MONITORING OF A TIDAL SANDBANK: EVOLUTION OF BEDFORMS, VOLUMETRIC TRENDS, SEDIMENTOLOGICAL CHANGES

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I. INTRODUCTION

The shelf sandbanks on the Belgian Continental Platform are subject to a number of sediment dynamic processes in which tidal currents and waves play a mayor role. These processes model the environment and their impact can be evaluated from time-series of morphological and sedimentological data.

Chronosequential bathymetric and side scan sonar recordings coupled to regular sampling operations on tidal sandbanks made it possible to evaluate the volumetric evolution of sand ridges, to analyse the changes in direction of the residual bottom load fluxes, to assess the movement, growth and decline of sandwaves and to deduce changes in sedimentological characteristics.

The Laboratory of Physical Geography of the University of Gent has been studying for over a decade different shelf sandbanks. The principal results of this research programme for one of these banks, the Kwintebank, are presented in this paper.

II. ENVIRONMENTAL SETTING

1. Geometry of the bank

The Kwintebank (DE MOOR, 1985) is a shelf sandbank located on the Belgian Continental Platform between the Kwinte swale and the Negenvaam swale (fig. 1). It has a length of 25 km, a width between 1 and 3 km and a relative elevation above the seabottom of 10 to 20 m. The mean water depth varies from 6 m in the central part to more than 20 m in the northern and southern edges. Having a SSW-NNE orientation, the Kwintebank runs oblique to the coastline. The bank shows a distinct and constant transversal asymmetry (fig. 2) with a steep western slope towards the Kwinte swale. This swale reaches greater depths than the Negenvaam swale situated at the eastern side which presents a shallow threshold at its landward end.

2. Hydrodynamics

The hydrodynamics around the Kwintebank are characterized by semi-diurnal tides of megatidal range with a distinct difference between neap and spring tidal range. Near to the coast, situated at about 25 km, the mean tidal range reaches 4.5 m. The average tidal movement corresponds to an elongated current ellipse with a southwest-northeast axis. The general direction of the flood peak and ebb peak currents are approximately from southwest to northeast and from northeast to southwest respectively. The velocity of the surface peak currents reaches up to 2 Kts (VAN CAUWENBERGHE, 1981).

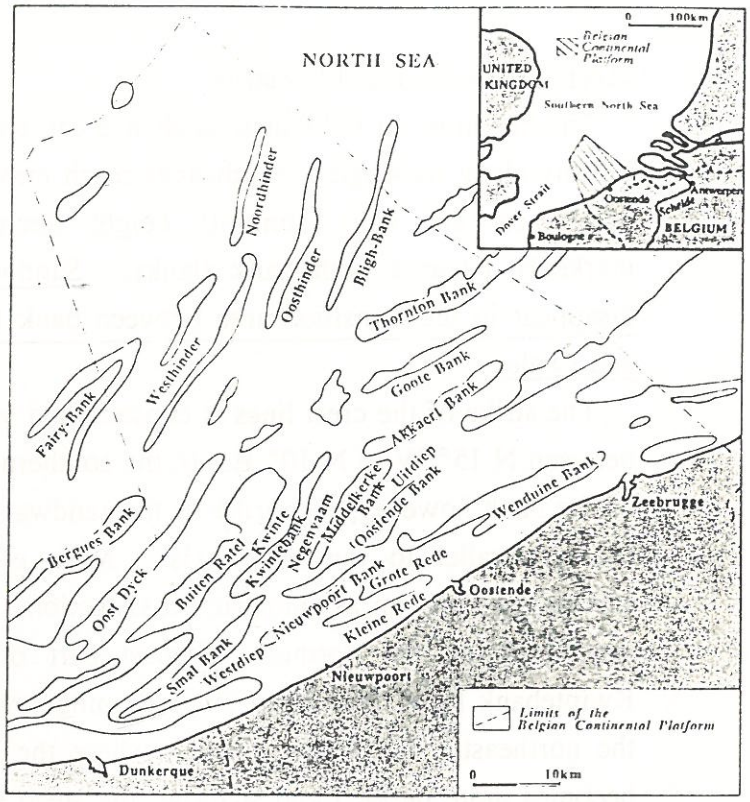

Fig. 1. : The Kwintebank and the Belgian Continental Platform.

3. Bedforms

a) *Sandwaves*

Sandwaves occur in well defined fields on the flanks and summit of the Kwintebank, especially on its northern and southern edge (fig. 3) (DE MOOR and LANCKNEUS, 1988). No sandwaves occur on the central part of the bank. The sandwaves on the bank have a length of several hundreds of metres, a width of several tens of metres and a height

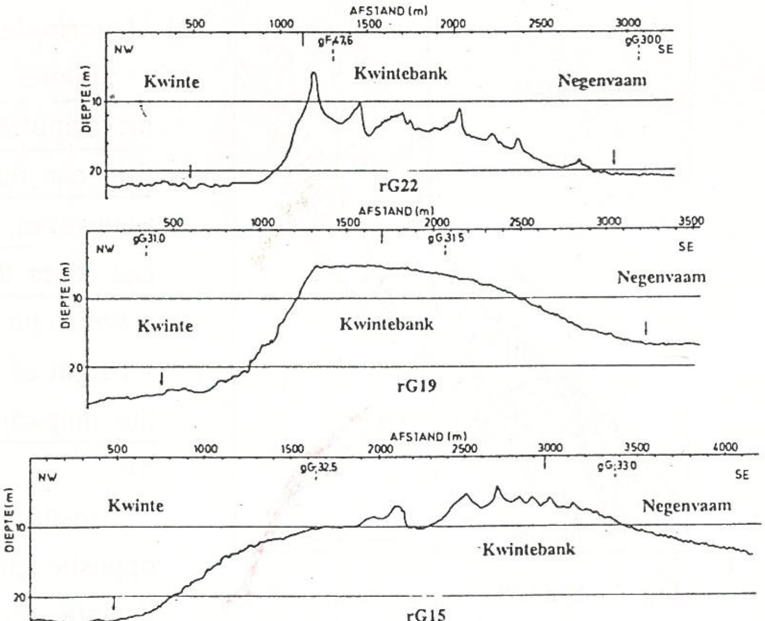

Fig. 2. : Bathymetric profiles across the northern, the central and the southern part of the Kwintebank.

varying between 1 and 8 metres.

The height of an individual sandwave can change notably along its length. Sandwaves reach maximal height on the bank summit; height decreases markedly towards both bank flanks. Sandwaves disappear in the transition area between bank flank and swale.

The strike of the crest lines is constant and varies between N 15° W to N 10° E. In the southern part of the bank however, the strike of the sandwaves is nearly parallel to the bank axis. Most of the sandwaves show an asymmetric cross-section. The sandwaves on the northern, deepest part of the Kwintebank have their steep slope dipping towards the northeast. Towards the south where the bank becomes more defined and shallow, the steep slope of the sandwaves dips generally towards the east on the western flank and towards the west on the eastern flank. Exceptions occur on both flanks. Symmetric sandwaves can be detected as well between both types of asymmetric structures.

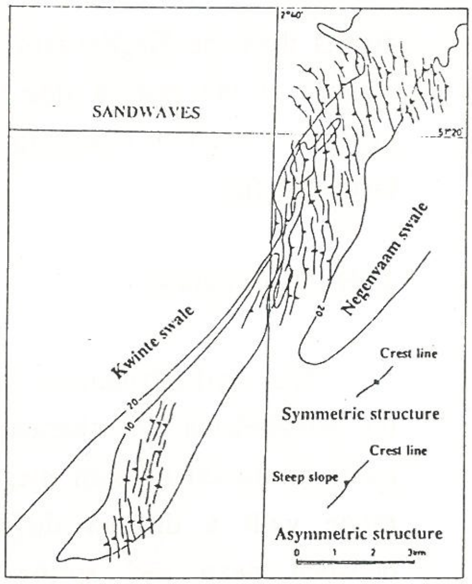

Fig. 3 : Synthetic representation of the sandwaves on the Kwintebank based on bathymetric data and sonographs collected between 1983 and 1990.

There are about no sandwaves in the adjacent swales with the exception of the northern edge of the Kwinte swale where some of them occur with a NW-SE orientation and steep slopes dipping to the north.

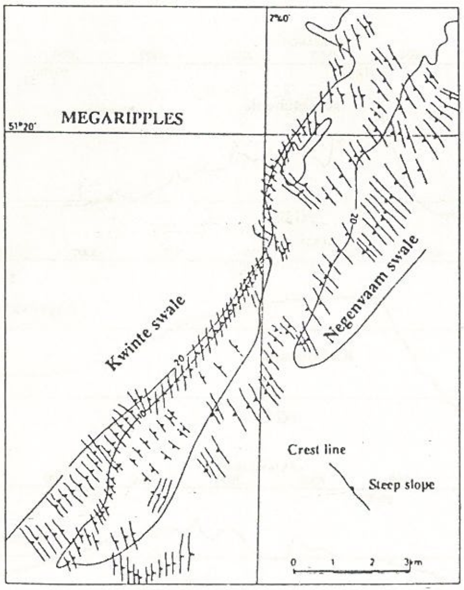

Fig. 4 : Synthetic representation of the megaripples on the Kwintebank and in a part of the adjacent swales based on sonographs collected between 1983 and 1990.

b) Megaripples

Smaller bedforms, commonly named megaripples, are found on the Kwintebank, where they can mantle the stoss and/or steep slope of the sandwaves, and in the adjacent swales, where they can cover the flat seabottom (fig. 4). They have a wavelength varying between one and ten metres and a height of some tens of centimetres. The strike of the megaripples in the swales is dominantly NW-SE.

Mostly, the asymmetry of the megaripples is opposite on both sides of the Kwintebank. In the Kwinte swale the steep slopes of the megaripples dip to the northeast while in the Negenvaam swale they dip to the southwest. On both flanks of the bank, the megaripples are deflected towards the crest line of the bank. Their steep slope is generally directed towards the bank summit. Megaripples occur as well on the bank summit with an orientation nearly perpendicular to the bank's axis and with steep slopes dipping either to the northeast or to the southwest (DE MOOR and LANCKNEUS, 1990).

III. METHOD

1. Monitoring of volumetric changes

In order to monitor the volumetric changes of the Kwintebank, sequential bathymetric profiles are sailed at 10 Kts along a number of reference tracks which correspond to loxodroms between fixed start and end points situated upon red Decca lines of the 5 B network (fig. 5) (DE MOOR et al., 1989). These reference lines were sailed three to five times per year during nearly ten years.

Navigation and positioning have been based on Decca and Toran up to 1987 and on Syledis since 1988. The bathymetric recordings are realised with a Atlas Deso XX echosounder. The registrations were recorded in analog form after which they were digitized with the help of a digitalization tablet up to 1991. Since 1992, depth and positioning data are recorded digitally twice per second by the ship's HP1000 computer using the ODAS acquisition programme, developed by the Management Unit of the Mathematical Model North Sea.

The raw bathymetric data are processed by the laboratory computer. The processing comprises tidal reduction (VAN CAUWENBERGHE, 1977) and corrections for variations in the ship's velocity and heading. Net bathymetric profiles are then plotted in relation to a zero level which corresponds to the local MLLSS.

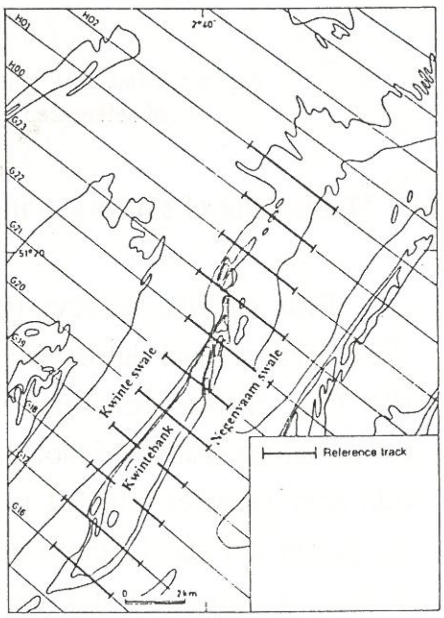

Fig. 5 : Reference tracks across the Kwintebank.

In order to monitor the volumetric evolution of a sandbank, a numeric method was developed. Unit volumes were defined corresponding to the volumes determined by the surface of a transversal bank cross section with a width of 1 m. These surfaces are delimited by the bank profile and by the intersecting line with reference planes, situated at intervals of 2.5 m beneath the zero reference level. Two unit volumes will be considered in this paper. The total bank unit volume corresponds to the volume defined by the lowest reference plane intersecting the bank above the highest base concavity; the top slice unit volume is defined at the bottom by the highest reference plane intersecting the bank.

Such unit volumes are calculated per reference line and per registration datum. These volumes can be displayed in a graphical way as on figure 6 which represents the total bank unit volumes based on data from 1983 to 1992 along a number of reference tracks. Regression analysis is then applied to the time-series of unit volumetric data for each reference transversal. This analysis provides values for the mean annual change of the unit volume expressed in absolute values ($m^3/m/y$) and in relative values (%/year). These relative values are obtained by normalizing the absolute values in relation to a reference unit volume, corresponding to the volume on the linear trend line of the first recording data of the time series.

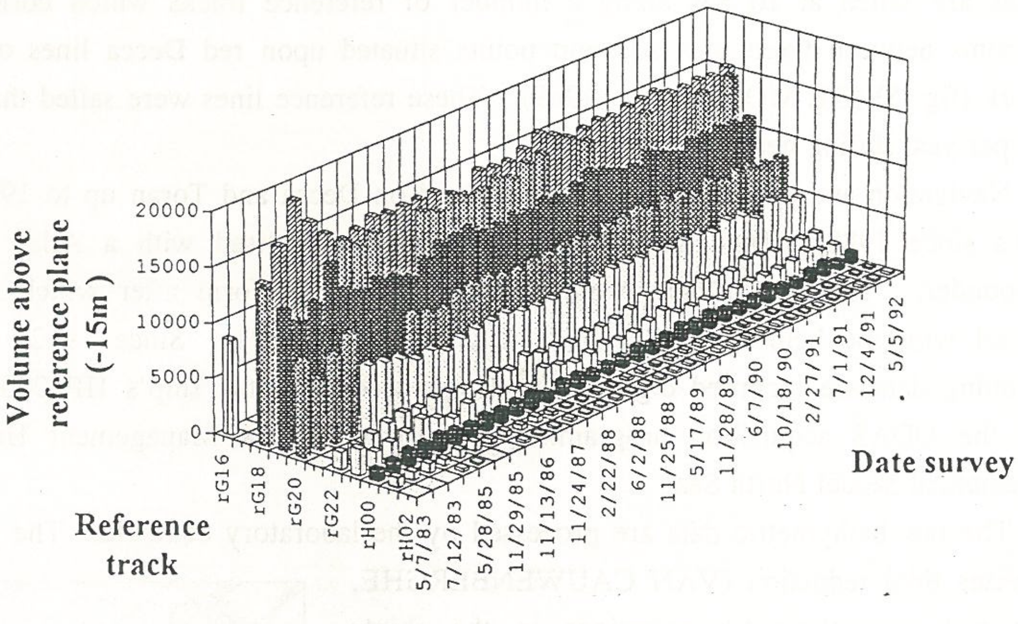

Fig. 6 : Total bank unit volumes based on data from 1983 to 1992 along a number of reference tracks across the Kwintebank

2. Monitoring of sandwave movement

Four detailed surveys (February 1989, June 1989, November 1989 and February 1991) were carried out on the northern Kwintebank between the red Decca lines H02 and H01 (fig. 7) using echosounder and side scan sonar equipment. Each survey was carried out in approximately 15 hours. The sonographs were obtained with a Klein dual-channel side scan recorder coupled to a 500 kHz transducer. During the four survey periods, navigation and positioning were performed by the Syledis system with a positional accuracy of 3 m. A ship speed of 5 Kts was maintained during the operations.

The recordings were made along tracks 141 m apart which allowed a complete sonograph coverage of an area of 5.500 m by 1.500 m. The sonographs were processed into an isometric representation of the seafloor according to FLEMMING (1976). The position of the crest lines and of the basal concavities, the height of the crests and the asymmetry of the sandwaves were drawn on maps of a scale of 1/5.000 (fig. 8) (LANCKNEUS and DE MOOR, 1991).

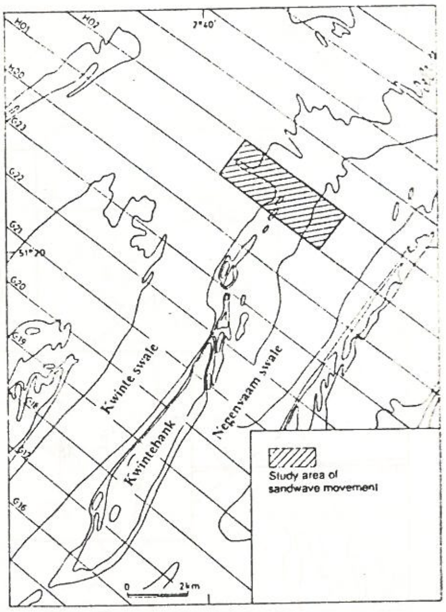

Fig. 7 : The survey area on the northern Kwintebank selected for the study of the sandwave movement.

3. Monitoring of the residual sediment transport paths

The residual sediment transport paths on and near the Kwintebank were analysed by recording sonographs along the same reference tracks which are used for the bathymetric recordings (fig. 5) (LANCKNEUS et al., 1989). Sonograph registrations along these tracks were realised in May 1983, November 1986, November 1987 and February 1991. Echosounder, side scan sonar and positioning equipment were used as described here above.

Residual transport paths can be deduced from the strike and asymmetry from either sandwaves (CASTON 1972) or megaripples (McCAVE & LANGHORNE, 1982). Megaripples on the Kwintebank are usually oriented at an oblique angle to the sandwaves with a divergence of approximately 35°. If we superimpose data from three current meters, deployed on the northern Kwintebank in the period of April 1991, on the bedform characteristics which were deduced from sonographs recorded in November 1989, we see distinctly that only the megaripples' are oriented nearly perpendicular to the direction of the flood peak currents (fig. 9) (LANCKNEUS and DE MOOR, 1992). As there is no indication that the directions of the peak currents change significantly in time and as the

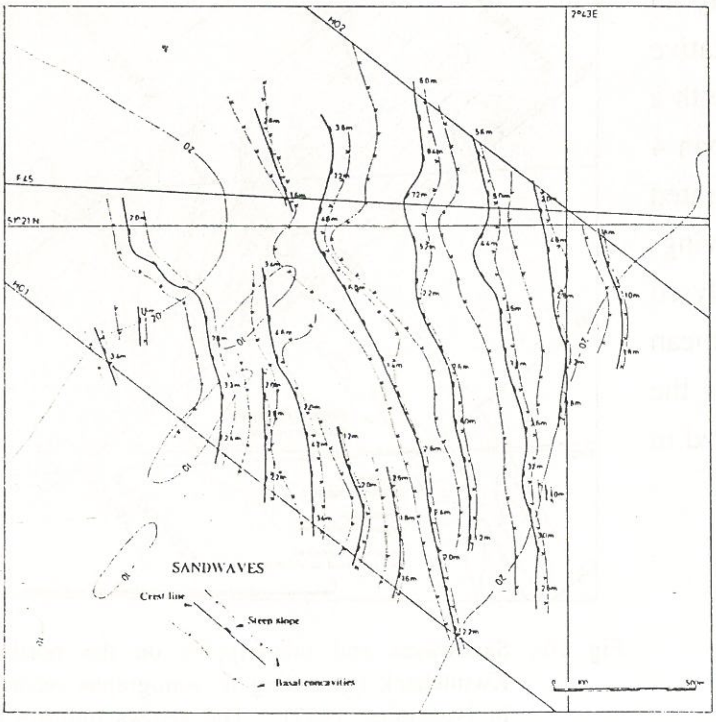

Fig. 8 : Example of a detailed sandwave map deduced from the sonographs recorded in June 1989.

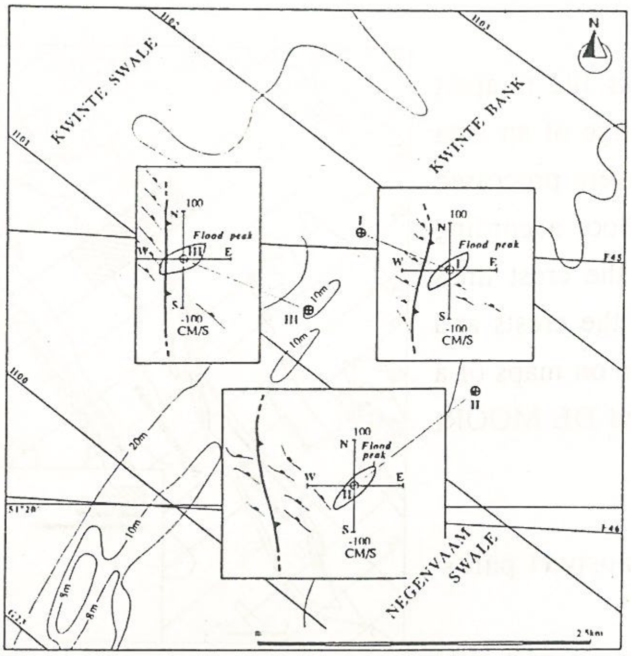

Fig. 9 : Current ellipses and strike of sandwaves and megaripples in the vicinity of the current meter mooring sites on the northern Kwintebank.

direction of the net sediment displacement generally corresponds to that of the more intense current (JOHNSON et al., 1981), we will base our residual sediment transport analysis on the strike and asymmetry of the megaripples.

Figure 10 gives an example of the deduction of the residual sediment transport paths from the geometric characteristics of megaripples.

4. Monitoring the grain-size changes

The superficial sediment of the northern Kwintebank (fig. 11) (LANCKNEUS, 1989) was sampled in November 1989 and in June 1991. During each sampling campaign, eighty four samples were collected with a Van Veen bottom sampler (fig. 12). The exact location of the samples was deduced from the Syledis position which was recalculated taking into account the longitudinal and transversal translation from the Syledis antenna to the Van Veen bottom sampler.

The samples, consisting of ± 2 kg of sediment, were dried at room temperature. A small representative sample of ± 200 gr was separated with a sample splitter. Fractions coarser than 4 mm and finer than 50 μm were separated respectively by dry and by wet sieving. The sand fraction was further analysed by dry sieving. The results of the mean values (FOLK & WARD, 1957) and the gravel content (>4 mm) are presented in this paper.

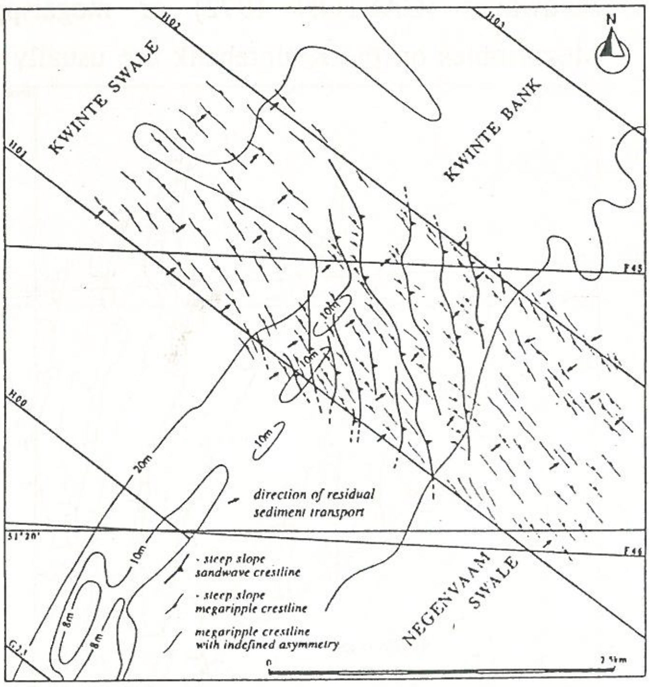

Fig. 10 : Sandwaves and megaripples on the northern Kwintebank (according to sonographs recorded in November 1989). The arrows indicate the directions of the residual sediment transport based on megaripples.

IV. RESULTS

1. Volumetric evolution

a) Total bank evolution

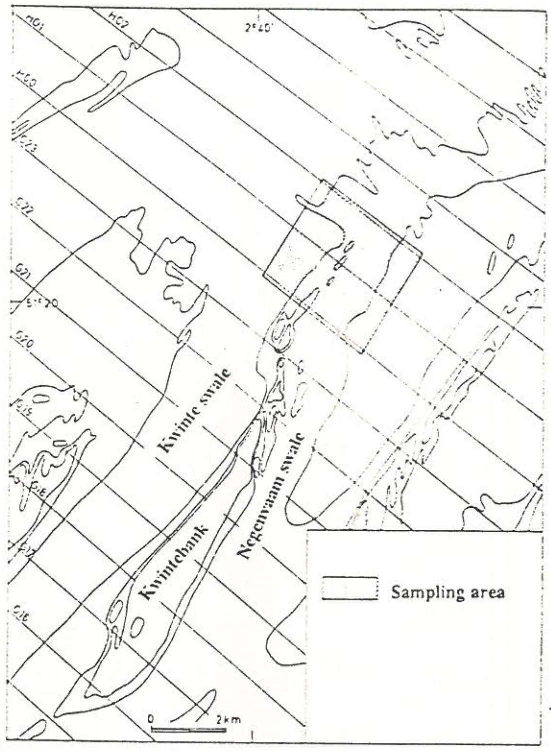

Fig. 11 : Sampling area on the Kwintebank

The mean annual change of the absolute total bank unit volume along the successive reference tracks is shown in figure 13a. Sediment losses occur nearly along all reference lines. Small gains are situated along the lines H00 and G22. The impact of these gains and losses upon the morphology of the bank can be represented by the mean annual change of the relative total bank unit volumes (fig. 13b). All values, except for one along the most northern reference line, vary between -1% and +1%. These figures indicate that the total bank volume can be considered as stable during the last ten years.

b) Evolution of the bank top

Evolution of the bank top slice is shown by the mean annual change of the absolute unit volume of the bank top slice along the reference lines (fig. 14a). On the northern part of the Kwintebank, the bank shows a general sediment loss, which is, if compared with the relative figures of figure 14b, quite important. South of this area, a section exists with relative high gains. The central and southern part of the bank do not show a significant evolution. The loss in the northern part could be explained by sand dredging activities which are important in this area.

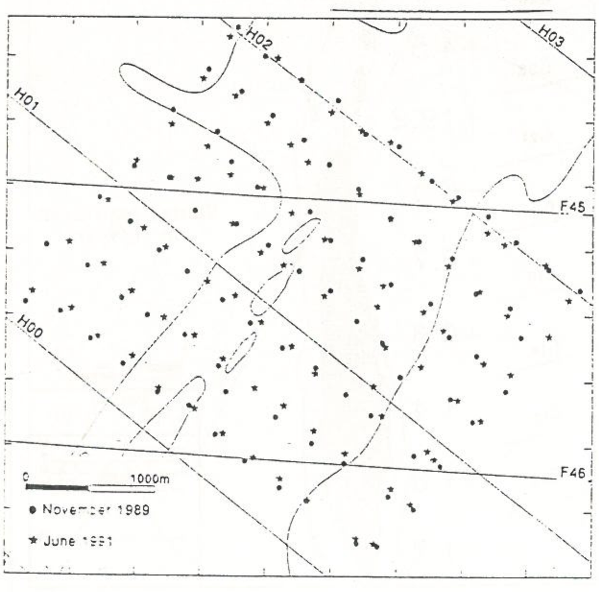

Fig. 12 : Sampling grids of November 1989 and June 1991.

c) Height difference map

Analysis of the volumetric evolution of the bank can be realised too with height difference maps. Figure 15 shows such a map realised with bathymetric data acquired in February and June 1989 along lines 140 m apart. The map indicates an accretion in the western part of the bank while erosion

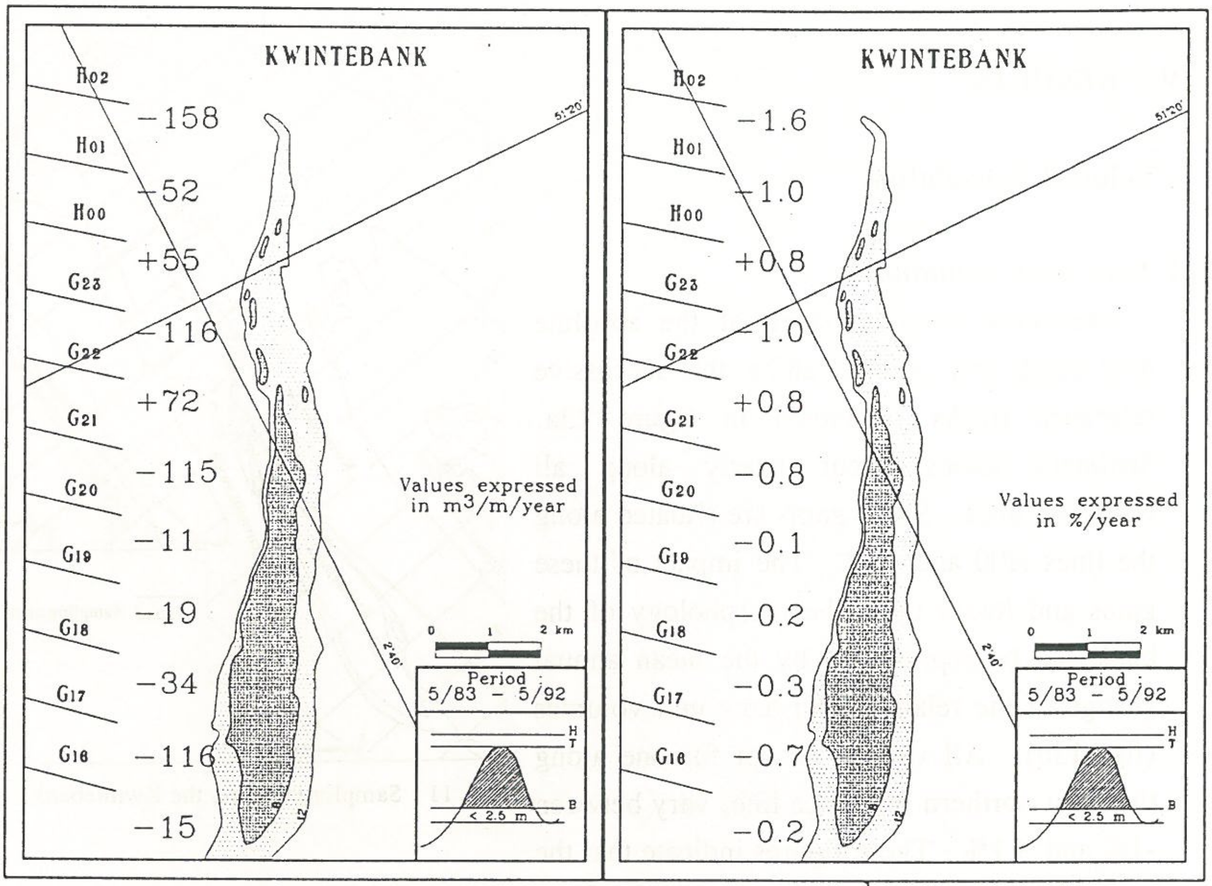

Fig. 13. Mean annual change of the total bank unit volume in the period May 1983–May 1992 expressed in absolute (a) and relative (b) units.

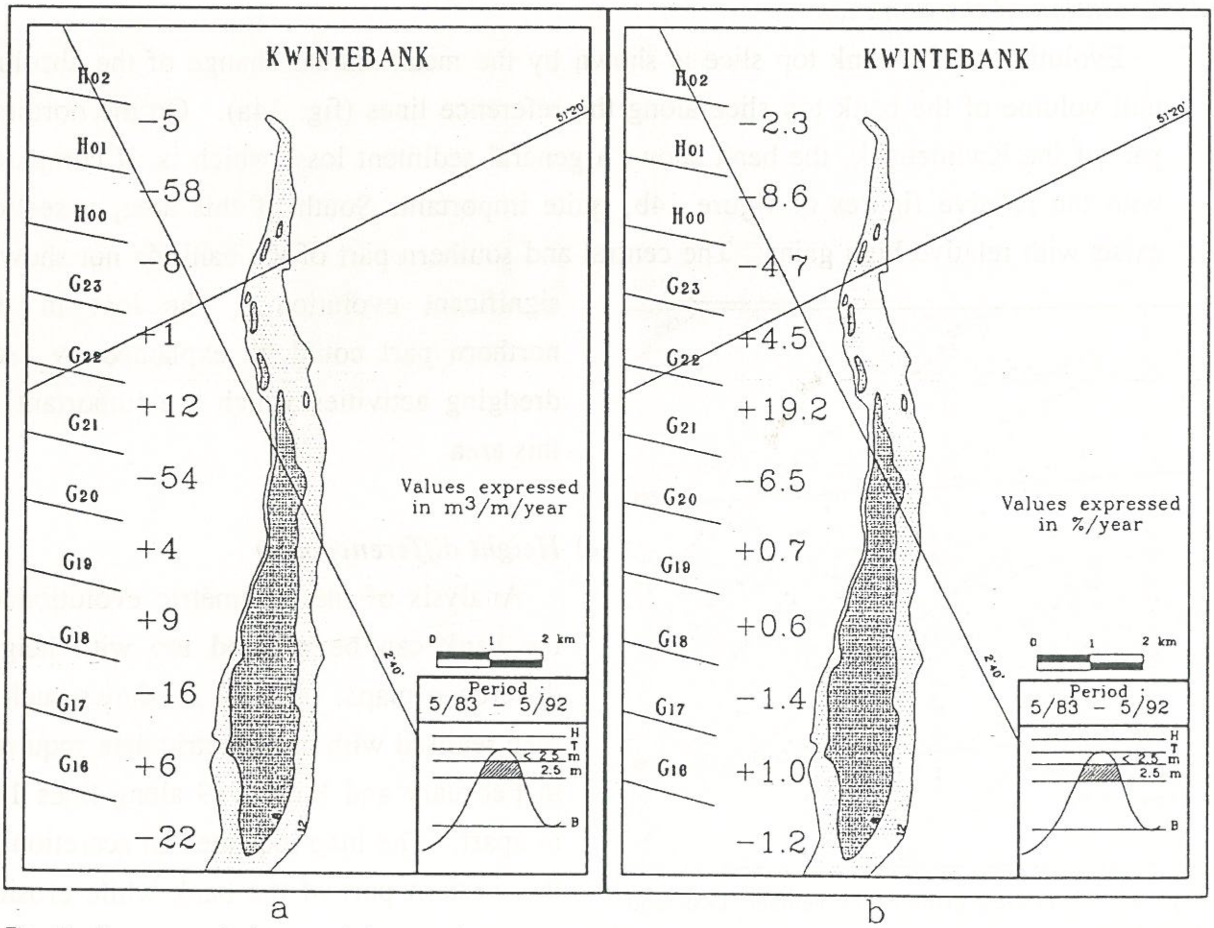

Fig. 14. Mean annual change of the top slice unit volume in the period May 1983–May 1992 expressed in absolute (a) and relative (b) units.

occurs in some sections of the central and eastern part of the bank.

2. Sandwave movement

a) Movement between February 1989 and June 1989 (fig. 16).

The general characteristics of the sandwaves such as strike and asymmetry remained unchanged. However, the position of the sandwaves and the height of the crest lines were subject to changes during this period. All sandwaves show a net movement of the crest positions over an average horizontal distance of 30 m towards the west. Small variations in the amplitude of the crestal movement occur along the length of the individual features. Notable here is that the movement of the sandwaves occurred in the direction of their gentle slope. The length of some smaller structures decreased or increased by 100 to 200 m. The height of the sandwaves changed as well. Table 1 gives an overview of the differences in heights which were detected along the four most easterly sandwaves (fig. 16). A general increase of height can be noted which can reach locally 2.2 m.

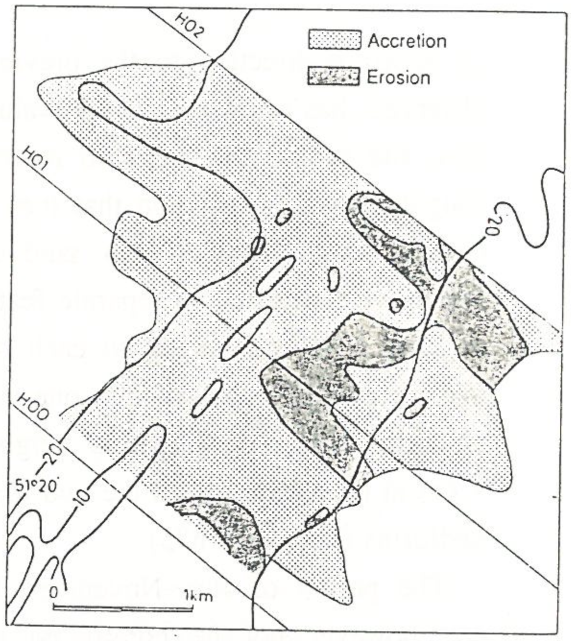

Fig. 15 : Height difference map of the northern Kwintebank deduced from bathymetric data recorded in February and June 1989.

b) Movement between June 1989 and November 1989 (fig.17)

	Febr.89 - June89		June89 - Nov.89		Nov89 - Feb.91		Feb.89 - Feb.91	
Sandwave n°	Max.height difference	Mean height diff.	Max.height difference	Mean height diff.	Max.height difference	Mean height diff.	Max.height difference	Mean height diff.
1	+2.2 m	0.0 m	-2.2 m	-0.2 m	+2.0 m	+0.1 m	+2.0 m	+0.5 m
2	+0.8 m	+0.2 m	-1.2 m	-0.1 m	+1.6 m	+0.3 m	+1.0 m	+0.4 m
3	+0.8 m	-0.1 m	+1.4 m	+0.9 m	-1.2 m	-0.1 m	+1.1 m	+0.5 m
4	+1.1 m	+0.5 m	+0.2 m	+0.2 m	-0.7 m	-0.7 m	+0.6 m	+0.3 m

Table 1: Maximum and mean height differences of sandwave crest lines between February 1989 and June 1989, June 1989 and November 1989, November 1989 and February 1991, February 1989 and February 1991

During this period the sandwaves kept their general characteristics unchanged as well, but this time shifting of the crestlines was generally towards the east. This movement, in an opposite direction to the previously observed, has again an average value of 30m and caused the crests to return to roughly the same position that they had eleven months ago. Two sandwaves which were detected as separate features in June 1989, converged to each other and were finally merged into one single structure which developed a height of 4.4m in the area between the two former bedforms (sandwave n°5).

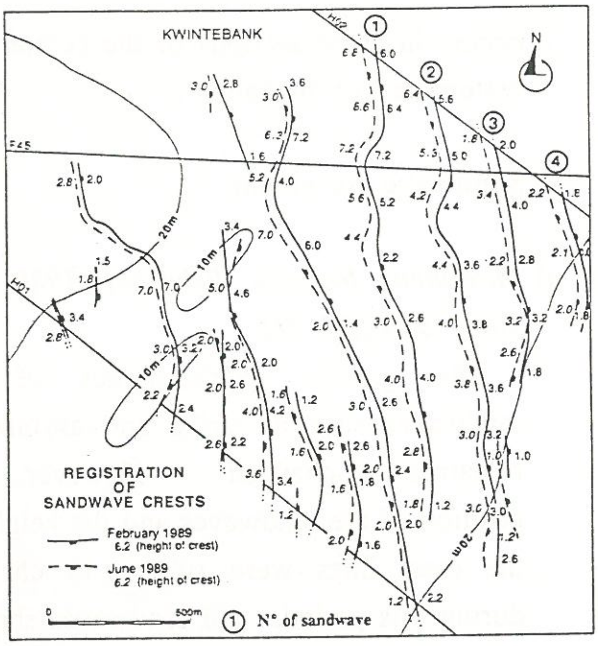

Fig. 16 : Position of crest lines of sandwaves on the northern Kwintebank in February and June 1989. Heights of sandwaves were deduced from echosounding recordings.

The period of June-November 1989 can however not be considered as a period of general sandwave growth as for example the southern edge of the most eastern feature in the study area decreased several hundreds metres in length (sandwave n°4). Changes in sandwave height occur as well (table 1): the height of the two most easterly sandwaves is still increasing while sandwaves 1 and 2 suffer a decrease in height.

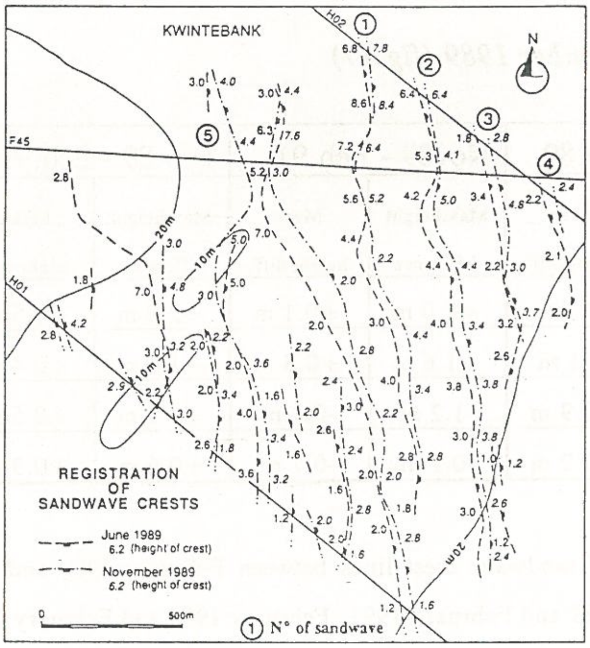

Fig.17: Position of crestlines of sandwaves on the northern Kwintebank in June and November 1989. Heights of sandwaves were deduced from echosounding recordings.

c) Movement between November 1989 and February 1991 (fig. 18)

Once more, few important changes occurred from November 1989 to February 1991 and the majority of the features can easily be recognized. A new shifting of the sandwave crests of the order of 30 to 50 m occurred towards the west. The most easterly sandwave (sandwave n°1) whose length decreased considerably in the former period of observation, grew once more towards the south in a quite significant way as its height reaches 2.4m in this new extension. A substantial development of the sandwaves is visible too in the western part where an existing sandwave (n° 6) grew several hundreds meters into the adjacent swale where a complete new feature (n° 7) developed as well. At the same time the northern extremity of sandwave 8 was subject to branching.

For the first time in the two-year observation period we note a change in asymmetry along certain sections of some sandwaves. The steep slopes of the majority of the sandwaves remain however oriented towards the northeast. The height of sandwaves 3 and 4 decreased in a general way while sandwaves 1 and 2 were subject to a slight increase of their heights.

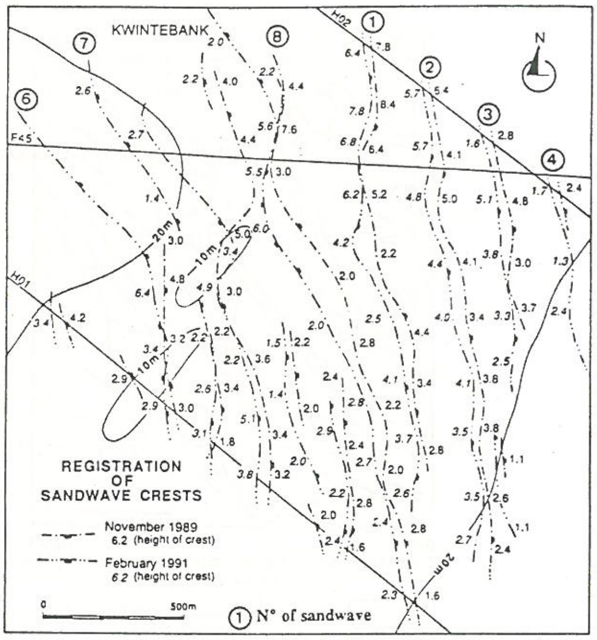

Fig. 18 : Position of crestlines of sandwaves in the northern Kwintebank in November 1989 and February 1991. Heights of sandwaves were deduced from echosounding recordings.

d) Movement between February 1989 and February 1991 (fig. 19)

Fig. 19 displays the net movement of the sandwave crests in the period between February 1989 and February 1991. The changes the sandwaves suffered in this two-year period are minor and consist of a shifting of the crestlines towards the west of the order of some tens of metres. In the western part of the study area a new sandwave (n° 7) appeared with a recorded maximum height of 2.6 m. The length of the northern extremities of two sandwaves (n° 6 and 9) increased several hundreds of metres into the western swale. The height of the sandwaves (table 1) increased in a general way with a mean value of 0.5m.

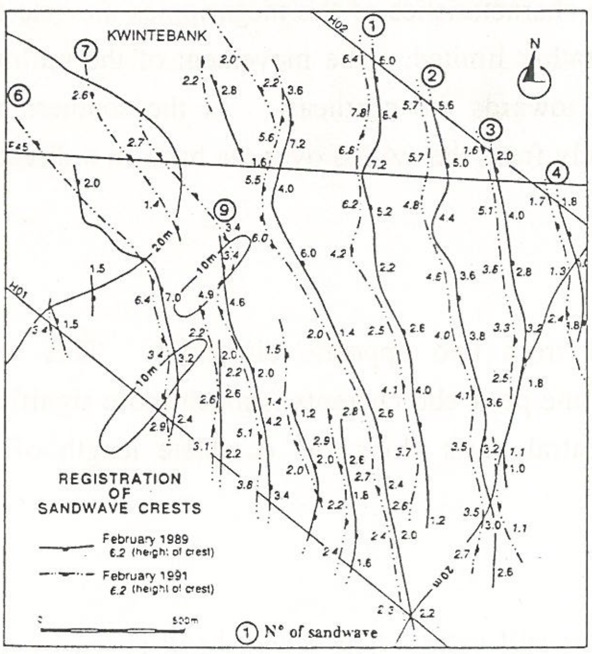

Fig. 19 : Position of crestlines of sandwaves in the northern Kwintebank in February 1989 and February 1991. Heights of sandwaves were deduced from echosounding recordings.

3. Residual sediment transport paths

a) Situation in May 1983 (fig. 20)

In the eastern part of the Kwinte swale the residual sand transport is

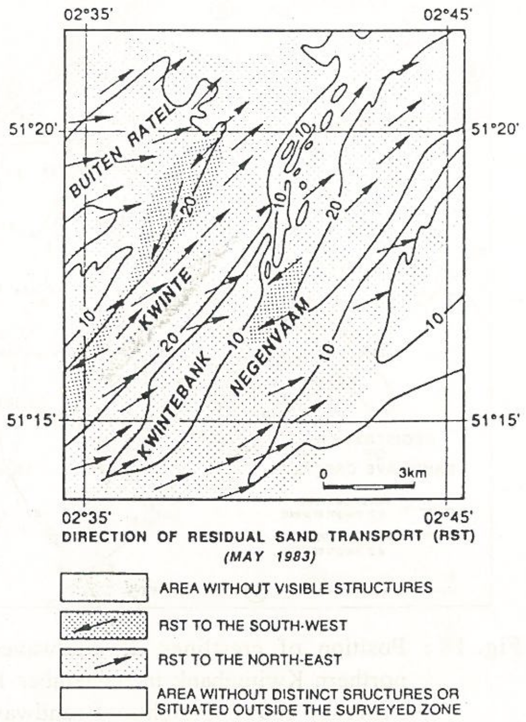

Fig. 20 : Directions of residual sand transport on the Kwintebank based on sonographs recorded in May 1983.

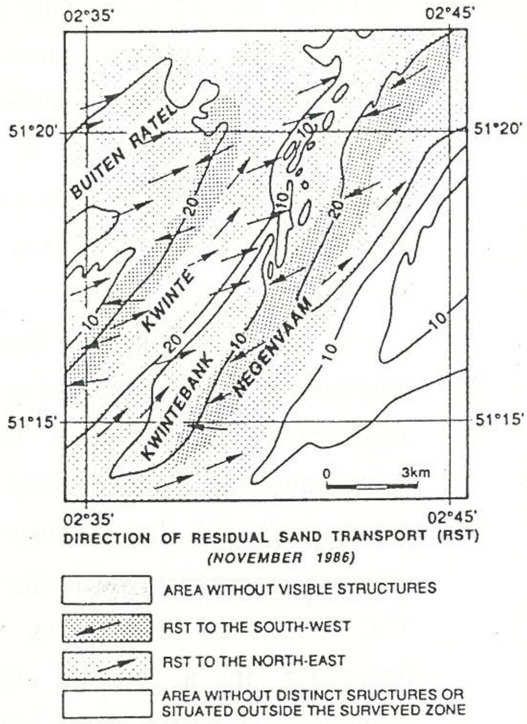

Fig. 21 : Directions of residual sand transport on the Kwintebank based on sonographs recorded in November 1986.

commanded by the peak flood currents from the southwest. The peak ebb currents, directed towards the southwest, are responsible for a residual sand transport in a small central section of the Negenvaam. The Kwintebank receives sand from both adjacent swales in opposite directions although the characteristics of the megaripples indicate that the contribution from the Negenvaam is rather limited. The movement of the sediment on the summit of the bank is restricted towards the northeast. At the southern and northern edges sediment is passing obliquely from the swales over the bank in a direction from southwest to northeast.

b) Situation in November 1986 (fig.21)

Again the Kwintebank receives sand from two opposite directions. This time, however, the flux of sand commanded by the peak ebb currents is much more significant causing a sand uppiling towards the central parts along the complete length of the Kwintebank.

c) Situation in November 1987 (fig. 22)

Our general model of sand movement is still valid. The Kwintebank is fed by sand coming from both adjacent swales in opposite directions.

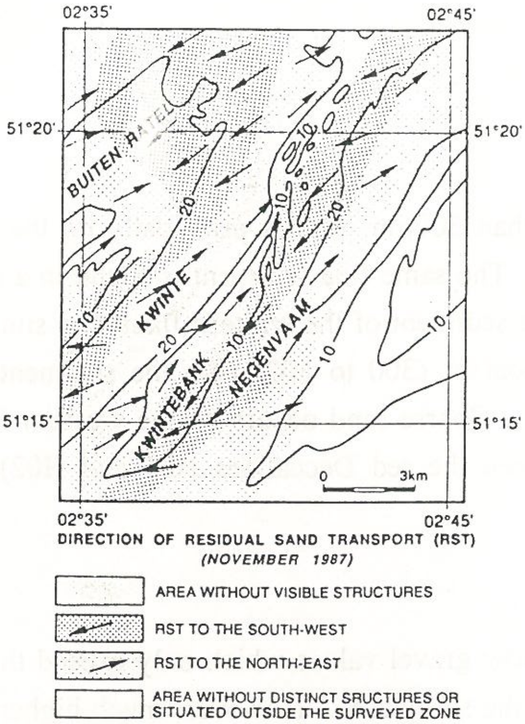

Fig. 22 : Directions of residual sand transport on the Kwintebank based on sonographs recorded in November 1987.

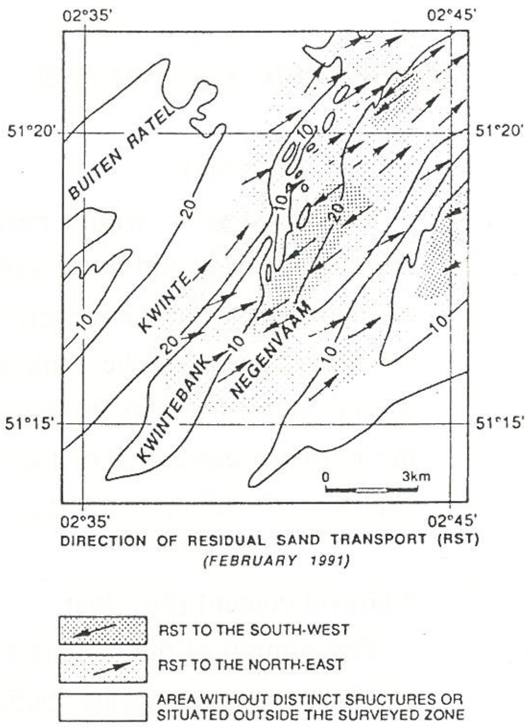

Fig. 23 : Directions of residual sand transport on the Kwintebank based on sonographs recorded in February 1991.

Clear evidence exists as well which stresses the importance of longitudinal transport of sand on the bank summit. This transport is dominantly southwestward in the deeper northern part of the bank. In the central and southern part, sand is processed longitudinally along two paths, one to the northeast (western path) and one towards the southwest (eastern path). The influence of the peak ebb currents is moreover still much more significant than in November 1986. This is demonstrated for example by the presence of a clear sand transport towards the southwest on the northern edge of the Buiten Ratel, an adjacent bank.

d) Situation in February 1991 (fig. 23)

The situation in February 1991 is similar to the one observed in May 1983. Again the peak flood currents dominate the residual sediment transport. The residual sediment transport towards the southwest is merely restricted to two areas located on the eastern flank of the Kwintebank.

4. Grain-size changes

a) *Situation in November 1989*

* Mean (fig. 24a)

The finest sand, with a mean smaller than 300μm, occurs principally on the eastern flank of the bank and in the eastern swale. The same fine sediment is found in a number of small patches in the western swale. The sediment of the western flank and situated on the western part of the bank summit is coarser (300 to 500μm) ; the sediment in the Kwinte swale presents the same grain-size. Coarse sand occurs on the western flank of the northern extremity of the bank (between the red Deccalines H01 and H02) where values are found up to 1500μm.

* Gravel content (fig. 25a)

The summit of the bank has extremely low gravel values which only exceed the value of 1% in one patch in the southern part of the study area. However, much higher values are found on the western bank flank where gravel is concentrated in a narrow, elongated ribbon parallel to the axis of the bank. Values up to 12% were detected in the northern section of this ribbon which corresponds to the area with the coarsest sand. Both Kwinte and Negenvaam swales present areas with slightly higher gravel contents.

b) *Situation in June 1991*

* Mean (fig. 24b)

The mean of the sediments from June 1991 show a strong similarity with the grain-size situation as observed in November 1989. The major difference lies in the splitting up of the northwestern patch of coarse sediment into two smaller spots which correspond to maximum grain-size values of 700 to 900 μm.

* Gravel content (fig. 25b)

The gravel content of the western flank of the bank decreased in a general way. Small local additional spots of higher gravel contents appeared on the bank summit. Slightly higher gravel values were found too in the eastern swale.

c) *Difference maps*

* Mean (fig. 26a)

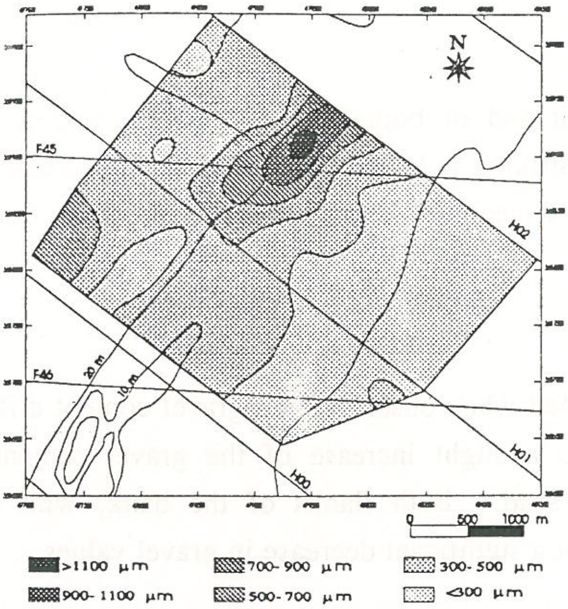

Fig. 24a : Mean (November 1989)

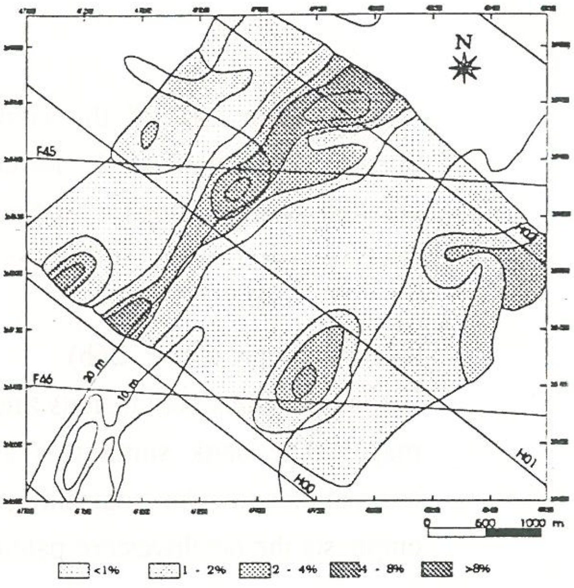

Fig. 25a : Gravel Content (November 1989)

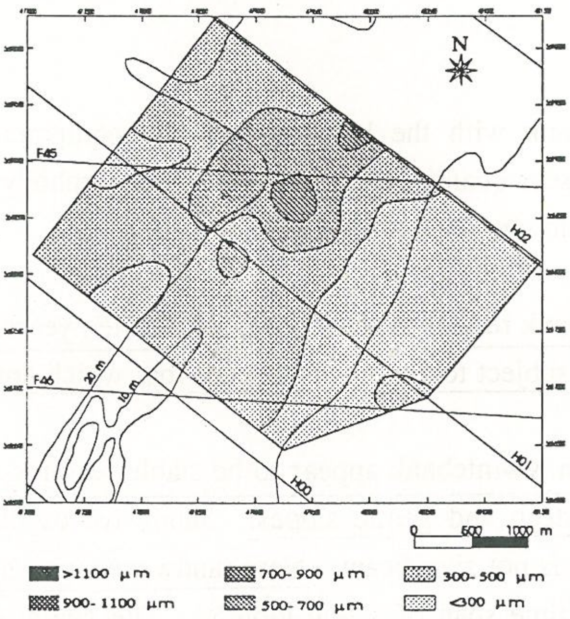

Fig. 24b : Mean (June 1991)

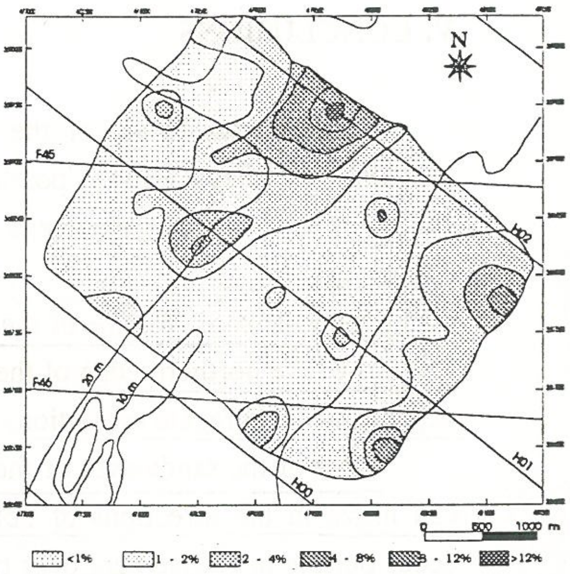

Fig. 25b : Gravel Content (June 1991)

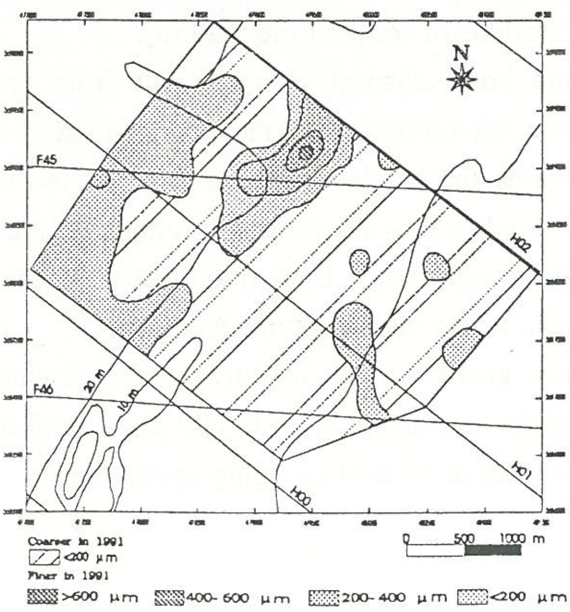

Fig. 26a : Difference map mean (November 1989 - June 1991)

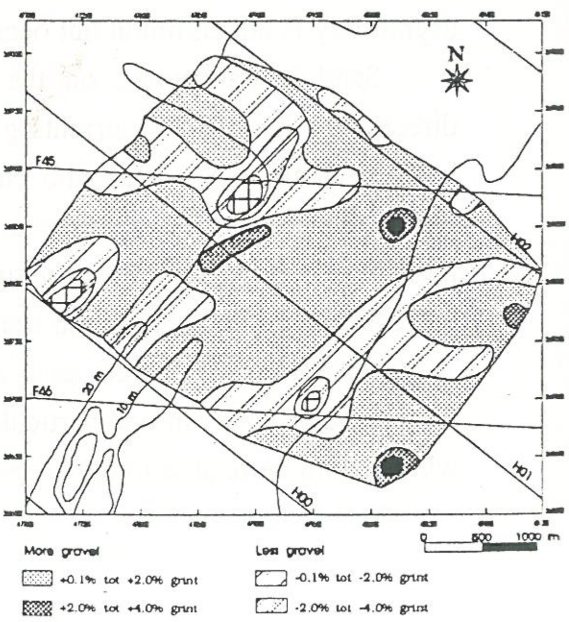

Fig. 26b : Difference map gravel content (November 1989 - June 1991)

The major part of the bank summit and of both flanks are characterized by the presence of coarser sand. Much more striking is however the grain-size decrease in the northwestern patch where sediments show mean grain-size values up to 600μm finer than the ones observed in November 1989.

* Gravel content (fig. 26b)

The previous conclusions are confirmed when observing the gravel content difference map. The bank summit is subject to a slight increase of the gravel content what corresponds to the coarsening of the sand. Both flanks of the bank, with special emphasis the northwestern patch, present a significant decrease in gravel values.

V. CONCLUSIONS

Detailed monitoring of the Kwintebank with the help of geosonic equipment and sampling operations made it possible to assess quantitatively a number of morphodynamic and sediment dynamic phenomena. The following conclusions can be made :

The total bank volume of the Kwintebank remained stable over the last ten years. The top part of the northern edge of the bank is subject to a quite significant loss which could be explained by aggregate extraction.

Most of the sandwaves of the northern Kwintebank appear to be stable features which can move in the directions of both their steep and gentle slopes. Sandwave oscillations occur but the net movement over two years is not significant. New sandwaves with heights up to 4.5m can develop or disappear in a time span of a few months. The height of the sandwave crest can easily increase or decrease with 2m in that period. Change in asymmetry is not common but occurs along sections of some of the features.

Sand is transported on the bank from both adjacent channels but from opposite directions. Peak flood currents give rise to a net northeasterly movement of sand on the western flank, while peak ebb currents towards the southwest move sand on the eastern flank. The extension of the areas in which sand is moving residually either by the flood peak or ebb peak currents vary significantly through time. Both flood peak and ebb peak currents can dominate the sand transport on and in the vicinity of the bank.

Grain-size parameters such as mean and gravel content on the northern Kwintebank vary through time. In one particular area a grain-size decrease up to 600 μm was observed, which could be related to either seasonal processes or to sand dredging operations.

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