maps are automatically generated without prior knowledge on the sedimentary environment and if specific derivatives are needed.

Moreover, it is recommended to set-up guidelines and protocols on the prerequisites of mapping and sampling projects since this would largely facilitate the set-up and evaluation of environmental impact assessments (EIA). If indeed a GIS on the BCS seabed would exist, it could provide standardised background information. It could also include numerical reference material to guide sediment budgeting studies. In any case, an overall data management seems inherent to efficiently anticipate on future needs and to facilitate the decision-making.