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The dynamical behaviour of shallow-marine dunes

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Abstract

In the period 1995-1999, a detailed morpho- and sediment dynamical investigation was carried out in the western Belgian near coastal area, in water depths of –3 to –15 m MLLWS. Through chronosequential bathymetrical and digital side-scan sonar registrations supplemented by intensive samplings, a quantitative monitoring of the most dynamic zones was accomplished. Although, the area is generally devoid of bedforms, well-constraint zones of very large dunes occur where the bed shear stresses are highest. Since, suspended load accounts for more than 80 %, the dimensions seem to be largely controlled by the amount of the total load actually taking part in bedform development. A clear differentiation exists between the morphology of the dunes and their surficial sediments, the troughs being up to 0.30 phi finer than the crests. During the observation period, the similarities in crestline positions were more striking than the differences and showed a maximum shift of only 20 m. The data set allowed to differentiate the vulnerability of the area to varying hydro-meteorological conditions and showed that the area recovers fairly quickly from stormy periods.

1-Methods

The Belgian coastal zone is a siliciclastic macro-tidal environment (tidal range of 4.5 m) of which the nearshore is characterised by a sandbank – swale morphology (for a localisation see also Van Lancker et al., this volume). The velocity of the flood (NE) tidal currents amount up to 1.18 m/s and have a high sediment resuspension potential. To better understand ongoing sediment transport processes, an integrated research strategy was set up, involving chronosequential sedimentological and geo-acoustical observations. This enabled to reveal changes in the sedimentary pattern on a short-, medium- and long-term basis (Van Lancker 1999).

2-Results

The transport of sediments in the coastal zone is strongly affected by a variety of hydrodynamical processes including wind-induced residual currents that may have a direct effect on sediment resuspension and bedform morphology. Due to the intensity of the hydrodynamic forces in water depths of –3 to –15 m MLLWS, it seems acceptable that bedform development may be largely inhibited. The measurements in the period 1995-1999 did confirm this generality, still well-constraint zones of very large dunes were observed. Most peculiar is the interaction zone of two major sandbanks characterised by a small sandbank and an adjacent field of large dunes (Figure 1).

In December 1995, echosoundings and side-scan sonar registrations witnessed the presence of large dunes of up to 2 – 3 m in the Baland Bank area. A more detailed investigation revealed a field of dunes, east of the small sandbank. Side-scan sonar images gave evidence of quasi straight-crested bedforms, having a spacing of more than 100 m; this justified the usage of the term "two-dimensional very large dunes" (Ashley 1990). The strike of the 2D dunes gradually varied from 140° in the northeastern part, up to 183° in the vicinity of the bank itself. Wavelength values ranged between 125 and 200 m. Given the restricted area in which the dunes occur, each dune had a fairly lateral continuity with localised branching of the crestlines. In September 1996, the asymmetry of the very large dunes pointed in a southwestern direction. This was rather exceptional as this phenomenon was not observed during 12 other campaigns, also sailed in a timespan of 3 hrs before, up to 4 hrs after High Water. Although side-scan sonar recordings only vaguely showed a superposition of small to medium dunes, the term "compound dunes" seemed to be valid. Generally, they have a spacing of maximum 5 m and have straight, 2D crestline patterns, with a strike around 135°. They were observed in the troughs of the larger dunes, in water depths deeper than - 7 m, but seemed to be absent in the shallower regions. Along the western, steeper slope of the Baland Bank, from roughly -8 m to -6 m, well-defined small to medium sized dunes could be observed. Their spacing varied around 4-5 m, the strike around 120°. A slight veering to 130° occurred in a northwards direction. The steep side of those bedforms pointed in a northeastern direction concordant with the dominant flood current. Side-scan sonar observations over the shallowest regions revealed a wave dominated ripple-like morphology, superimposed on the crestline of the small sandbank and dipping in a coastward direction.

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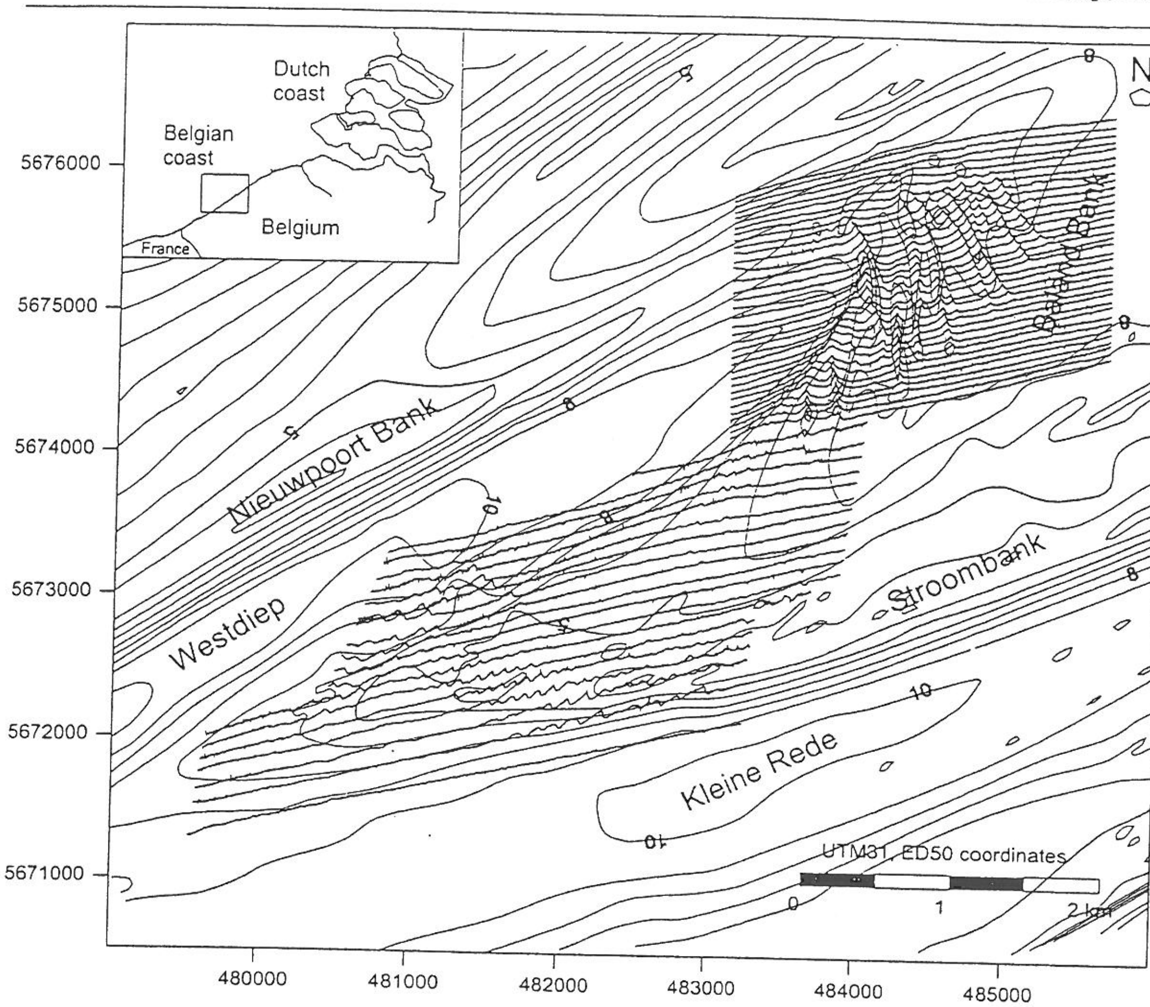

Figure 1 – *A compilation of echosounding profiles covering the Westdiep swale, the western extremity of the Stroombank, the interaction zone of the Stroombank and the Baland Bank (data of March 1998, June 1998).*

The bedforms in the interaction zone of the Nieuwpoort Bank and the Stroombank (narrowest part of the Westdiep swale) are characterised by dunes with a less-differentiated morphology. Still, one pronounced very large dune of almost 2 m in height is observed. Generally, the height of the bedforms ranged between 0.50 and 1.25 m, with a wavelength varying from 100 to 150 m. A slight veering of the strike of the dunes could be observed from 200° for the most western dunes up to 136° for the easternmost dune. The asymmetries of all dune-like structures always pointed in a northeastern direction. Remarkable is the restricted area over which the bedforms occur. They could only be observed over a distance of 1600 m from the western end of the Stroombank and seemed to be restricted to water depths shallower than - 9 m. Side-scan sonar images failed to show the crestlines of these dunes, though patches of molluscs appeared downstream of the steep side of these bedforms.

On the Stroombank, the height of the very large dunes reached a maximum height of up to 2 m, having a wavelength of 150 - 200 m. Sometimes, they were superimposed by smaller scale ripple-like features. Although their presence is fairly irregular, bedforms are expected from a depth of - 7 m. At the western end of the Stroombank, a succession of large dunes of about 1 m in height and a wavelength of 100 m could be observed and were restricted to water depths shallower than - 5 m. These bedforms quickly die out towards the central part of the bank.

In general, the interaction zone of the near coastal area and the Flemish Banks is characterised by the presence of well-defined bedforms. In particular, the southern end of the Middelkerke Bank and the Ravelingen area were investigated. This enables to compare bedform dynamics in the offshore and nearshore areas. Table 1 gives an overview of the bedform heights in the areas areas Baland Bank, Westdiep swale, the southern end of the Middelkerke Bank and the Ravelingen sand bank.

Table 1 – *Frequency of occurrence (in %) of bedform heights along the areas Baland Bank, Westdiep swale, the southern end of the Middelkerke Bank and the Ravelingen Bank (Field data of March 1998).*

	Height	*Baland Bank dune area*	*Westdiep swale*	*Ravelingen*	*Middelkerke Bank (south)*
small dunes	0.50-0.75 m	10.7	25	13.4	15.5
large dunes	0.75-1.00 m	19.1	31.3	19.8	18
	1.00-1.25 m	20.8	37.5	16.1	13
	1.25-1.50 m	21.3	6.3	12.4	13
	1.50-1.75 m	11.2	0	13.4	15.5
	1.75-2.00 m	3.9	0	4.1	9.3
	2.00-2.25 m	6.7	0	3.7	9.3
	2.25-2.50 m	2.2	0	6.9	3.1
	2.50-2.75 m	1.7	0	4.1	1.2
	2.75-3.00 m	1.1	0	2.8	1.9
very large dunes	3.00-3.25 m	1.1	0	1.8	0
	3.25-3.50 m	0	0	1.4	0
Max. height		3.2 m	1.9 m	3.4 m	2.9 m
% Flood		66	95	69	41
% Ebb		10	0	12	25
% Symmetrical		24	5	19	34

Environmental controls

Figure 2 shows some relations plotted for the large dunes in the different subenvironments. The height versus wavelength relation shows smaller height values than would be calculated from the wavelength using the equations of Flemming (1988) or Allen (1984). A cloud can be observed, showing that a range of dune heights can be found for a range of wavelengths and that no real relation between both can be determined. However, if the height of the dunes is calculated according to Van Rijn (1984) taking into account the ratio of bedload versus total load, then the dimensions become much smaller and a fairly good agreement is found between the dimensions of the dunes in the field and the calculated ones. This means that a lot of sediment is just bypassing and does not take part in bedform development.

For the figure 'asymmetry index versus water depth', a distinction was made between progressive and symmetrical dunes, independent of the direction in which the dunes were dipping. This was done as it was expected that depending on the depth, the dunes would show a degree in vulnerability with regard to the hydrodynamic forces. However, no relation is seen and apparently, as well progressive and symmetrical dunes can be found in the range of water depths. The plot showing the height of the dunes versus the water depth is most interesting. Contrasting to the relationship of Allen (1984), it seems that the highest dunes occur in the shallowest areas. It is believed that the current is the major controlling factor in the development of bedforms and that the highest bedforms correspond with zones of maximum interaction of both flood and ebb residual currents. Hereby, it is supposed that the flood brings in sediment, whilst the ebb current merely keeps the bedforms in shape. The wavelength versus the water depth shows no coherent pattern, and apparently a variety of wavelengths occurs in the range of water depths, from roughly -3 to -8 m.

Figure 3 shows the relation of sediment grain-size and the morphology in the Baland Bank dune area. A clear differentiation is seen between the surficial sediments of the bedform crests and the troughs, the latter being clearly finer in texture. The difference can amount to 0.30 phi. Although the sorting coefficient between a crest and a trough is not always significantly different, it is more likely that the troughs have a poorer sorting. Towards the east, the surficial sediments gradually become finer corresponding with the regional sediment transport in a northeastern direction (Figure 4).

Temporal variability

The migration history of the very large dunes in the different subenvironments has been determined based on the accurate positioning of the dune crests in the period 1996 - 1998. Figure 5 shows the crestline positions in the Baland Bank dune area.

In general the similarity of the observations is more striking than the differences. Only minor modifications occur between the successive campaigns. The general shape of the bedforms is unchanged; only some flexing of the sinuous crest lines is observed. Under rough conditions the larger bedforms do not seem to be moulded or blurred by storm activity. Still, storm-wave and storm-current activity likely increase the sediment transport rates significantly. As the area is fairly shallow, a minor rebuilding of the crests of the larger dunes over a tidal cycle is to be expected, though without major changes in height.

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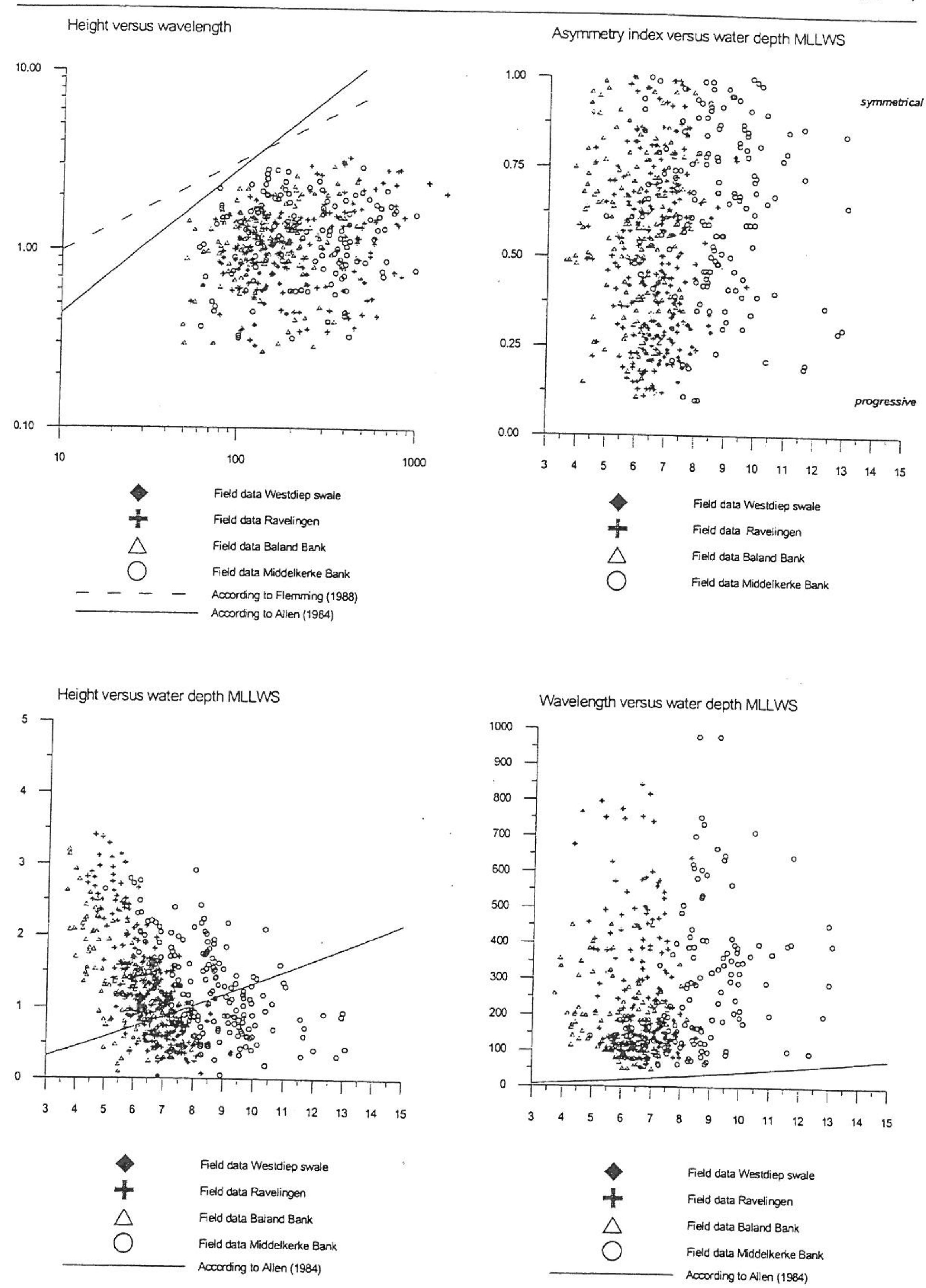

Figure 2 – *Bedform characteristics of four shallow-water environments (Field data of March 1998).*

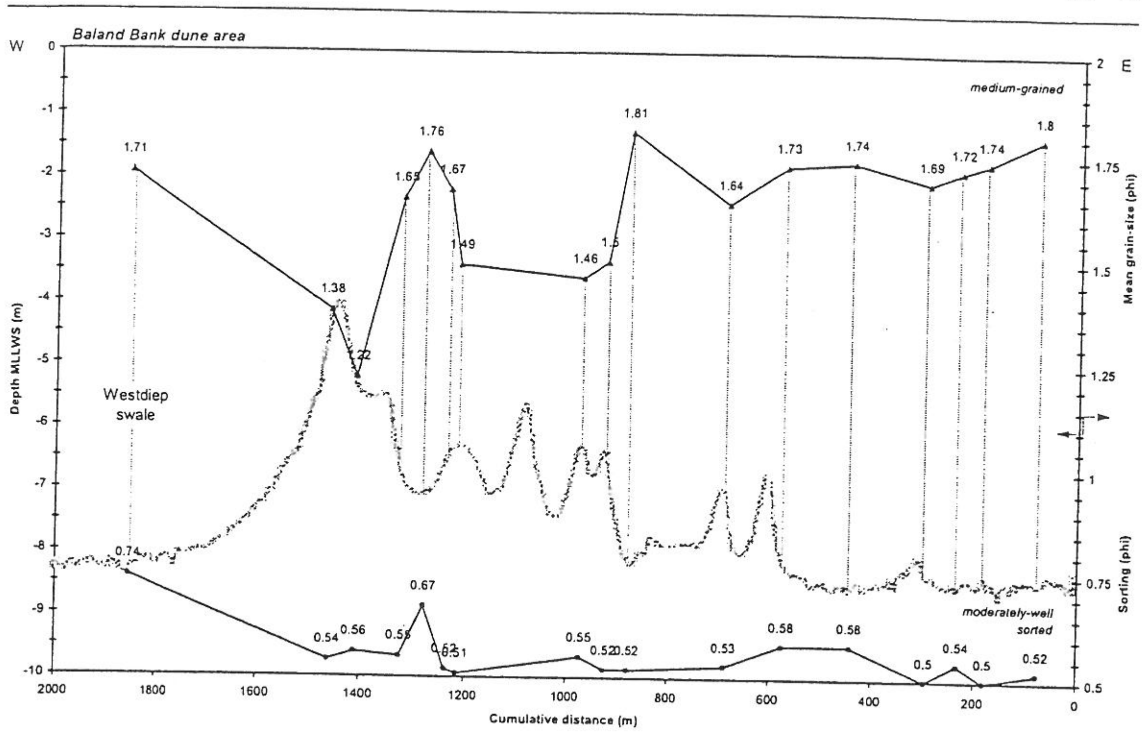

Figure 3 – *Relation of the morphology of the Baland Bank dune field and its grain-size characteristics.*

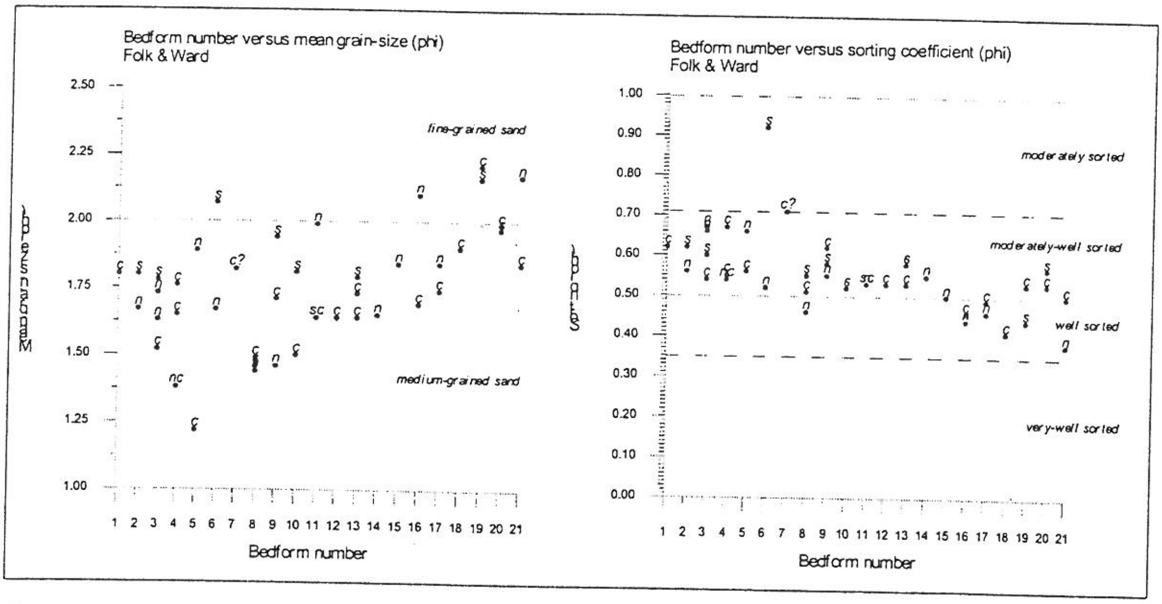

Figure 4 – *Grain-size characteristics of the very large dunes in the Baland Bank area.* The data points are labelled according to the relative position of the sample along the crestline: "n" northern extremity, "c" central, "s" southern extremity.

Given the flood dominance in the area, the steep slope of the bedforms is generally pointing in a northeastern direction. This also implies a movement of those bedforms in that direction. Still, from the evidence, the bedform movements are merely fluctuating and the crestlines of the bedforms migrate in as well the flood as the ebb direction. Most remarkable are the crestline positions measured in September 1996. All larger dunes in the Baland Bank area and along the southern part of the Middelkerke Bank showed a reversed asymmetry regardless of the general flood dominance in the area. Comparing this situation with the crestline positions of March 1998, the crestline of the sandbank itself had shifted 20 to 38 m towards the northeast whilst in the dune field, an average shift of 20 m was observed.

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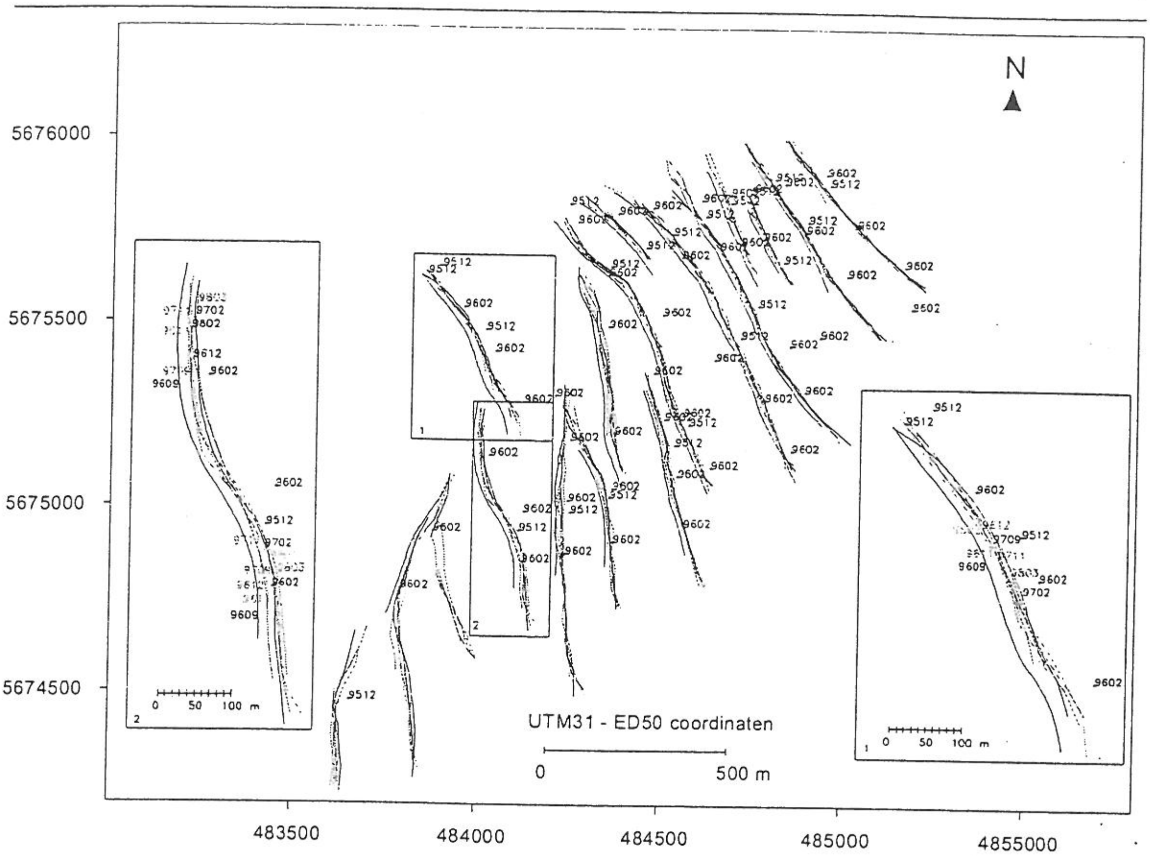

Figure 5 – *Dune migration history in the Baland Bank area (December 1995, February, September, November and December 1996, February, September and November 1997, February and March 1998).*

The differential movement observed in Figure 5 only represents the crestline, hence the zone most vulnerable to changes. This implies that these changes may merely reflect short-period reversals in the net sediment transport without taking into account the global behaviour of the bedforms. In order to better evaluate the changes between the successive campaigns, contour maps were generated for each survey and the intersurvey height changes were determined by chart differencing. Figure 6 shows the volume variations over the period September 1996 to March 1998 relative to March 1998.

Temporally, the volume changes are most interesting for the Baland Bank dune area. The September 1996 campaign is clearly lowest in volume. Although the survey was preceded by some storm depressions characterised by strong winds from a NW direction, it seemed that a period of 8 days of ENE winds of less than 6 Bf, just before the campaign, determined the morphological pattern. However, it is believed that this could only be accomplished as the area was destabilised by the NW conditions preceding the campaign. The sediment volume increased significantly afterwards as the wind blew predominantly from a SW direction. Interestingly, the majority of the sediments were deposited in the troughs and along the stoss sides of the dunes. The results of December 1996 showed a decrease in volume which was most severe for the shallow regions. Deeper than - 8 m, the volumes seem to be stable. The intersurvey period was characterised by calm weather conditions. An important increase in volume was observed between the December 1996 and February 1997 campaigns due to successive SW storms. It should be noted that the extra amount of sediment was partly deposited on top of the sediments that originated from the period in between September and November 1996. Remarkable is the strong decrease in sediment volume represented by the September 1997 results. It is however interesting that the trend resembles the results of the September 1996 campaign. The November 1997 volumes were again much higher, whilst afterwards they decreased again as is shown for the February and March 1998 campaigns. Apparently, few events of NW winds changed the residual pattern. Moreover, the winter months are generally characterised by an intense sediment transport due the combined action of currents and waves.

From the observations, there seems to be a clear relation between the morphological changes and the ruling hydro-meteorological conditions. The volume variations along the Baland Bank show that the lowest volumes are generally associated with summer to autumn conditions, whilst the winter months witness the highest volumes. The sediment volumes in the spring period likely fall within the range of both.

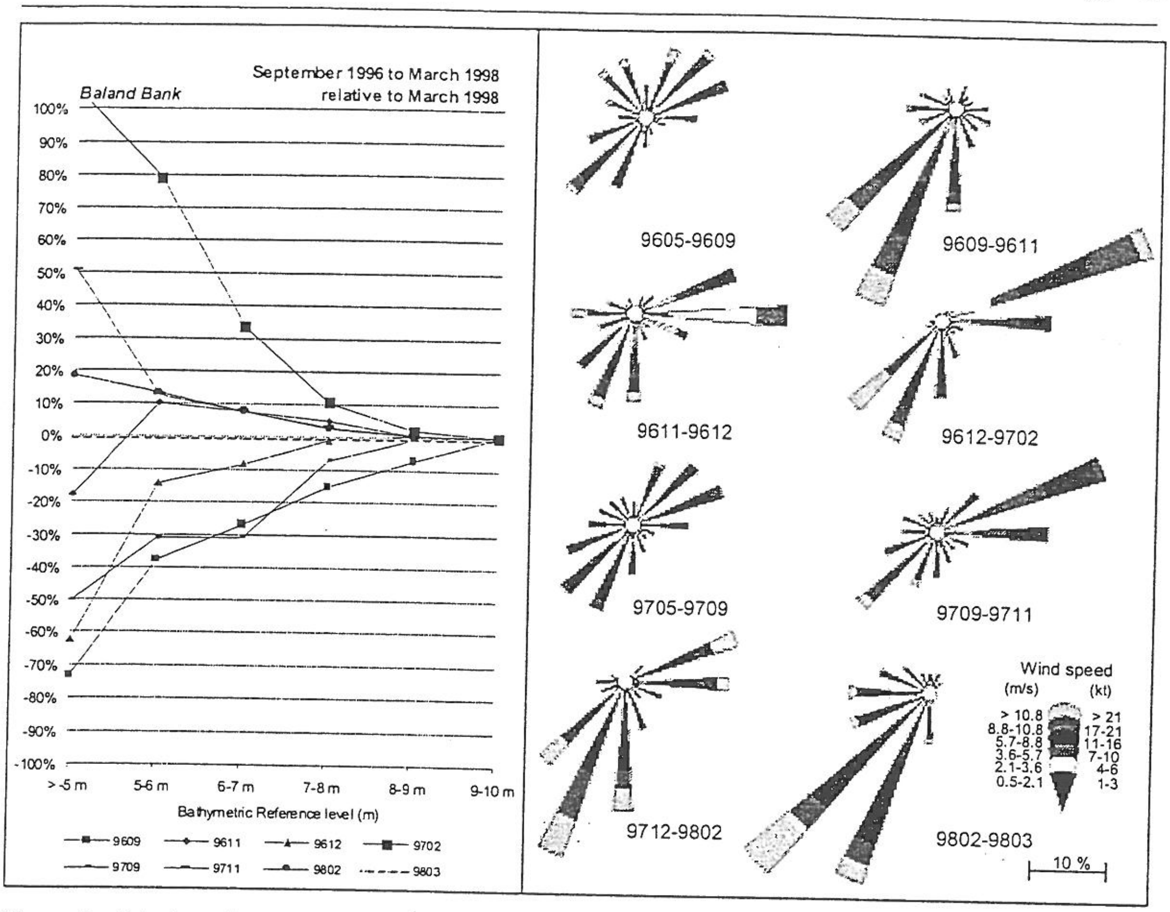

Figure 6 – *Relative volume variations in the dune area of the Baland Bank and the associated meteorological conditions.*

Related to the hydro-meteorological conditions, some conclusions can be drawn.. They are particularly supported by the observations along the Baland Bank area, but are confirmed along the other environments:

- From the observations, it seems that the smallest sediment volumes are associated with periods of NE to NNE winds. These frontal winds are merely associated with erosion, especially along the interaction zone of the near coastal area and the Flemish Bank system;
- From the morphological changes, the impact of NE to E winds can not be fully shown. Such a situation was characteristic for the winter period of 1995 – 1996. These winds likely enhance the sediment transport capacity of the ebb tidal current. If these winds persist in time, the reinforced ebb tidal currents are able to alter the bedform pattern. Still, under most circumstances, the crestlines witness the dominance of the flood current;
- Winds blowing from an E to S direction are clearly inferior; hence, they are not considered important to explain changes in morphology;
- Periods characterised by winds blowing from a SSW – SW direction are most interesting. As this wind direction aligns with the dominant flood current and with the general configuration of the swales, a lot of sediment can be advected along the swales. Generally, these situations are associated with an accumulation of sediments. However, if the current is strongly enhanced, hydraulic sorting processes are intensified. This explains the stability to slightly erosional trend along the axis of maximal force;
- Storms associated with winds from a NW direction are generally the most severe, though as their duration is mostly short, their long-term effect can be minimal. Given the height of the waves associated with such events, it seems that the areas are flattened. Although this impact can not be fully estimated, these events likely evoke a destabilisation of the environment. The period following such an event will determine the morphological evolution.