Sediment transport pathways in the Broers Bank - Westdiep coastal system Preliminary results

Vera R.M. VAN LANCKER[1], Steve D. HONEYBUN[3] and Geert P.M. MOERKERKE[2]

1 University of Gent, Renard Centre of Marine Geology, Krijgslaan 281-S8, 9000 Gent-Belgium.
Fax. +32 9 264 49 67
Email: Vera.VanLancker@rug.ac.be
2 University of Gent, Sedimentary Geology & Engineering Geology, Krijgslaan 281-S8, 9000 Gent-Belgium.
Fax. +32 9 264 49 43
Email: Geert.Moerkerke@rug.ac.be
3 University of Wales, School of Ocean Sciences, Menai Bridge Gwynedd, LL59 5EY, North Wales, U.K.
Fax +44 1703 593059
Email: osp407@bangor.ac.uk

Abstract
A reconnaissance study on sediment transport pathways has been carried out in the Broers Bank – Westdiep coastal system with the aim of physically characterising the habitat structure of shallow marine ecosystems. Sediment transport modelling on the basis of current meter data and sedimentological information revealed that the tidal currents have a high potential for sediment movement. Due to a high sediment influx and the ability to erode older Tertiary clay layers, deposition of fine-grained material is high; hence the development of bedforms is often inhibited. Still, medium to large dunes occur where medium sands are predominant; hence where the bed shear stress is highest. Due to the shallowness of the area, the dynamics of the dunes will be largely dependant on the prevailing hydro-meteorological conditions.

Introduction

A preliminary study on sediment transport pathways was carried out in the nearshore area of the western Belgian coastal zone (Figure 1). The area is characterised by a bank – swale hydrography witnessing water depths of 0 to -15 m MLLWS. Because of the geomorphological diversity in combination with the presence of several shallow sites (Broers Bank), the area has been proposed as a special area within the EC-Habitat Directive. The geomorphological structure, being the most diverse along the Belgian coast, is directly responsible for the high biological diversity and richness of the area (Degraer et al. 1999); hence 3400 ha is proposed as the first Belgian marine protected area.

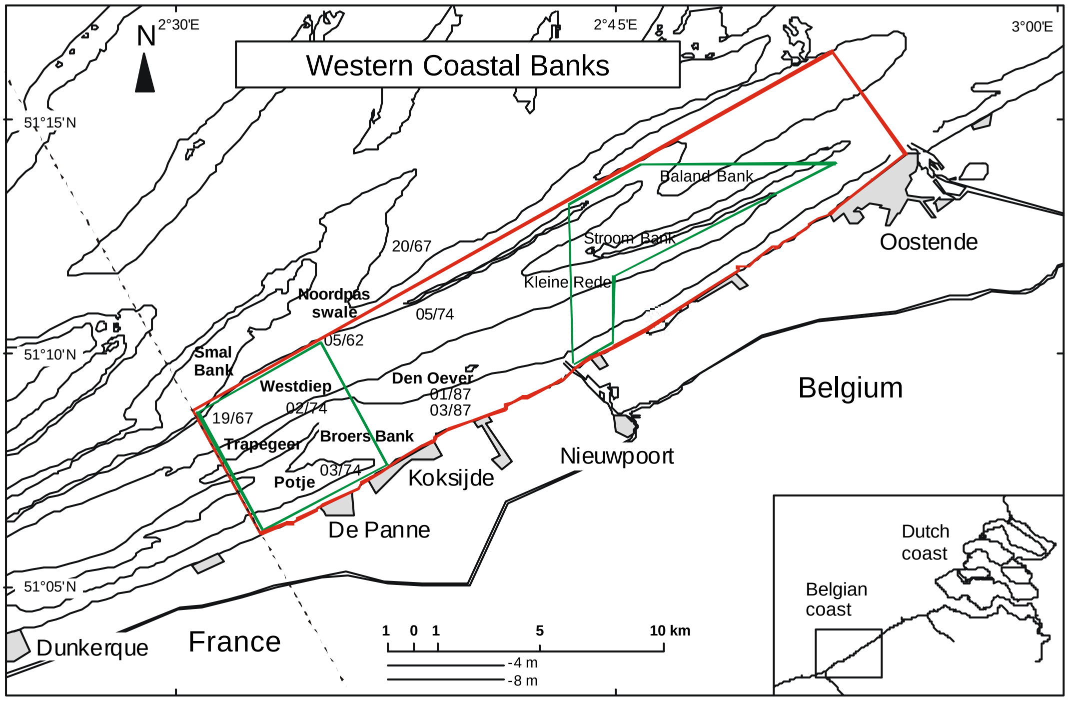

Figure 1 - *Localisation of the Broers Bank - Westdiep system and adjacent coastal areas with an indication of ecologically important areas* (Degraer 1999). The numbers correspond with current meter deployments by the Belgian Waterways Coast Division.

From this perspective, the Belgian Federal Office for Scientific, Technical and Cultural Affairs (DWTC) granted a project to provide for data necessary for the definition and evaluation of a future scientific support plan.
In order to meet these requirements a interdisciplinary approach was set up integrating both biological and geological expertise. The present results focus on the characterisation of the bedforms of the coastal ecosystem and will serve as a basis for an intense interdisciplinary research during the course of the HABITAT project (1999-2001).

1-Methods

As a first study on the sediment dynamics of the Westdiep - Broers Bank coastal system, sediment transport calculations were performed on the basis of available current meter information provided by the Belgian Waterways Coast Division and supplemented with sedimentological data from the study area. For the threshold current speed, the approach of Soulsby (1997) was adopted:

$$\overline{U}_{cr} = 7\left(\frac{h}{d_{50}}\right)^{1/7} \left[g\,(s-1)\,d_{50}\; f\,(D_*)\right]^{1/2} \quad for \quad D_* > 0.1$$

$$f\,(D_*) = \left(\frac{0.30}{1+1.2\,D_*}\right) + 0.055\left[1-\exp\left(-\,0.020\;D_*\right)\right]$$

where

$\overline{U}_{cr}$ = threshold current speed (m/s);

D_* = dimensionless diameter

$$D_* = d\left[\frac{g\,(s-1)}{n^2}\right]^{1/3};$$

d = grain diameter (m) (i.e. d_{90} is the grain diameter for which 90 % of the grains is finer);
g = acceleration due to gravity (m/s²);
s = ratio of densities of sediment (φ_s) and water (φ_w) (φ_s = 2650 kg/m³ ; φ_w = 1027 kg/m³) and
ν = the kinematic viscosity of water (m²/s).

The threshold Shields parameter for the initiation of suspension was calculated according to Van Rijn (1993).

$1 < D_* \leq 10$: $$q_{crs} = \frac{16}{D_*^2}\;\frac{w_s^{\;2}}{(s-1)gd_{50}}$$

or for $D_* > 10$: $$q_{crs} = 0.16\;\frac{w_s^{\;2}}{(s-1)gd_{50}}$$

q_{crs} = threshold Shields parameter for initiation of suspension;
w_s = settling velocity (m/s).

Bathymetric surveys of the Broers Bank – Westdiep system were undertaken by the Belgian Waterways Coast Division during the Spring and Autumn of 1997. In the framework of this study, the heights and approximate positions of bedforms along the survey tracks were extracted from the analogue sounding traces and transferred to a mosaic that provided the basis for bedform height and asymmetry charts that were interpreted in terms of transport pathways.
In March 1999, sediment samples were collected in the Westdiep swale and analysed for their grain-size distribution using a laser diffractometer. Complemented with a dataset obtained from the *Marine Biology Section* of Gent University (B), sediment transport was also derived on the basis of the areal distribution of sedimentological parameters.

2-Results

Sediment transport

The transport of sediments and other marine properties in the coastal zone is strongly affected by a variety of hydrodynamic and meteorological processes. Especially in shallow waters, wind induced residual currents can not be neglected, moreover the wave climate has a direct effect on sediment suspension and bedform morphology. The area under investigation is characterised by semi-diurnal tides of macrotidal range. The tidal currents are characterised by elongate and asymmetrical tidal current ellipses with a north easterly-directed residual flood displacement that controls the sediment transport pathways. In the Westdiep swale, spring near-surface flood currents in a NE-ENE direction can amount up to 1.32 m/s whilst a maximum of 0.86 m/s is reached during the SW-WSW ebb currents (station 19/67, Figure 1). At this location, the tidal amplitudes at spring and neap tides are 5.42 m and 2.89 m respectively.

Table 1 shows the resuspension potential at some current meter locations (Figure 1) calculated according to Van Rijn (1993). The Table shows that the surficial sediments are mainly mobile during spring and mid tide, from generally 1 hour before up to 1 hour after High Water. Interestingly, is the Westdiep swale and the Noordpas swale where also the ebb tidal current is able to resuspend sediments. Table 2 gives an indication of the transport capacity of the flow calculated for each phi quarter, ranging from 2.50 phi up to 1.25 phi (177 µm - 420 µm). Under currents alone, the calculations show that sediments having a median size of up to 420 µm can be transported during the flood under spring conditions. The ebb tidal current is at least able to transport sediments with a mean size of 177 µm. It needs emphasis that these results represent a minimum competence, since the combined action of currents and waves non-linearly enhances sediment transport.

Sedimentological characterisation

The sedimentology of the area was firstly studied by Bastin (1974). The results showed clearly the diverse nature of the sediments, mainly due to the strong currents locally able to erode older Tertiary clay layers in the swales (i.e. Westdiep). Also, the close to the coast swale, Potje, is characterised by strong tidal flood currents, hence its erosive nature may threaten the beaches around Koksijde (Figure 1).

Generally, the area is characterised as having a high potential for the deposition of fine-grained sediments. This might seem quite remarkable given the sediment transport calculations presented in the Tables 1 and 2. Apart from a high availability, the rectilinear nature of the tidal currents implies that halfway the tidal cycle, the current velocity may reduce to a minimum enabling the settling of the finest fractions. This is especially the case in the Potje and Westdiep swale where the transversal component (2-3 hrs before or after High Water) of the flow is largely reduced.

The sedimentological investigation of the present study shows that the sand and silt fractions are the main constituents of the surficial sediments within the Broers Bank - Westdiep system. The sediments get coarser towards the top of the bathymetric highs, including a rise in the Westdiep swale (thick contour line of –13 m MLLWS, Figure 2). The sand bank areas are indeed generally coarsest, whilst the surficial sediments of the swales can have high percentages of the silt fraction. The shallow Broers Bank (up to 0 m MLLWS) is characterised by coarse shell fragments. Still, the sorting is, generally, best on the bank summits and poorest in the swales. Throughout the study area, the mean grain-size ranges from fine sands of 2.75 phi (~ 150 µm) up to medium sand of 1 phi (500 µm). Figure 2 is a contour map of the distribution of the fine and medium sands. Given the limited density of sampling points south of the Trapegeer, this zone should be treated with more caution. In October 1999, 124 samples with a grid resolution of 500 m have been taken and will allow a detailed investigation of the surficial sediments and a validation by side-scan sonar imagery.

Sediment transport pathways have been derived from the textural differentiaton of the surficial sediments. On the basis of the spatial distribution of the parameters mean, sorting and skewness, it is believed that the combined trend, whereby sediments become either finer, better sorted with a more negative skewness or coarser, better sorted and with a more positive skewness, is indicative of residual sediment transport (Gao & Collins 1992). As a first approach, such a grain-size trend analysis was performed on the available sedimentological information using the Gao (1996) programme. The vectors primarily indicate a transport of sediment from the Westdiep swale upslope the Trapegeer whilst closer to the coast, the vectors merely point in a southwestern direction. To the southwest, where the surficial sediments of the Trapegeer consist of medium sands, a transport direction to the northeast is derived. The results may indicate a winnowing trend from the Westdiep swale to the Trapegeer and is mainly tidally driven. Near the coast the textural differentiation is likely more biased by wave breaking and refraction. Moreover, in the shallowest areas, the highest sediment resuspension processes are expected during the ebb; an observation also found during beach experiments, eastwards of the study area (Voulgaris et al. 1998). Still, it needs emphasis that more groundtruthing is needed to validate the value of the results.

Table 1 – *Resuspension potential at some current meter locations (using the* Van Rijn (1993) *criterion of the initiation of suspension). (For location, see Figure 1)*

				Spring tide		**Mid tide**		**Neap tide**	
Station	***Location***	***d50* (mm)**	***Uavcrs* (m/s)**	***Flood* (%)**	***Ebb* (%)**	***Flood* (%)**	***Ebb* (%)**	***Flood* (%)**	***Ebb* (%)**
05/62	Westdiep	327	0.69	15 (1a-HW)	0	0	0	0	0
19/67	Westdiep	210	0.61	23 (1a-1p)	15 (5a-4a)	23 (1a-1p)	0	0	0
20/67	Noordpas	210	0.59	8 (1a)	8 (5a)	8 (1a)	0	0	0
02/74	Trapegeer	204	0.59	8 (1a)	0	0	0	0	0
03/74	Potje	179	0.53	15 (2a-1a)	0	15 (2a-1a)	0	8 (2a)	0
05/74	WK70 Westdiep	210	0.59	23 (1a-1p)	0	23 (1a-1p)	0	0	0
01/87	WK3 Oostduinkerke	194	0.58	15 (1a-HW)	0	8 (1a)	0	0	0
03/87	Trapegeer	204	0.59	15 (1a-HW)	8 (5a)	15 (1a-HW)	8 (5a)	0	0

Key: Uavcrs is the average critical velocity at the initiation of suspension; it is here averaged over spring, mid and neap tides, as the value is dependant upon the depth differences at each hour of the tidal cycle. The particle diameter (d50 µm) is extracted from the sedimentological data base together with external information. The percentages of mobility refer to the time during which the average bed shear velocity exceeds the threshold value; they are supplemented by the time over which the sediments can be resuspended (1a-1p: from 1 hr before (a) High Water at Zeebrugge up to 1 hr after (p) High Water).

Table 2 - *Transport capacity of the flow under the influence of currents alone. (For location, see Figure 1).*

	2.50 f **~ 177** mm		**2.25** f **~ 210** mm		**2.00** f **~ 250** mm		**1.75** f **~ 297** mm		**1.50** f **~ 354** mm		**1.25** f **~ 420** mm	
Location and station	***Flood*** S-M-N (%)	***Ebb*** **S-M-N (%)**	***Flood*** S-M-N (%)	***Ebb*** **S-M-N (%)**	***Flood*** S-M-N (%)	***Ebb*** **S-M-N (%)**	***Flood*** S-M-N (%)	***Ebb*** **S-M-N (%)**	***Flood*** S-M-N (%)	***Ebb*** **S-M-N (%)**	***Flood*** S-M-N (%)	***Ebb*** **S-M-N (%)**
Westdiep (05/62)	23-23-0	8-M-0	15-15-0	M-0-0	15-M-0	0-0-0	15-0-0	0-M-0	15-0-0	0-0-0	15-0-0	0-0-0
Westdiep (19/67)	**31**-23-M	23-M-0	**23**-23-M	15-0-0	**23**-15-0	**15**-0-0	**23**-15-M	M-M-0	**23**-15-0	**M**-0-0	**23**-15-0	0-0-0
Trapegeer (02/74)	15-8-0	8-0-0	8-M-0	0-0-0	8-0-0	0-0-0	M-0-0	0-0-0	M-0-0	0-0-0	M-0-0	0-0-0
Potje (03/74)	23-15-8	0-0-0	15-15-M	0-0-0	15-M-0	0-0-0	8-M-M	0-0-0	8-0-0	0-0-0	8-0-0	0-0-0
OD (01/87)	15-15-0	M-0-0	15-8-0	0-0-0	8-8-0	0-0-0	8-8-0	0-0-0	8-M-0	0-0-0	8-M-0	0-0-0
Trapegeer (03/87)	15-15-15	23-23-8	15-15-M	15-8-M	15-8-M	8-8-0	8-8-M	M-M-0	8-8-0	0-0-0	8-8-0	0-0-0

Key: S-: Spring tide, M-: Mid tide, N-: Neap tide. M is indicated when only flood or ebb maxima are able to transport sediment of the indicated range. The critical depth-averaged velocity for the initiation of suspension for the given grain-sizes is calculated according to Van Rijn (1993). The percentages of mobility refer to the time during which the average bed shear velocity exceeds the threshold value

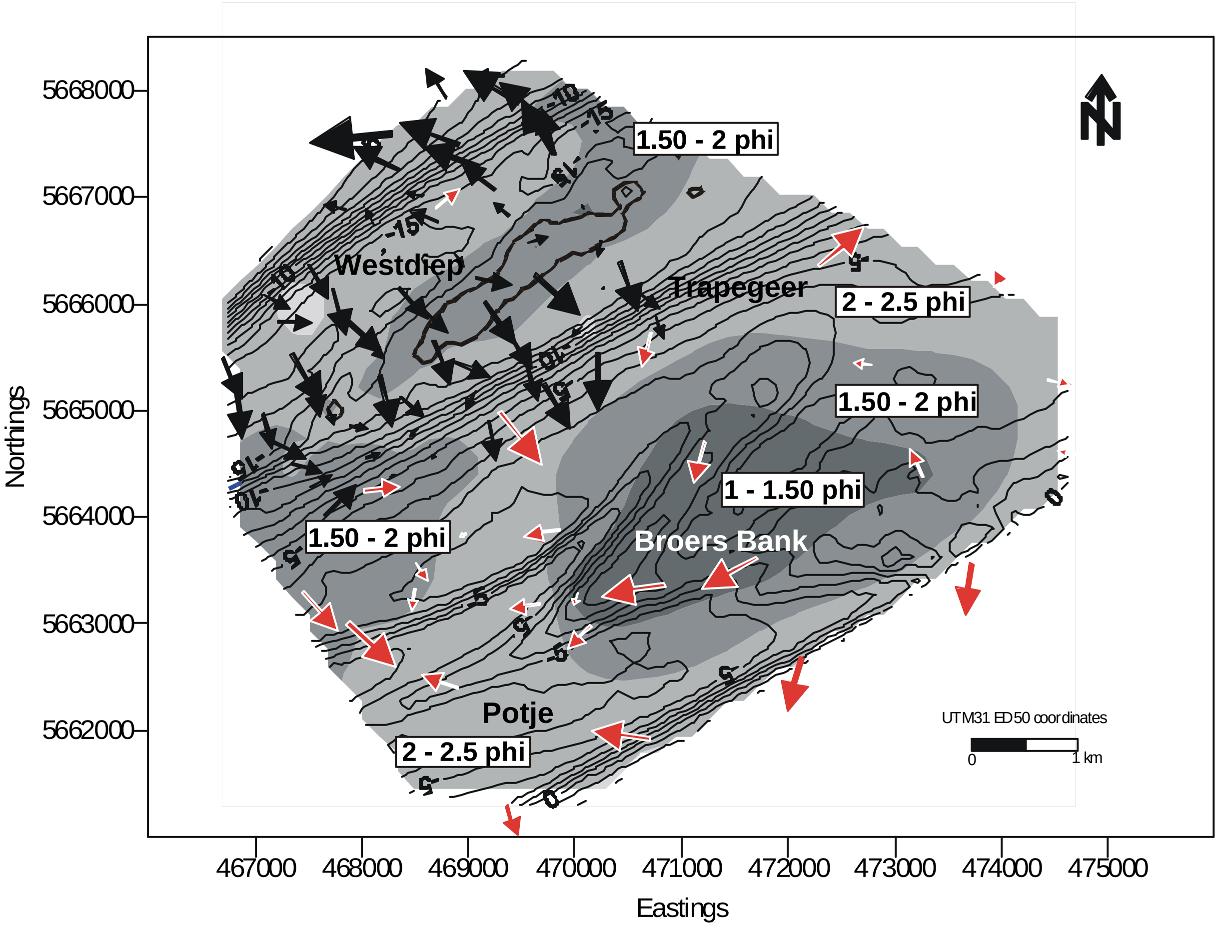

Figure 2 - *Contour map of the mean grain-size of the surficial sediments* (moment values). (medium sand: 1–2 phi / 250-500 µm; fine sand: 2-3 phi / 125-250 µm) (Honeybun 1999). The vectors represent residual transport directions based on a grain-size trend analysis according to Gao & Collins (1992).

<u>Bedform distribution</u>

Striking is the correlation of the presence of medium sands with the areal distribution of medium to large dunes (terminology according to Ashley 1990) (Figure 3). Especially, in the Westdiep swale and the Trapegeer, the zones of bedform occurrences completely follow the delineation between surficial sediments having a mean size of medium and of fine sands. It is also clear that high silt percentages as observed at the foot of the Trapegeer and in the Potje swale inhibit bedform development. The same correlation was found eastwards of the area, in the Baland Bank - Westdiep - Stroombank interaction zone (Figure 1) (Van Lancker 1999).

From offshore to onshore, bedforms in the range of medium to large dunes (up to 0.8 m in height) occur within the Westdiep swale, below the -10 m isobath. On the northern and southern slopes of the Westdiep swale, only small sand dunes are found with a maximum height of 0.4 m. However, moving up onto the Trapegeer, the bedforms increase in height and terminate in a line of medium to large sand dunes where water depths are shallower than -2 m MLLWS. On the Broers Bank, large sand dunes of more than 1 m occur at the broad summit area, whilst no bedforms were observed on its lower slopes (below the -4 m isobath) and concurrent with the Westdiep and Potje swales. In the latter swale, a few medium sand dunes were still recorded, but no bedforms were evident on the shoreface above the -5 m isobath. Still, at and above the MLLWS level a series of swash bars (up to 0.8 m in height) occurs, running parallel to the shore. Generally, the bedform asymmetries are orientated up the slopes of the banks and other bathymetric features. Within the Westdiep swale, the bedform asymmetries converge corresponding with a rise in the deepest part of the swale (thick contour line). Asymmetry convergence also occurs along the crest of the Trapegeer and on the Broers Bank summit area. Symmetrical dunes occur along these lines of convergence and within the Westdiep swale at the northeastern end of the raised area.

The first field experiments within the HABITAT project were carried out in October 1999. The area was subdivided into three zones to enable a mosaic of very-high resolution digital side-scan sonar imagery per zone. The general scheme of bedform distribution as shown in Figure 3 was confirmed, still, the images revealed very sharp delineations of bedform occurrences (i.e. Figure 4) likely induced by the strong tidal currents. Due to the bank - swale hydrography, the spatial variability is indeed high; hence the bedform dimensions vary from small to large dunes on very short intervals. In the shallowest zones (0 m MLLWS) complex seafloor patterns were observed.

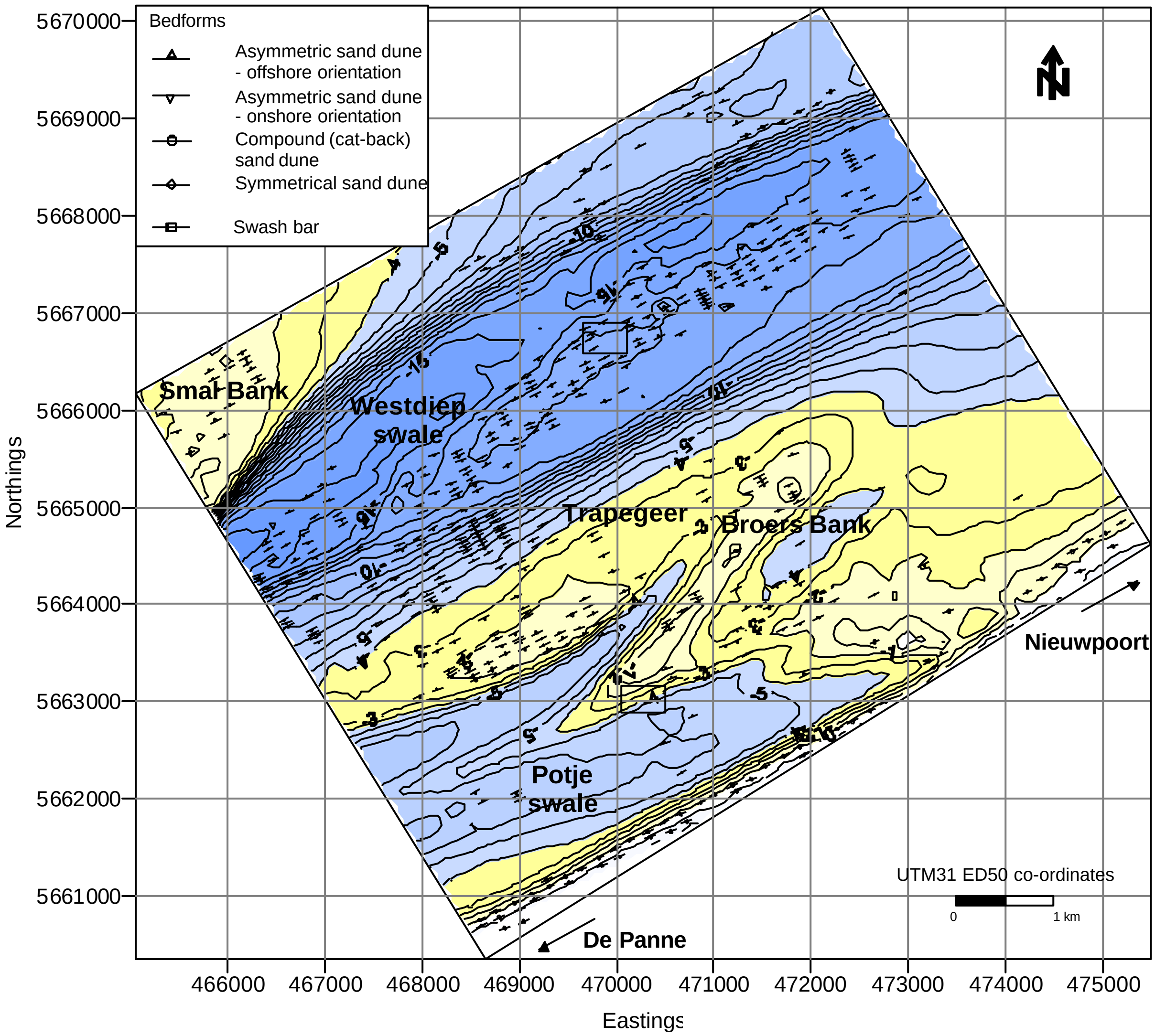

Figure 3 – *Scheme of the bedform distribution in the Westdiep – Broers Bank coastal system* (Depths are in m MLLWS) (Data supplied courtesy of: the Belgian Waterways Coast Division, Ministerie van de Vlaamse Gemeenschap) (Honeybun 1999). The boxes indicate the side-scan sonar images in Figure 4 and 5.

Figure 5 is a side-scan sonar registration witnessing large dunes at the northern slope of the Potje swale. In Spring 2000, the side-scan sonar mosaics will be integrated with a hydrodynamical model with a grid resolution of 250 m which will enable to correlate the amalgamating bedform patterns to the complex nature of the tidal currents.

From the bedform distribution map in Figure 3, sediment transport seems to be mainly driven from the swales upslope the bathymetric highs. Even along a small rise in the deepest part of the Westdiep swale, the bedforms orientations show a convergent pattern suggesting the building-up of an incipient sandbank. Still, from the side-scan sonar registrations obtained in October 1999, the larger sand dunes have a strike perpendicular to the maximum tidal current velocity.

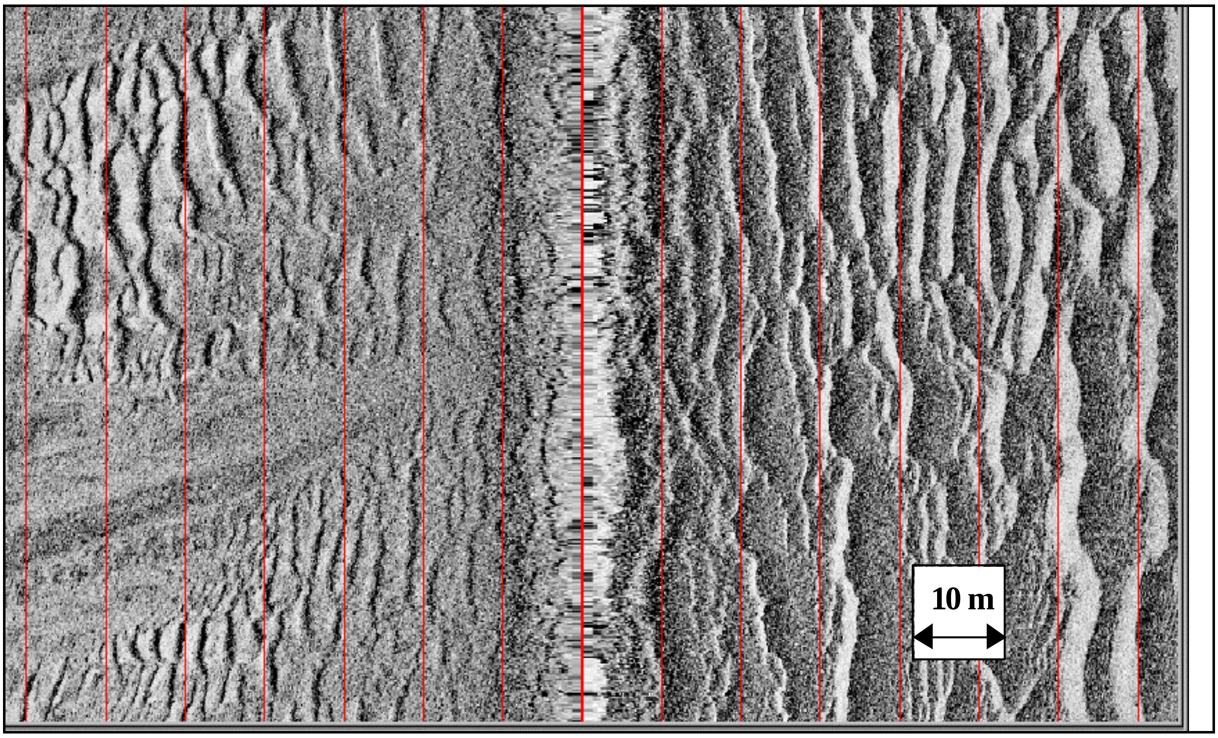

Figure 4 - Corrected side-scan sonar image near the rise in the Westdiep swale (Localisation Figure 2-3)

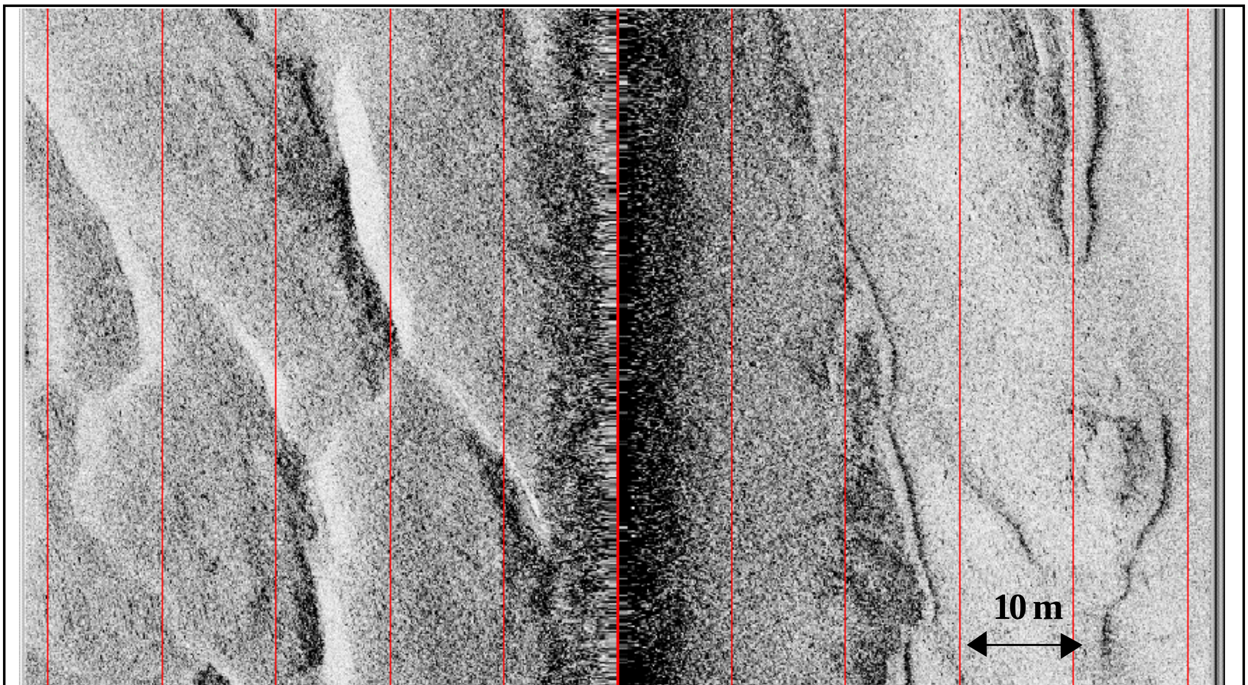

Figure 5 - Corrected side-scan sonar image at the northern slope of the Potje swale (Localisation Figure 2)

3-Conclusions

Due to the shallowness of the area, the bedforms are highly vulnerable to the hydrodynamic forces and hence likely restricted in dimensions. Still, from the evidence, the relative heights of the bedforms seem to be merely constraint by the texture than by the water depth. The highest dunes occur where the bed shear stress is highest being at the summit area of the Broers Bank, but also in the Westdiep swale where the tidal currents are funneled. These zones are characterised by surficial sediments constituting of medium sands often with an admixture of coarse shell fragments. Analogue findings were observed somewhat northeast of the area by Van Lancker et al. (1997). As to the dynamics of the bedforms, the availability of the sand fraction will be most

important. Especially in an area where the influx of suspended load is high and where the tidal currents are able to erode older Tertiary clay layers, the bedforms can easily be faded out. As shown for the adjacent area, the dimensions of the dune structures will largely depend on the prevailing hydro-meteorological conditions (Van Lancker 1999).
Future research within the HABITAT project will include hydrodynamical modelling and measurement of the velocity profile throughout the tidal cycle whilst very-high resolution digital side-scan sonar imagery will provide insight into the relation seabed morphology, its texture and the acting hydrodynamic forces. As such, the approach will form the physical basis of the habitat characterisation of the complex depositional environment of the Westdiep - Broers Bank coastal system.

Acknowledgements

The Belgian Waterways Coast Division is greatly acknowledged for providing bathymetrical and hydrodynamical data for the present study. The Marine Biology Section of Gent University (B) gave access to their sedimentological data collected in the period 1995-1999.
The research was carried out as a reconnaissance study for the project HABITAT funded by the Federal Office for Scientific, Technical and Cultural Affairs (DWTC) (1999-2001). Within this framework, the Belgian Waterways Coast Division provided shiptime on board "Ter Streep" and "Oostende XI"; the field experiments being strongly enhanced by an intense cooperation between the crew and both the biology and geology teams. The firm MAGELAS was responsible for the acquisition of the very-high resolution digital side-scan sonar imagery. Hydrodynamical modelling will be performed by the Management Unit of the Mathematical Model of the North Sea and the Schelde Estuary. This institute also provided shiptime on the Belgian oceanographic vessel "Belgica".

References

Ashley, G.M., 1990. Classification of large-scale subaqueous bedforms: a new look at an old problem. *J. Sediment. Petrol*. **60**, 160-172.

Bastin, A., 1974. *Regionale sedimentologie en morfologie van de zuidelijke Noordzee en van het Schelde Estuarium*. Unpublished PhD Thesis, KUL, Leuven, 91 pp.

Degraer, S., Vincx, M., Meire, P. and Offringa, H., 1999. The macrozoobenthos of an important wintering area of the common scoter *(Melanitta nigra)*. *Journal of the Marine Biologists Association of the U.K*., **79**, 243-251.

Degraer, S., 1999. *Macrobenthos of shallow marine habitats (Belgian Coast) and its use in coastal zone management*. Unpublished PhD Thesis, Universiteit Gent, 158 pp.

Gao, S., 1996. A fortran program for grain size trend analysis to define net sediment transport pathways. *Computers & Geosciences*, **22**(4): 449-452.

Honeybun, S., 1999. *Sediment transport pathways in the Broers Bank - Westdiep coastal system (Transport pathways obtained by sonar and grain size trend analysis techniques)*. Msc Thesis, Bangor (UK). University of Wales, School of Ocean Sciences; Gent (B). University of Gent, Renard Centre of Marine Geology, 135 pp.

Soulsby, R., 1997. *Dynamics of marine sands. A manual for practical applications*. Thomas Telford Publishing, London, 249 pp.

Van Lancker, V., O' Sullivan, A., Jacobs, P. & Stolk, A., 1997. An integrated strategy for the determination of spatial and temporal variability in a coastal system: the Belgian Coastal Zone. IN: Actes du colloque BORDOMER 97 *"Coastal Environment Management and Conservation*, Vol. 3, Add., pp. 1-11. Bordeaux (FR), 27-29/10/1997).

Van Lancker, V., 1999. *Sediment and morphodynamics of a siliciclastic near coastal area, in relation to hydrodynamical and meteorological conditions: Belgian continental shelf*. Unpublished PhD Thesis, Universiteit Gent, 194 pp.

Van Rijn, L.C., 1993. *Principles of sediment transport in rivers, estuaries and coastal seas*, I11. AQUA Publications, Amsterdam.

Voulgaris, G., Simmonds, D., Michel, D., Howa, H., Collins, M.B. and Huntley, D.A., 1998. Measuring and modelling sediment transport on a macrotidal ridge and runnel beach: an intercomparison. *Journal of Coastal Research*, **14**(1): 315-330.