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Shallowing of the Blankenberge harbour entrance: morphodynamical evolution and sediment transport processes

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SUMMARY

The shallowing of the Blankenberge harbour-entrance channel is caused by a complex of interacting coastal processes with different intensities at different places within the Belgian coastal zone. The channel, which is perpendicular to the shore, forms an obstacle to longshore eolian and aquatic sediment movement. There is a clear mutual interaction between the choking of the channel and the nearby beach dynamics. The research highlights the importance of net longshore sediment transport, both eolian and aquatic, in this part of the Belgian coast. It shows that important quantities of sand are moved in relatively short periods of time.

SAMENVATTING *Aanzanding in de havengeul te Blankenberge - Morfodynamische evolutie en sedimenttransportprocessen.*

De aanzanding van de Blankenbergse havengeul wordt veroorzaakt door een complex geheel van elkaar beïnvloedende kustprocessen die met verschillende intensiteiten op verschillende plaatsen van de kustzone inwerken. De vaargeul die dwars op de kust staat, onderbreekt zowel de eolische als de akwatische sedimentbeweging die evenwijdig met de kust loopt. Er is een duidelijke wederzijdse beïnvloeding tussen het toezandingsproces van de geul en de nabije stranddynamiek. Het onderzoek toont het belang aan van het residueel sedimenttransport dat, zowel eolisch als aquatisch, in dit deel van de Belgische kust evenwijdig met de kust plaatsgrijpt. Het toont aan dat op relatief korte tijd belangrijke hoeveelheden zand verplaatst worden.

RESUME - *L'ensablement du chenal de Blankenberge - Evolution morphodynamique et processus du transport des sédiments.*

L'ensablement du chenal du port de Blankenberge est déterminépar un ensemble complexe de processus côtiers qui s'interpénètrent et qui agissent avec des intensités différentes dans des parties différentes de la zone côtière. Etant orienté perpendiculairement à la côte, le chenal interrompe le transport des sédiments aquatiques et éoliens le long de la côte. Le processus d'ensablement est lié clairement à la dynamique des plages environnantes. La recherche montre l'importance du transport de sédiment résiduel, aquatique aussi bien que éolien, le long de cette partie du littoral belge. Elle prouve que d'importantes quantités de sable sont déplacées en très peu de temps.

1. GEOGRAPHICAL SITUATION

The study area is on the Belgian North-Sea coast near the Scheldt estuary (fig. 1). This part of the southeastern shoreline of the southern North-Sea Bight is a macrotidal environment characterized by a semi-diurnal, tidal regime.
The tidal amplitude varies between more than 4 m at spring-tide and less than 2 m at neap-tide. The important variation in tidal height creates tidal currents of over 2 m/s in the offshore zone. The open elongated tidal ellipses which have their longest axis subparallel to the coastline, are an indication for the existence of a net longshore mass transport from southwest to northeast.

The offshore zone is a relatively shallow westward dipping submarine plain with some typical systems

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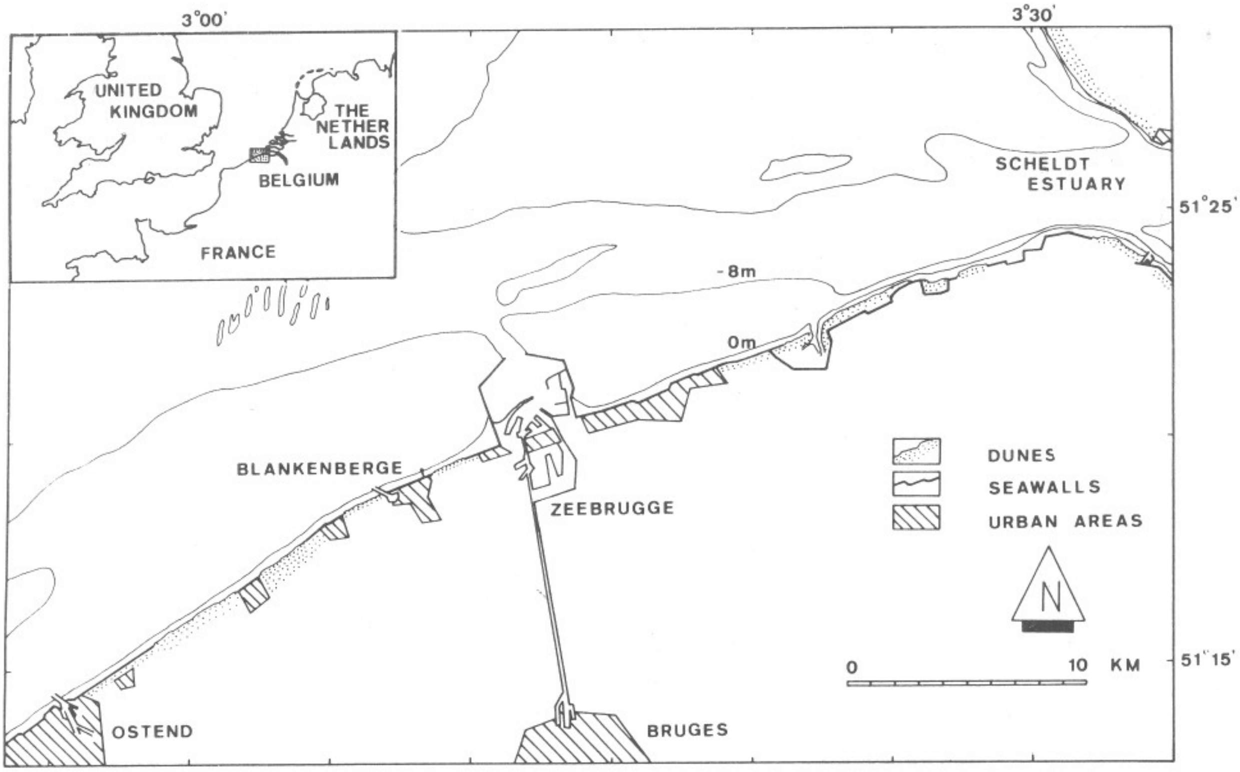


Fig. 1. The Blankenberge harbour entrance.
De havengeul van Blankenberge.
Le chenal d'accès au port de Blankenberge.

of tidal dominated sandbanks superimposed on it. The best known and intensely studied sandbank system is that of the Flemish Banks (G. DE MOOR, 1985). The interbank subtidal channels reach depths down to 40 m while the crests are less than 3 m below low-water level. The general orientation of the sandbanks is subparallel to the coast.

The foreshore zone is a broad and shallow flat surface, only reaching depths of 5 m at a distance of 5 km off the coast. At this point the nearshore zone borders the deeper channel leading to the Scheldt estuary. The area has a sandy character with a predominance of medium to fine grained sands and with the occurrence of mud fields nearer to the shore (G. DE MOOR, 1983; G. CEULENEER & B. LAUWAERT, 1987).

At the study site, the coastline itself is a sandy beach of about 250 m wide at low tide and less than 40 m wide at high tide. It is characterized by a low beach angle (generally less than 2 %) and a ridge and runnel morphology. The beach is bordered by a narrow dune belt.

Due to tidal currents and prevailing westerly winds there is a net longshore sediment transport, both eolian and subaquatic, in a northeasterly direction. This residual sediment-transport direction causes accretion on the western side and erosion on the eastern side of transversal structures such as the Zeebrugge harbour breakwaters.

2. PROBLEM STATEMENT

The tidal harbour of Blankenberge is a relatively small port with at present a mostly touristical and recreational function. The harbour entrance channel is a man made structure, perpendicular to the coastline and having a width of about 50 m. The channel is bordered on both sides by a pier surmounting a groin.

At the western side of the entrance channel, the

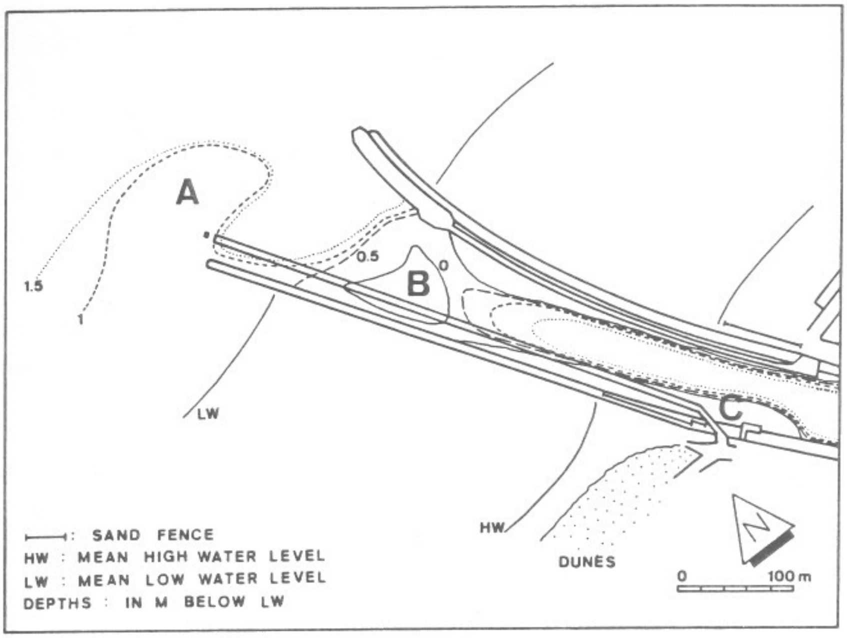


Fig. 2. Yearly mean general outline of the silting up during the period 1984-1989. A: Outside spit forming, B : Central silting up, C : Eolian edge accumulation.
Jaarlijkse gemiddelde toestand van de aanzanding in de periode 1984-1989. A : Buitengaatse haakwalvorming, B : Centrale aanzanding, C : Eolische randaanzanding.
La situation annuelle moyenne de l'ensablement pendant la période 1984-1989. A : Formation de flèche hors des passes, B : Ensablement central, C : Accumulation éolienne de bordure.

high beach is backed by a dune belt. At the eastern side there is a sea-wall (fig. 2).

The beach sector in which the channel is located, is, at least since 1984, in a stable or even in an accretional phase of beach evolution (fig. 3).

Each year again an important sandy and muddy accumulation develops in the entrance channel, thus causing a substantial obstruction to navigation. The choking is that important that a great part of the channel bottom emerges at low tide. To ensure harbour accessibility yearly dredging works are necessary.

As proved by historical documents, the choking is not a recent phenomenon (Ph. KONINGS, 1988). The same problems are encountered since the digging of the channel in 1865. Until the 1970's a 7,5 ha great basin was filled at high tide, allowing sluicing of the channel at low tide. Since then, the sluices have been removed and the basin is now part of the harbour. Nevertheless, the sluicing method has never been very successful in keeping the entrance channel at a navigable depth.

3. RESEARCH METHOD

Our present research on the morphological evolution and the morphodynamics of the accumulative structure in the entrance channel, as well as on the sedimentological processes which causes the infilling, began in 1984 and uses data as from 1980. Considering the local geographical situation, the issue of the shallowing has been studied as a part of the total coastal evolution of the region.

Sedimentologically as well as morphodynamically, the evolution of a coastal region has to be considered as being part of the evolution of the coastal system as a whole. In the particular case of the Blankenberge harbour, this is undoubtedly necessary to understand the problem.

As the entrance is perpendicular to the shoreline,

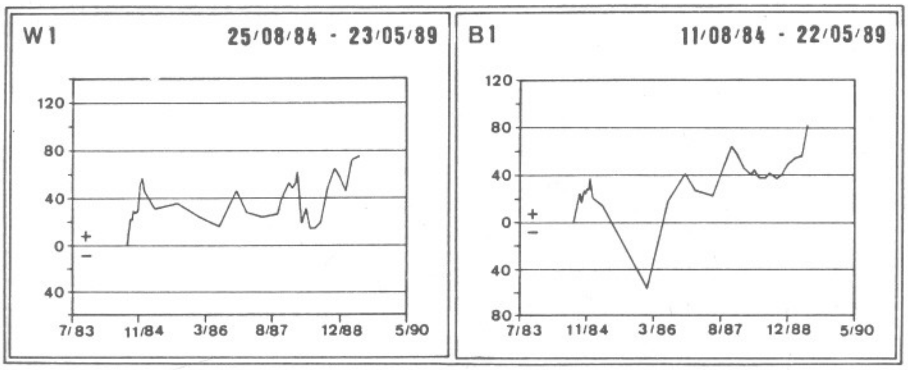


Fig. 3. Residual beach-budget evolution (m^3/m beach width) of the adjacent beach sectors. Reference date is August 1984 (beach-profile location cf. fig. 8).

Balansevolutie (m^3/m strandbreedte) van het residueel strand van de nabijliggende strandsektoren. Referentiedatum is 1984 (lokalizatie van de strandprofielen cf. fig. 8).

Evolution du bilan (en m^3/m de largeur de la plage) de plage résiduel des plages environnantes. Date de référence : août 1984 (cf. fig. 8 pour la localisation des profils de plage).

it is a transversal structure for longshore aquatic and eolian sediment-transport processes. Not only will such a transversal channel influence the surrounding coastal area, but its evolution will itself be determined by coastal processes acting in that same area.

In order to provide a view of the problem as complete as possible, we made use of longitudinal and transversal bathymetric profiling, granulometrical analysis of beach and channel samples, direct measurements of the mud layer in the channel, research on micromorphological structures, surface-current measurement, meteorological and wave data.

Moreover, coastal processes such as eolian sand transport, longshore drift, beach drift, migration of the ridge and runnel system, beach and nearshore evolution are studied hand in hand with the present research.

4. RESULTS

4.1. Global view of the accumulation

The general morphology is schematized in fig. 2 which shows the mean situation of maximum accumulation in early spring. The accumulation process can only be studied within a yearly (artificial) cycle, because dredging works are carried out each year again in late spring. The outlines (fig. 2) are based on yearly surveys since 1980. As demonstrated by fig. 4, there is very little variability over different years. It is the final phase of an accumulation process which starts soon after dredging the channel in spring at a depth of 3 to 4 m below low-water level.

In less than one year's time, over 4 m of sediment is accumulated at some places. With regard to both morphogenetics and sedimentation, three distinct accumulation zones can be distinguished : outside spit forming (fig. 2(A)), eolian edge accumulation (fig. 2(C)) and central silting up (fig. 2(B)).

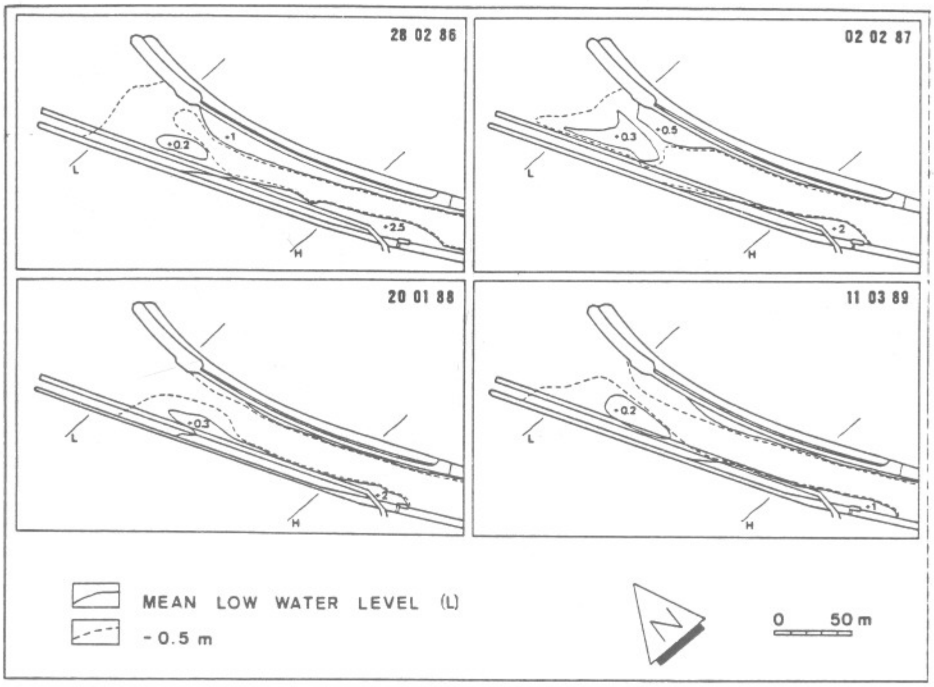


Fig. 4. Yearly general outline of the silting up in the period 1986-1989. Each figure shows the final stage of silting up just before the yearly dredging in spring.

Jaarlijkse algemene toestand van de aanzanding in de periode 1986-1989. Elke figuur toont het eindstadium van aanzanding juist voor de jaarlijkse baggerwerken in het voorjaar.

Situation générale annuelle de l'ensablement dans la période 1986-1989. Chaque figure montre la phase finale de l'ensablement juste avant le dragage printanier.

4.2. Outside spit forming

The morphology, the localization and especially the morphological evolution of the accretional structure off the harbour entrance indicate a close relationship with the nearshore sediment-transport processes.

The lobate structure offshore the piers which, in early autumn, starts growing rapidly in an eastward direction, reaches already in late winter a stage in which the western part of the channel is silted up to nearly low-water level. As in this zone it was dredged in late spring to a depth of 5 m below mean low-water level, the channel bottom is raised by 4 to 5 m in only a few months.

The structure reaches a seaward extent of 100 m. To the north-east, it fills in the entrance channel over a distance of 80 m. Its prograding north-eastern side is a steep slip-face while the south-western part is connected with the nearshore bar. This makes the spit-like structure an extension of the nearshore bar.

At the extreme low tide of February 22, 1988 the nearshore morphology could be measured by beach profiling seaward from the normal low-water mark and further than the end of the pier. The nearshore bar crest is located at the extremity of the groin which borders the channel (fig. 5). As evidenced by frequent observations of the breaker zone above the bar, this longshore ridge remains nearly on that position throughout the year.

Fig. 6 shows 3 stages in the evolution of the accumulation. (A) shows the summer situation, some months after dredging took place. On the spit part between the two piers, the channel bottom is dredged at 3 m below mean low-water level, slightly increasing to 5 m in a seaward direction.

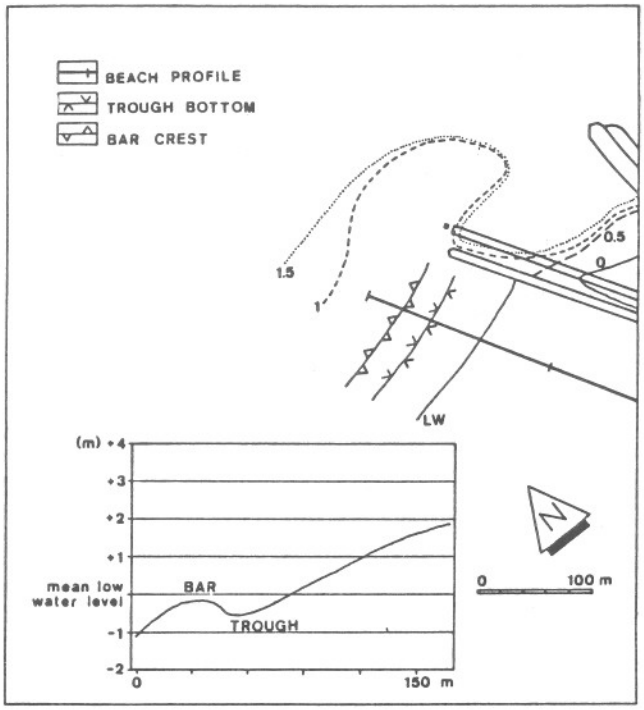


Fig. 5. Location and morphology of the nearshore bar and the outside spit.
Lokalizatie en morfologie van de voorstrandrug en de buitengaatse haakwalvorming.
Localisation et morphologie de la crête prélittorale et de la flèche hors des passes.

(B) is the typical autumn situation. Starting from the southwest, the rapidly northeastwards growing lobate structure reduces the original channel depth of 4-5 m to less than 1 m. The fastest growth takes place during autumn storms. In order to prevent total choking, some dredging is carried out in the seaward zone during winter. Nevertheless, the original outline can easily be reconstructed (C, dashed line).

All factors indicate that the nearshore structure can be classified as a spit. A spit is an accretional structure with a pronounced lateral growth parallel to the coast. Spit forming takes places where the coastline, followed by a littoral current, turns abruptly landward, as at the entrance of a bay or an estuary. Those accretional structures are characteristic for coasts with a net unidirectional littoral sediment transport. Growth takes place from an attachment point and over a spit platform, the latter having a steeper slope than the zone of shoaling waves and subject to less important wave action. The protected zone behind the spit is generally transformed into a low energy environment in which tidal flats and salt marshes can develop. When the spit finally reaches the other side of the bay, it is called a beach barrier.

On the Belgian coast, there exists an important residual longshore littoral drift to the northeast (see point 1). The very fast, stepwise accelerating growth of the spit during stormy periods can be explained as a consequence of increased sediment transport during these periods with intensified longshore tidal currents, important wave action and strong westerly winds.

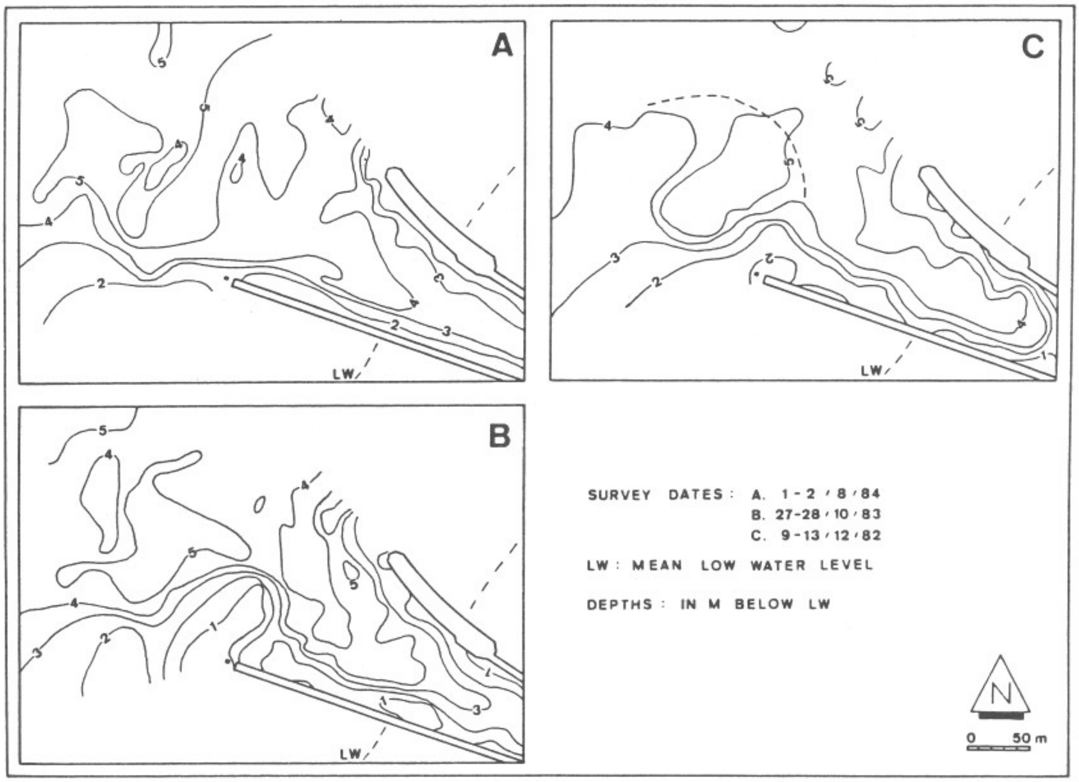
The morphological evolution of the spit from its attachment point (the groin near to the western pier) is in fact the northeastward expansion of the nearshore bar, caused by littoral drift. Thereby, longshore sediment-transport has been increased by obliquely incoming waves causing beach drift, as well as by increased current velocity in the nearshore trough. Both phenomena become more important if accompanied by strong longshore (westerly) winds. Strongly increased sediment load under such circumstances can be observed as a brownish coloured water mass at the end of the western pier.

Comparing the bathymetry of the mean September and the mean February situations (fig. 7), there is an estimated mean residual positive budget of nearly 16.000 m^3 per 6 months. During autumn, a monthly mean of over 2.650 m^3 of sand (88 m^3 per day) is deposited only in the considered area of 15.000 m^2. Considering this preliminary estimation of nearshore sediment transport, further detailed quantitative research will undoubtedly provide supplementary interesting information on longshore sediment transport on the Belgian coast.

4.3. Central silting up

What we call here the central silting up is the accretion inside the harbour-entrance channel, between the 2 piers and located between the high and low-water marks on the beach (fig. 8).

The most important part it is a central shallowness at about 100 m landward from the low-water line on the beach and having its greatest mass near the western groin. Landward and without interruption, it is connected with a relatively narrow sandy accumulation on the slope of



SURVEY DATES : A. 1-2/8/84
B. 27-28/10/83
C. 9-13/12/82

LW : MEAN LOW WATER LEVEL

DEPTHS : IN M BELOW LW

Fig. 6. Morphological evolution of the outside spit by bathymetrical survey, showing summer (A), autumn (B) and winter (C) situations (original data from the Belgian Coastal Service).

Morfologische evolutie van de buitengaatse haakwal. De batymetrische opnamen tonen de zomer-(A), herfst-(B) en winter-(C)-situatie (originele gegevens van de Belgische Dienst der Kust).

Evolution morphologique de la flèche hors des passes par levées bathymétriques, montrant la situation en été (A), automne (B) et hiver (C) (données originales du Service Côtier belge).

the western groin. This sand strip broadens and heightens towards the high-water line on the beach. On the eastern side of the channel a simular although less important accumulation develops mainly by longshore drift from the east. It is also connected with the central shallowness, but with a landward decrease in height and width.

From the dredging in spring until the late summer, the channel depth remains almost unchanged at its dredged level of -3 m. Rapid and stepwise accretion during the autumn months leads to the accumulative structure with the size and extent as shown in fig. 8 and described earlier.

Comparison of the August '84 and January '85 situations (fig. 9) demonstrates the velocity at which shallowing takes place. In August, the -3 m dredging level still remains unchanged, while 6 months later, silting up went on to above low-water level. The central shalowness is an asymmetrical rise with a gentle landward slope and a steep seaward side (fig. 8 & 10). The bottom slope which originally deepens seaward from 3 to 5 m is finally dipping in the inverse direction with a minimal depth at the central rise. During its development, sand supply from the beach causes the bar to grow in a seaward direction until the channel is totally choked (fig. 11).

Accretion goes on very rapidly and involves important volumes of sand. Between October '83 and May '84 nearly 30.000 m³ of sand was trapped in the seaward part of the entrance channel (fig. 12).

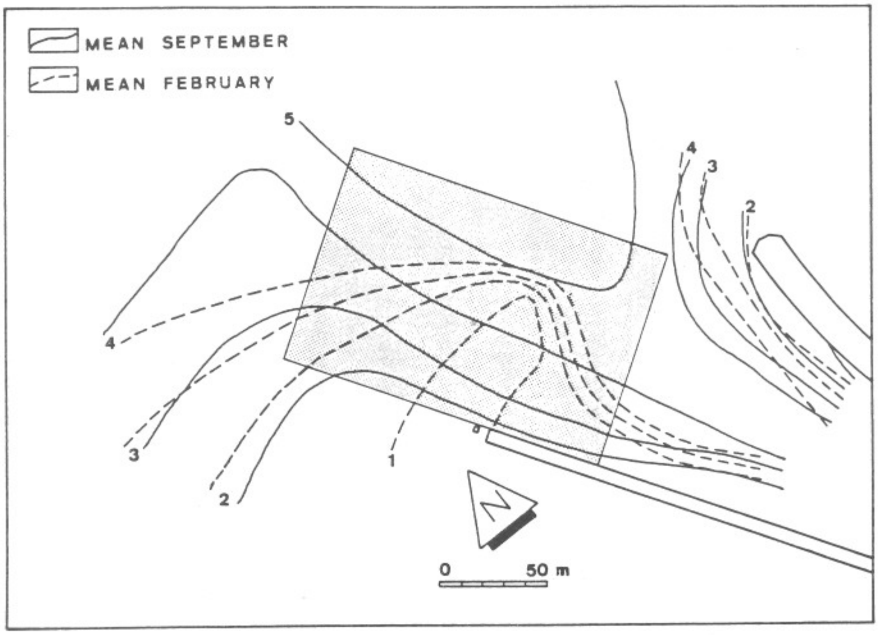


Fig. 7. The outside spit : comparison of the mean September and the mean February bathymetry (shaded area is zone with sand budget computation).
De buitengaatse haakwal : vergelijking tussen de gemiddelde batymetrie in september en in februari (in de gearceerde zone werden zandbalansen berekend).
La flèche hors des passes : comparaison entre la situation bathymétrique moyenne en septembre et en février (zone hachurée : bilans calculés).

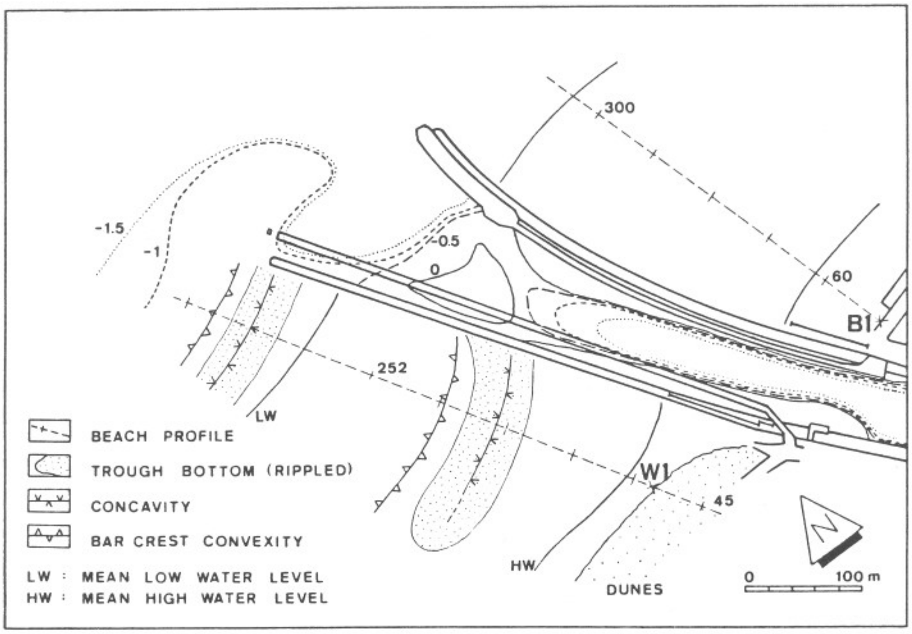


Fig. 8. Mean general outline of the silting up. Beach morphology and location of beach profiles (cf. fig. 3) are added.
Gemiddelde algemene toestand van de aanzanding, met aanduiding van de strandmorfologie en de lokalizatie van de strandprofielen (cf. fig. 3).
Situation générale moyenne de l'ensablement. La morphologie de la plage et la localisation des profiles de plage sont indiquées (cf. fig. 3).

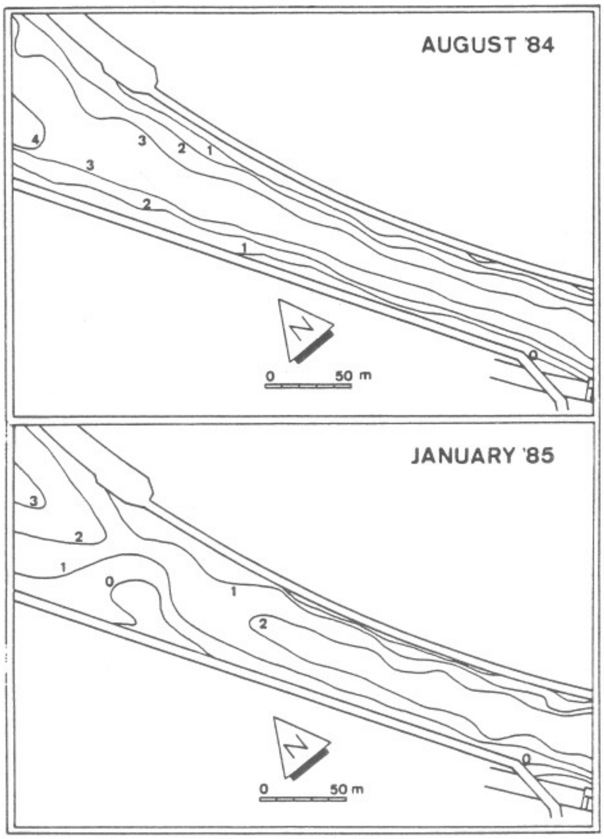


Fig. 9. The central silting up : comparison of the August 1984 and the January 1985 situations shows the shallowing speed.
De centrale aanzanding : vergelijking van de situatie in augustus 1984 en januari 1985 toont de snelheid van verzanding.
L'ensablement central : la comparaison de la situation en août 1984 et en janvier 1985 illustre la vitesse du processus d'accumulation.

Rapid and important accumulation can take place because a low-energy environment is created between the piers and groins on both sides of the channel. The channel with a less important wave action is favourable for depositing sediment which is transported by beach and littoral drift. Moreover, the process of shallowing accelerates itself because, as it accretes, the rise decreases the wave energy landward from it. The thick mud layer in the axis of the channel confirms the existence of a low-energy environment. Bottom sampling in the central axis of the channel shows a rapid seaward decrease of the muddy fraction (table 1).

Table 1. Mud percentage of bottom samples in the central axis of the channel (for localization see fig. 10).

G	% < 0,053 mm
0	97
2	98
4	96
6	96
10	56
20	19

At the beach high-water mark, the mud appears as a 40 cm thick mud layer. The layer thickness gradually decreases seaward with an increasing sand content and finally disappears.

The morphological evolution of the surrounding beach is one more argument for the conclusion that the central silting up is mainly caused by interrupting longshore sediment transport in the beach zone (fig. 3 & 8). On the other hand, the channel influences the beach morphodynamics. To evaluate the evolution of the channel within the general evolution of the coastal system, the adjacent beaches have been surveyed through topographical beach profiling. Within the general accretional trend, the residual beach-budget evolution shows a distinct seasonal cycle with beach accretion in summer-autumn and beach erosion in winter-spring (fig. 3). Maximum beach growth occurs in autumn. The beach reaches its highest overall budget in December and then falls rapidly to minimal values at about July.

During an accretion period, the sediment dynamics are such that sand input exceeds sand output. Sediment is supplied not only to the beach but also to the entrance channel. The supply is accelerated in autumn. At about December-January, the process is abruptly inverted. Under the influence of stormy conditions, sand output then exceeds input, thus causing beach erosion.

That period of accelerated beach erosion coincides perfectly with the period of accelerated silting up of the harbour-entrance channel. Stormy hydrodynamical conditions move beach sand in a longshore direction to the less turbulent environment of the entrance channel where consequently deposition takes place. The interruption of the northeasterly directed longshore sand-transport

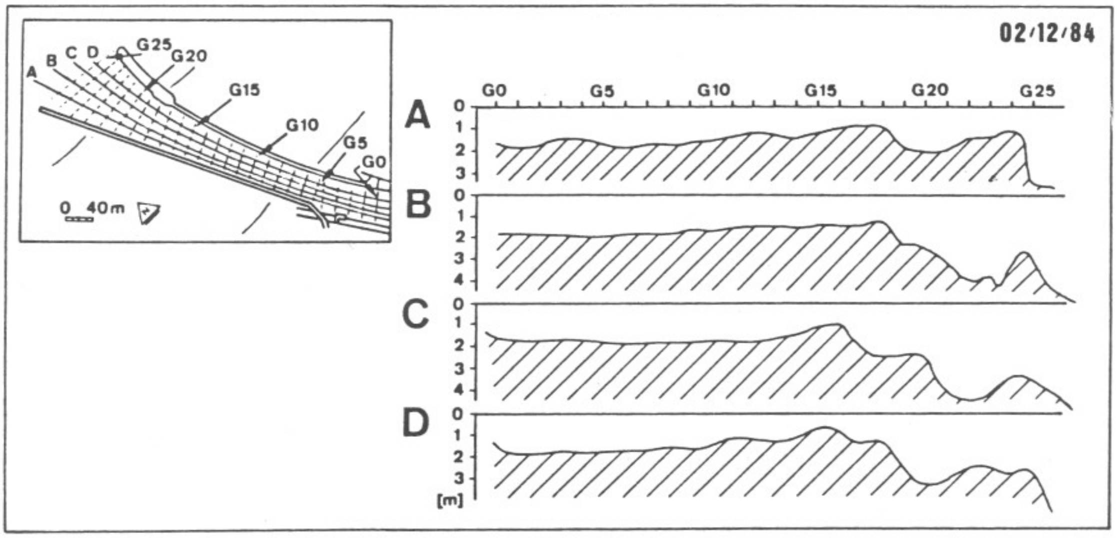


Fig. 10. Bottom topography of the channel along longitudinal profiles A, B, C and D. G0 to G25 : transversal profiles.
Topografie van de geulbodem volgens de longitudinale profielen A, B, C en D. G0 tot G25 : transversale profielen.
Topographie du fond de chenal selon les profils longitudinaux A, B, C et D. G0 à G25 : profils transversaux.

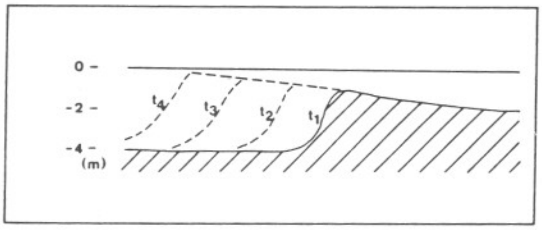


Fig. 11. Schematic evolution of bottom topography along the channel axis. The bar increases and heightens in seaward direction.
Schematische evolutie van de bodemtopografie volgens de as van de geul. De rug groeit aan en verhoogt in zeewaartse richting.
Evolution schématique du fond de chenal le long de l'axe central. Le banc s'accroît et s'agrandit vers la mer.

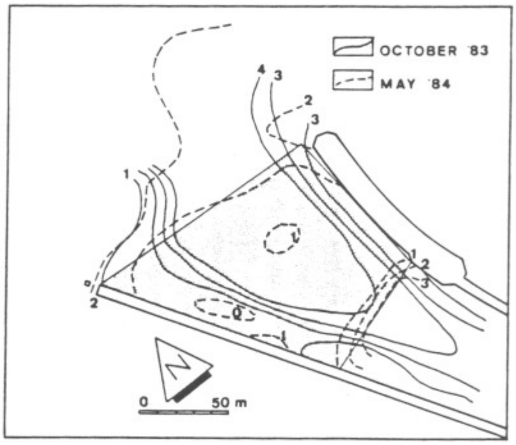


Fig. 12. The central silting up : comparison of the October 1983 and May 1984 bathymetry (shaded area is zone with sand-budget computation).
De centrale aanzanding : vergelijking tussen de batymetrie in oktober 1983 (in de gearceerde zone werden zandbalansen berekend).
L'ensablement central : comparaison de la bathymétrie en octobre 1983 et en mai 1984 (la hachure représente la zone dans laquelle des bilans de sable ont été établis).

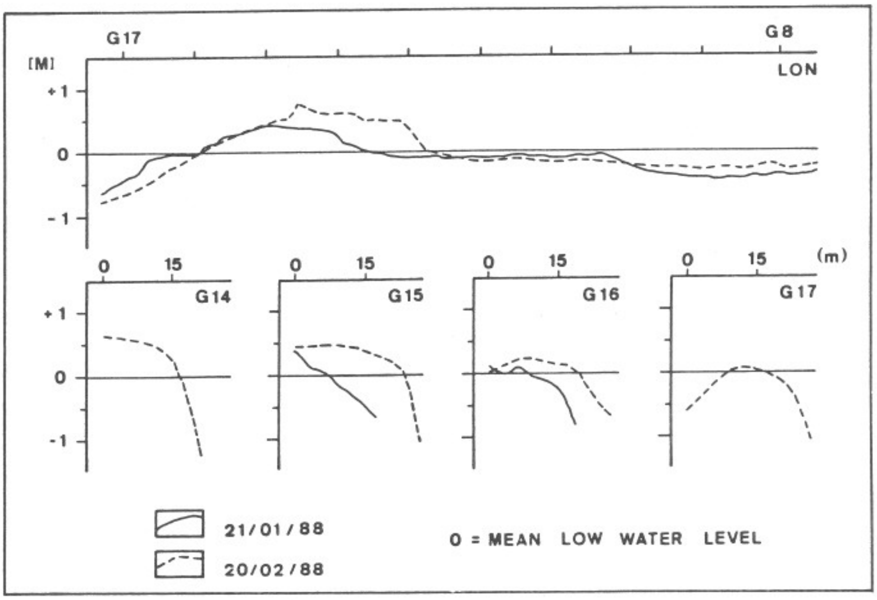


Fig. 13. Central-bar growth during February 1988. LON : longitudinal profile 1 m east of the western pier; G14 to G17 : transversal profiles starting at this pier (location cf. fig. 10).
Aangroei van de centrale zandbank in februari 1988. LON : longitudinaal profiel 1 m ten oosten van het westerstaketsel; G14 tot G17 : transversale profielen vanaf dit staketsel (lokalizatie cf. fig. 10).
L'accroissement du banc de sable central en février 1988. LON : profil longitudinal 1 m à l'est de l'estacade occidentale. G14 à G17 : profils transversaux à partir de cette estacade (cf. fig. 10 pour la localisation).

processes by the channel causes smaller beach fluctuations on the northeastern side of the channel. This clearly illustrates the buffer function which the channel exerts on adjacent beaches. The effects of erosional as well as of accretional phases are tempered. Sand supply from the western beach to the channel is determined by beach morphology, more specifically by the existence of a mid-beach runnel located between 2 ridges. The winter profile of the western beach is characterized by 2 troughs alternating with 2 bars (fig. 8). The seaward through is situated near the mean low-water level, while the less pronounced and wider landward one lies halfway the low and high-water mark. As can be deduced from the trough bottom micromorphology, draining takes place to the northeast, although a classical seaward draining gully is missing. Together with the relative position of the trough and the central rise, this shows the importance of the runnel effect (locally increased longshore-current velocities within the trough causing increased longshore sediment transport in this zone) in the process of sediment transfer from the beach to the channel. The local decrease of seaweed growth on the groin could be a consequence of locally increased sand transport in this particular zone. The little important yearly variations in the position of the central rise (fig. 3) can be correlated with changes in the beach trough localization.

The same beach-channel relationship applies to the eastern side of the entrance. However, because net longshore sediment transport is directed to the northeast, the sand transfer from the eastern beach is less important. Only storms from the north cause accelerated infilling along the eastern groin. If no such stormy periods occur during the winter, the eastern part of the channel is silted up to a much lesser extent (fig. 4).

Fig. 13 illustrates the rapid and stepwise development of the central silting up. In the space of a single month the sand volume increased from 2.476 m^3 (on 21 January '88) to 7.828 m^3 (on 20 February '88) corresponding to a growth of 5.352 m^3 per month. Between these two survey dates hydrodynamical conditions were favourable for

Table 2. Granulometrical parameters of channel bottom samples from the central rise (see fig. 10 for localization).

Sample points	Mean	Standard deviation	Skewness	Kurtosis	Shell % (>2 mm)
G14	2,042	0,418	-0,065	0,871	0,60
G15	2,125	0,379	-0,099	0,956	0,82
G16	2,067	0,412	-0,024	0,950	1,15
G17	2,092	0,393	-0,131	0,950	1,89
Mean	2,081	0,400	-0,080	0,932	1,11

Table 3. Granulometrical parameters of lower-beach samples from the western beach (profile W1 on fig. 8).

Sample points	Mean	Standard deviation	Skewness	Kurtosis
H-70	2,233	0,308	-0,005	1,639
H-144	2,225	0,395	-0,324	1,143
H-174	2,175	0,438	-0,301	0,990
H-199	2,250	0,353	-0,245	1,133
Mean	2,221	0,373	-0,219	1,226

transporting sediment. Partial beach budgets between 7 February '88 and 20 February '88, a period with almost continuous stormy conditions, indicate a pronounced erosion of the lower beach in the trough zone.

Granulometrical analysis of samples from the central rise provide supplementary evidence that the sand originates from the lower beach. The samples differ markedly from higher-beach sands which have been submitted to wind action, but resemble closely lower-beach sands. The mean grain size (0,250 mm = fine to medium grained sands) is somewhat higher than that of lower-beach sand (0,220 mm = fine sands). Probably the finer fraction was sorted out during transport. Standard deviation of beach and channel samples is identical and is classified as being well sorted. As for typical beach sands skewness has a negative value. The greater coarse fraction which has its effect on the kurtosis value (more platykurtic) is partly due to the greater shell content of the sand.

4.4. Eolian edge accumulation

On both sides of the entrance channel, but far more pronounced on the western side of it, an elongated, relatively narrow sand strip develops

Table 4. Granulometrical parameters of bottom samples from the western edge accumulation (see fig. 14). Mean beach parameters added for comparison.

Sample points	Mean	Standard deviation	Skewness	Kurtosis	Shell % (>2 mm)
G2	2,175	0,329	-0,023	1,002	0,00
G3	2,217	0,338	0,001	0,979	0,01
G4	2,217	0,310	0,051	0,970	0,00
G5	2,175	0,290	0,014	1,011	0,00
G6	2,217	0,281	0,072	1,112	0,00
G7	2,200	0,298	-0,013	1,066	0,00
G8	2,225	0,314	-0,025	0,964	0,03
G9	2,225	0,322	-0,048	0,956	0,01
G10	2,150	0,348	-0,097	1,002	0,03
G11	2,167	0,359	-0,070	1,014	0,03
G11B	2,250	0,324	-0,141	0,988	0,01
G12	2,192	0,352	-0,073	1,025	0,09
G13	2,117	0,379	-0,047	0,956	0,14
G14	2,042	0,418	-0,065	0,871	0,60
G14B	2,125	0,379	-0,099	0,956	0,82
G15B	2,092	0,389	-0,102	0,931	1,38
G16	2,067	0,412	-0,024	0,950	1,15
G17	2,092	0,393	-0,131	0,950	1,89
Mean dune and high beach	2,237	0,277	0,044	1,010	
Mean low beach	2,242	0,351	-0,207	1,195	

on the slope of the groin. At its seaward part, the western edge accumulation is connected with the central shallowness on the low-water level. The sand strip broadens and heightens landward where it reaches a maximal height of about 3 m above high-water level.

Considering the height difference (nearly 5 m) over a distance of only a few meters, the eastern slope has an important slope angle. Here again, rapid and stepwise accretion occurs during autumn and winter. In this case however the surface does not stagnate between 2 growth periods but undergoes a continuous reworking and lowering.

Localization, morphology, granulometry and morphodynamics of the surface all indicate that longshore eolian sand transport plays an important role in its genesis.

The edge accumulation which has a predominantly eolian character can be distinguished granulometrically from the central rise (fig. 14 & 15). Changes in grain-size characteristics correspond perfectly to the morphological separation of the 2 parts. Shell content and mean grain size are the clearest examples. All parameters indicate a gradually seaward increasing marine influence (lower-beach characteristics) and a landward increasing eolian influence (dune and higher

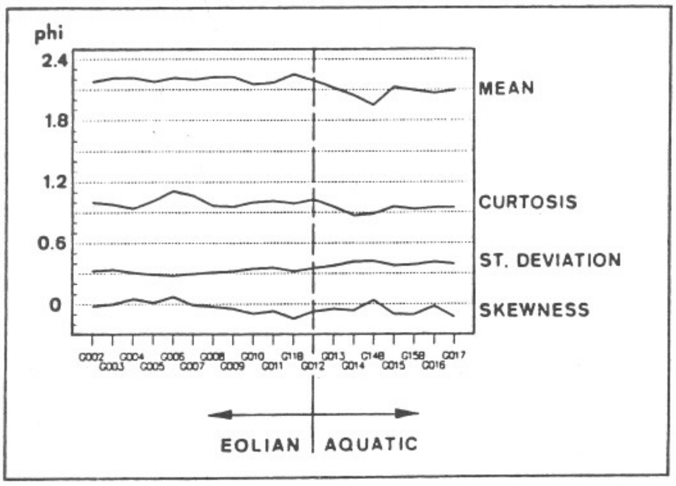


Fig. 14. Western-edge accumulation : granulometric parameters (FOLK & WARD). Samples location cf. fig. 10 & 15.
Aanzanding op de westelijke rand : granulometrische parameters (FOLK & WARD). Lokalizatie van de stalen cf. fig. 10 & 15.
L'accumulation de la bordure occidentale : paramètres granulométriques (FOLK & WARD). Localisation des échantillons cf. fig. 10 & 15.

beach characteristics). Moreover the latter is highly pronounced landward of the beach high-water mark (G7) and reflected in positive skewness values, a typical feature of eolian sands.

The granulometrical variations along the edge accumulation correspond to the geographical circumstances in the area. The landward part with pronounced eolian granulometrical characteristics is situated at the higher beach and dune zones. In this area, eolian sediment transport is the dominating sedimentological process. Further seaward, at the lower beach zone, aquatic sedimentological processes dominate.

The gradual seaward decrease of eolian characteristics of the sand samples is directly proportional to the decrease in intensity and occurrence of sand transport by wind action on the beach. Due to tidal movement, the time the beach surface emerges, increases landward. Potential eolian sand supply to the channel thus increases landward because the beach is exposed to air for a longer time. This also explains the landward heightening and broadening of the edge accumulation.

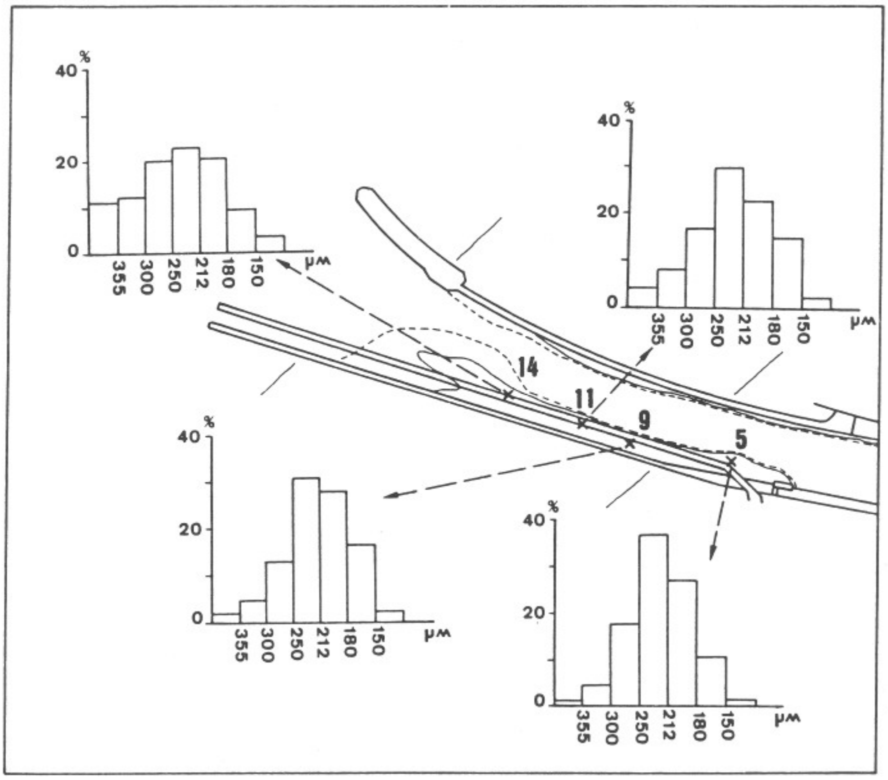


Fig. 15. Western-edge accumulation : variation of grain-size distribution.
Aanzanding op de westelijke rand : variatie in korrelgrootteverdeling.
L'accumulation de la bordure occidentale : variation de la distribution granulométrique des grains de sable.

The less important eolian sand supply from the northeast is responsible for the much smaller edge accumulation on the eastern side of the channel. Research on eolian sand transport in the study area points out that, during the winter period, the greatest quantities of sand are moved during stormy periods under westerly winds, thus creating a net longshore sand movement to the northeast. Subject to a decreased sediment input caused by the sediment trap effect of the channel, the eastern beach surface is situated at a lower level than the western beach. Moreover, a granulometrical selection process, induced by the existence of the channel, filters the coarser grained sands, thus increasing the compaction of eastern beach material. Comparison of tables 3 and 5 indicate differences in grain-size characteristics on both sides of the channel. At the eastern beach, mean grain size (0,200 mm) is smaller and sorting is better than on the western beach.

As a consequence of surface lowering and higher compaction, surface humidity increases. This puts the threshold wind velocity for eolian sand movement on a higher level. The result is a diminished eolian sand supply to the channel from the beach at the eastern side of it.

During the period September '87-March '88 the morphological evolution of the edge accumulation was measured in a detailed manner. Table 6 gives the potential eolian sand-transport volumes during this observation period. The sand-transport values are deduced from wind data, using an experimentally obtained relationship between wind velocity and eolian sand-movement rate (Ph. KONINGS & G. DE MOOR, 1988).

An important geographical factor which influences eolian sand supply to the channel is the existence of a 1 m high stone wall (sand fence) on the landward part of the groin, between the channel profiles G5 and G9 (fig. 16). Winds from the sector WSW-NW supply sand to the whole length of the entrance channel. Due to the stone wall and the weakened winds on the lee-side of the dunes, SSW and SW winds only supply sand seaward of G9. In table 5, TOTef is the potential sand supply from the sector WSW-NW, while TOTef+ is the potential eolian sand supply from the sector SSW-NW. Both values are in kg/m perpendicular to the wind direction. The resulting total supply to the channel is given in table 5 as a total (TOT140m+ from G5 to G12) and as subtotals (TOT80m+ from G5 to G9, TOT60m+ from G9 to g12).

High-frequency topographical surveying during the period September '87 to March '88 enables detailed study of the surface morphodynamics and local sediment dynamics. Due to the dense grid of measurement points, the morphological evolution can be deduced on an areal basis. The following results are obtained (fig. 17 to 22).

Westerly winds (SSW to NW) exceeding the threshold velocity for sand movement, supply eolian sand to the entrance channel (fig. 23). Most of the wind-blown sand accumulates on the lee-side of the western groin. At higher wind velocities however, part of the sand is directly blown into the channel itself. The sand accumulated on the groin slope is immersed at high tide. Following the falling water level during ebb, it sinks away downslope, activated by wave action. The down-

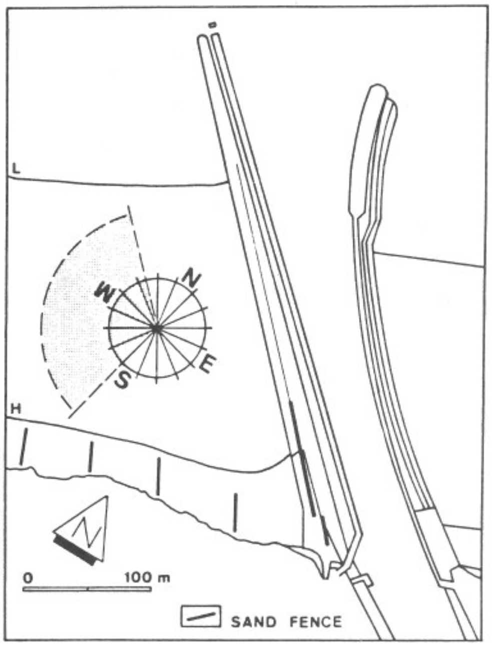


Fig. 16. Wind sector with potential eolian-sand supply to the channel. The sand fence on the groin is situated between the channel profiles G5 and G9 (localization cf. fig. 10).
Windsektor met potentiële eolische zandaanvoer naar de vaargeul. Het zandscherm op de golfbreker bevindt zich tussen geulprofiel G5 en G9 (cf. fig. 10 voor de lokalizatie).
Secteur des vents susceptibles de transporter du sable vers le chenal. Le petit mur pour empêcher le mouvement de sable se trouve entre les profils de chenal G5 et G9 (cf. fig. 10 pour la localisation).

Table 5. Granulometrical parameters of lower-beach samples from the eastern beach (profile B1 on fig. 8).

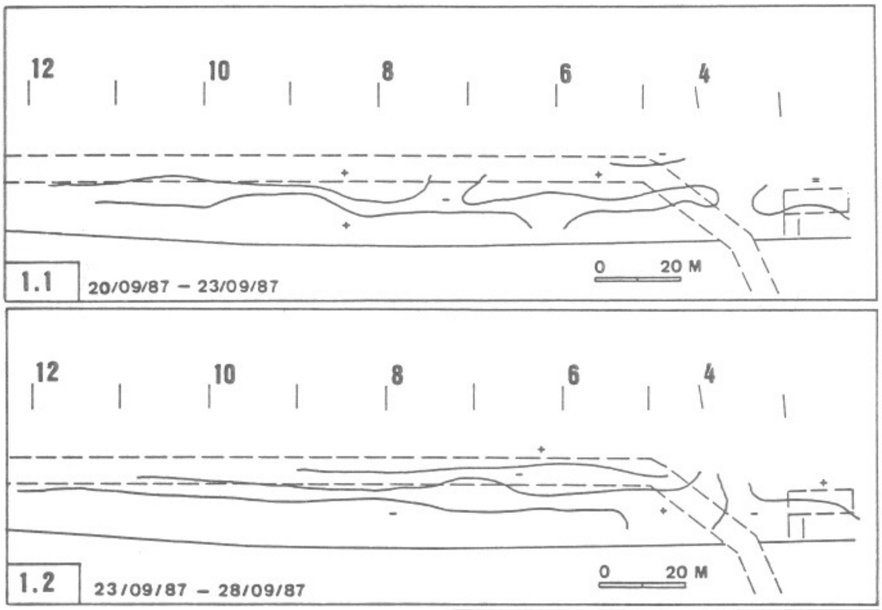
Sample points	Mean	Standard deviation	Skewness	Kurtosis
H-63	2,350	0,220	-0,465	1,366
H-99	2,558	0,101	-1,548	1,157
H-127	2,242	0,299	-0,083	1,200
H-157	2,250	0,377	-0,260	1,138
H-199	2,142	0,335	-0,064	1,202
H-266	2,258	0,337	-0,295	1,306
H-265	2,192	0,347	-0,093	1,204
Mean	2,288	0,285	-0,346	1,191

Table 6. Potential eolian sand supply to the channel (theoretical supply only considering wind velocity and direction).

	Potential sand supply to the channel				
Periods with eolian sand movement	TOTef	TOTef+	TOT80m+	TOT60m+	TOT140m+
	(kg / m)			(kg / x m)	
13/09-20/09	363	395	29.080	23.697	52.777
04/10-09/10	363	546	29.006	32.785	61.790
14/10-17/10	0	2.046	0	122.762	122.762
09/11-11/11	39	181	3.102	10.840	13.943
11/11-13/11	117	2.265	9.390	135.912	145.303
28/12-09/01	1.565	4.644	125.230	278.623	403.853
Total	2.448	10.076	195.807	604.619	800.428

slope movement results in a growing accumulation at the groin foot (fig. 22 series 5.1; fig. 17 series 1.1; fig. 19 series 3.1). The eolian accumulation on the higher groin slope is directly washed away during spring-tide, while during a neap-tide period the upper part of it remains on the groin until the next spring-tide period. Apart from an ebb-flood retardation effect (with a maximum delay of 6 hours between deposition on the groin and deposition in the channel) there is clearly also a spring-neap retardation effect (maximum delay of 14 days) on the sand supply to the channel surface (fig. 17 series 1.1, the surface accretion originates from eolian supply during the period 13 September '87 to 20 September '87).

The sand fencing effect of the little wall (between

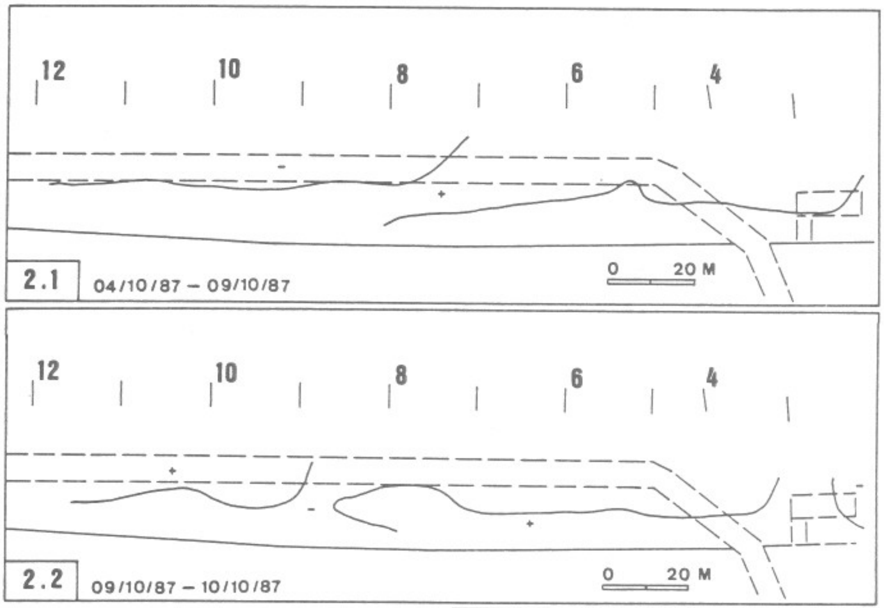


EROSIVE		ACCUMULATIVE	
- :	0 – 1 dm	+ :	0 – 1 dm
1- :	1 – 2 dm	1+ :	1 – 2 dm
2- :	2 – 3 dm	2+ :	2 – 3 dm

Fig. 17. (Series 1.1. to 1.2.) Morphological evolution of the intertidal sand surface of the edge accumulation. Period 20-09-87 to 28-09-87.

(Series 1.1. to 1.2.) Morfologische evolutie van het intertidale zandoppervlak van de randaanzanding. Periode 20-09-87 tot 28-09-87.

(Séries 1.1. à 1.2.) Evolution morphologique de la surface intertidale de l'accumulation de bordure. Période du 20-09-87 au 28-09-87.



EROSIVE		ACCUMULATIVE	
- :	0 – 1 dm	+ :	0 – 1 dm
1- :	1 – 2 dm	1+ :	1 – 2 dm
2- :	2 – 3 dm	2+ :	2 – 3 dm

Fig. 18. (Series 2.1. to 2.2.) Morphological evolution of the intertidal sand surface of the edge accumulation. Period 04-10-87 to 10-10-87.

(Series 2.1. to 2.2.) Morfologische evolutie van het intertidale zandoppervlak van de randaanzanding. Periode 04-10-87 tot 10-10-87.

(Séries 2.1. à 2.2.) Evolution morphologique de la surface intertidale de l'accumulation de bordure. Période du 04-10-87 au 10-10-87.

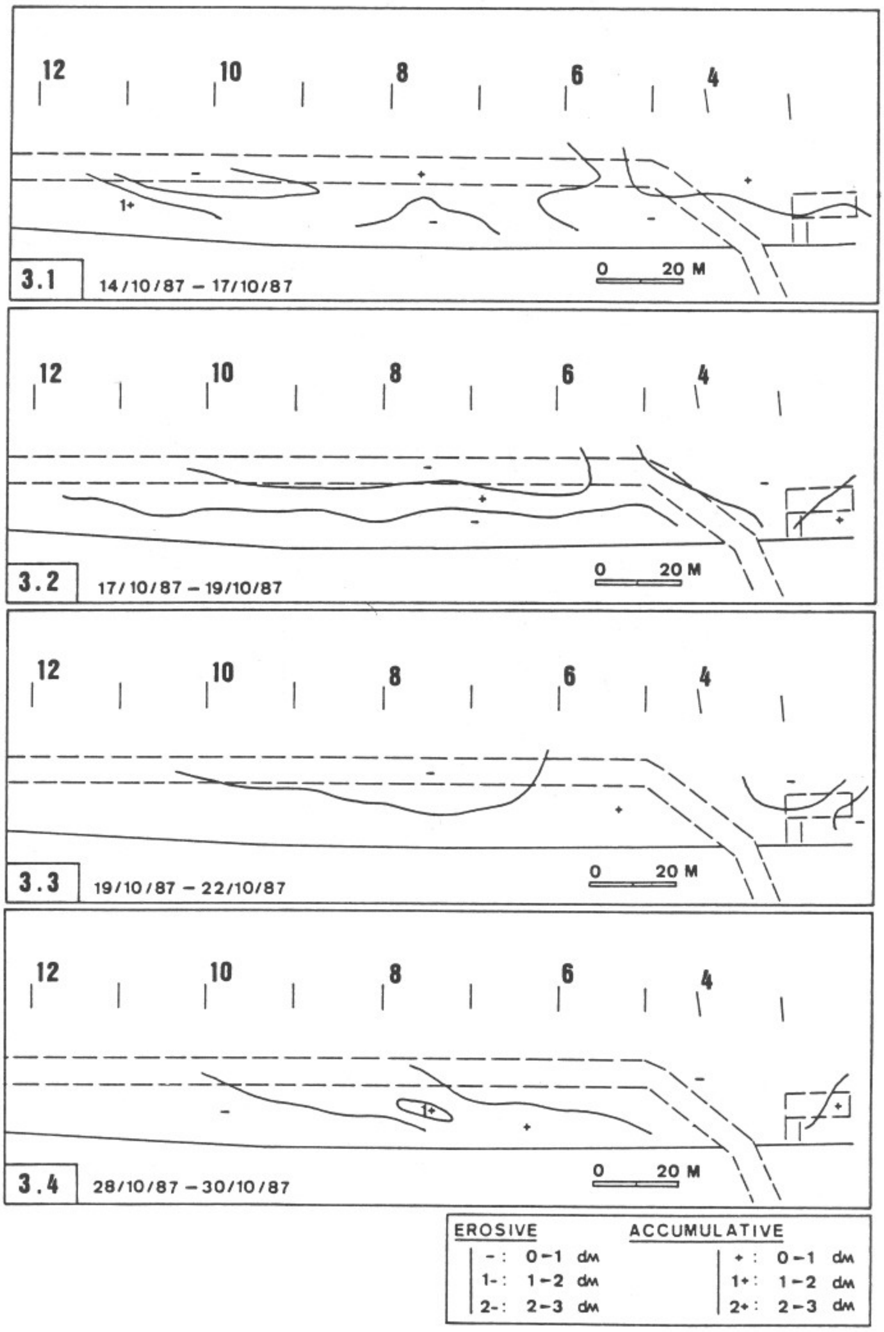


Fig. 19. (Series 3.1. to 3.4.) Morphological evolution of the intertidal sand surface of the edge accumulation. Period 14-10-87 to 30-10-87.
(Series 3.1. to 3.4.) Morfologische evolutie van het intertidale zandoppervlak van de randaanzanding. Periode 14-10-87 tot 30-10-87.
(Séries 3.1. à 3.4.) Evolution morphologique de la surface intertidale de l'accumulation de bordure. Période du 14-10-87 au 30-10-87.

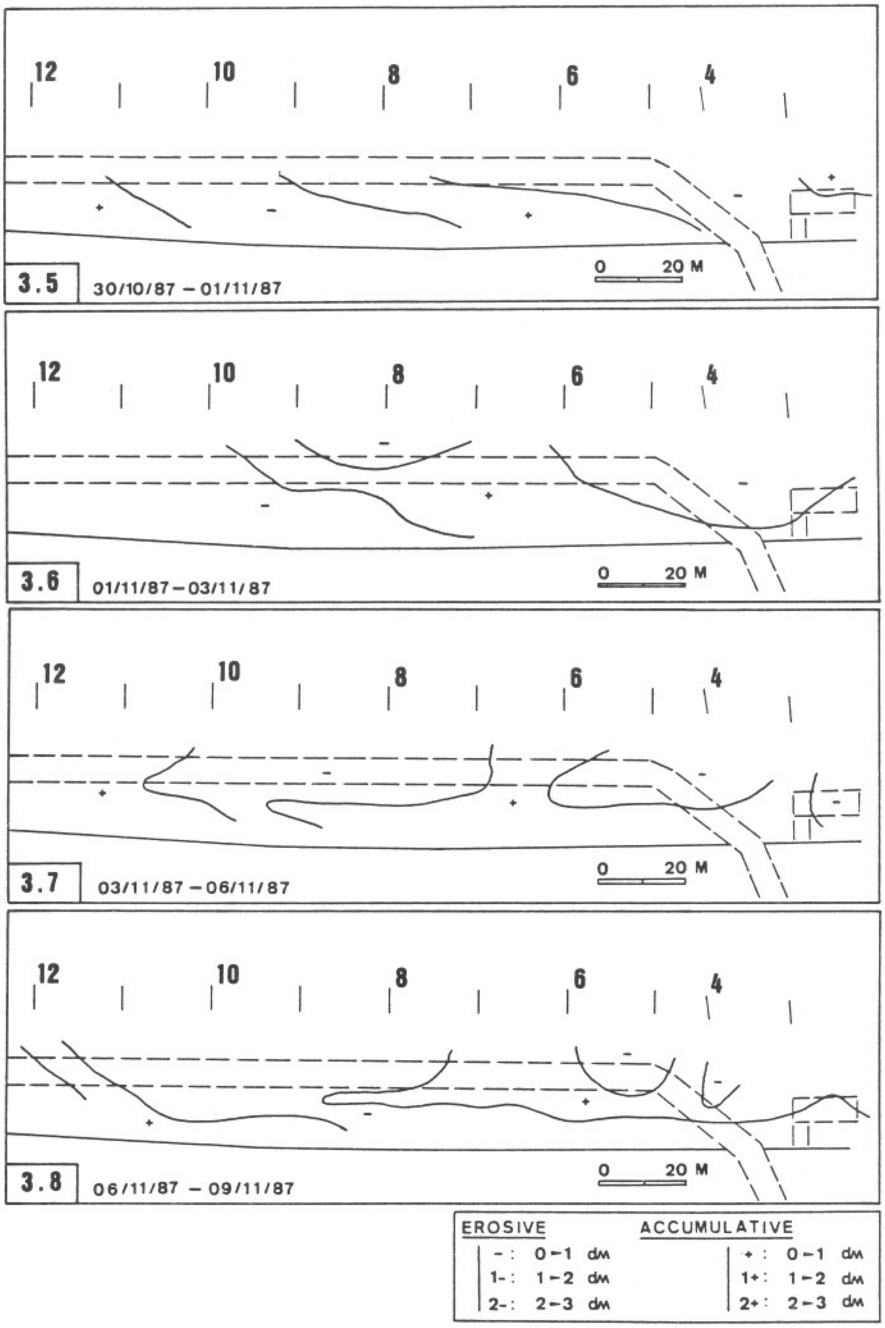


Fig. 20. (Series 3.5. to 3.8.) Morphological evolution of the intertidal sand surface of the edge accumulation. Period 30-10-87 to 09-11-87.
(Series 3.5. to 3.8.) Morfologische evolutie van het intertidale zandoppervlak van de randaanzanding. Periode 30-10-87 tot 09-11-87.
(Séries 3.5. à 3.8.) Evolution morphologique de la surface intertidale de l'accumulation de bordure. Période du 30-10-87 au 09-11-87.

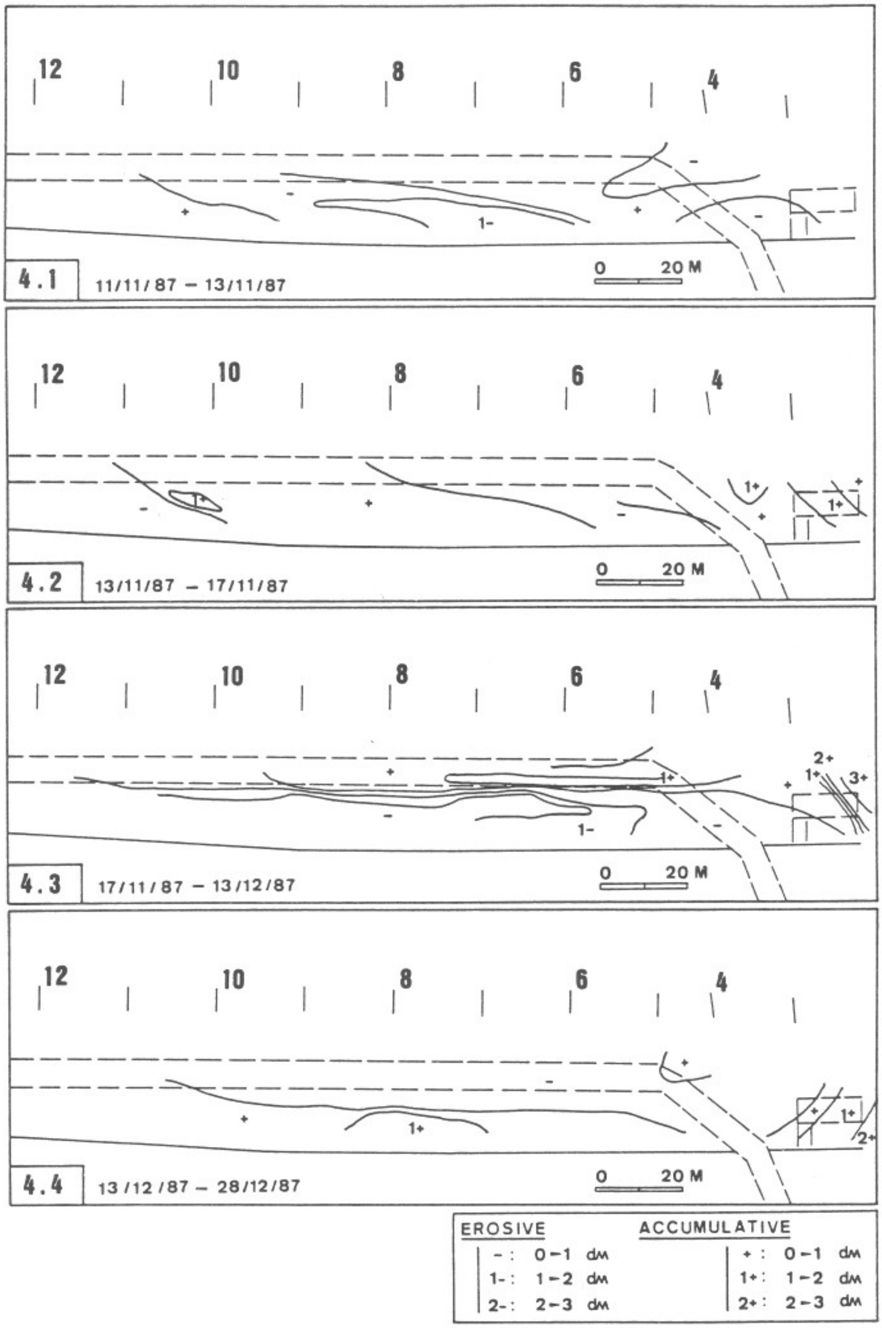


Fig. 21. (Series 4.1. to 4.4.) Morphological evolution of the intertidal sand surface of the edge accumulation. Period 11-11-87 to 28-12-87.
(Series 4.1. tot 4.4.) Morfologische evolutie van het intertidale zandoppervlak van de randaanzanding. Periode 11-11-87 tot 28-12-87.
(Séries 4.1. à 4.4.) Evolution morphologique de la surface intertidale de l'accumulation de bordure. Période du 11-11-87 au 28-12-87.

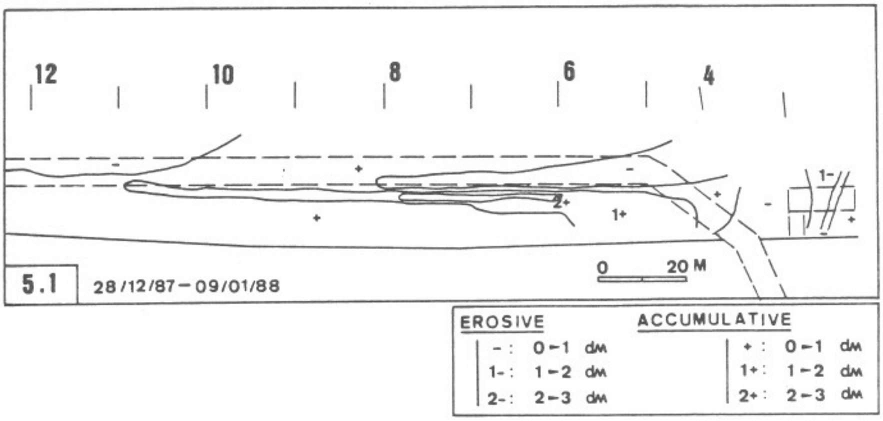


Fig. 22. (Series 5.1.) Morphological evolution of the intertidal sand surface of the edge accumulation. Period 28-12-87 to 09-01-88.
(Series 5.1.) Morfologische evolutie van het intertidale zandoppervlak van de randaanzanding. Period 28-12-87 tot 09-01-88.
(Séries 5.1.) Evolution morphologique de la surface intertidale de l'accumulation de bordure. Période du 28-12-87 au 09-01-88.

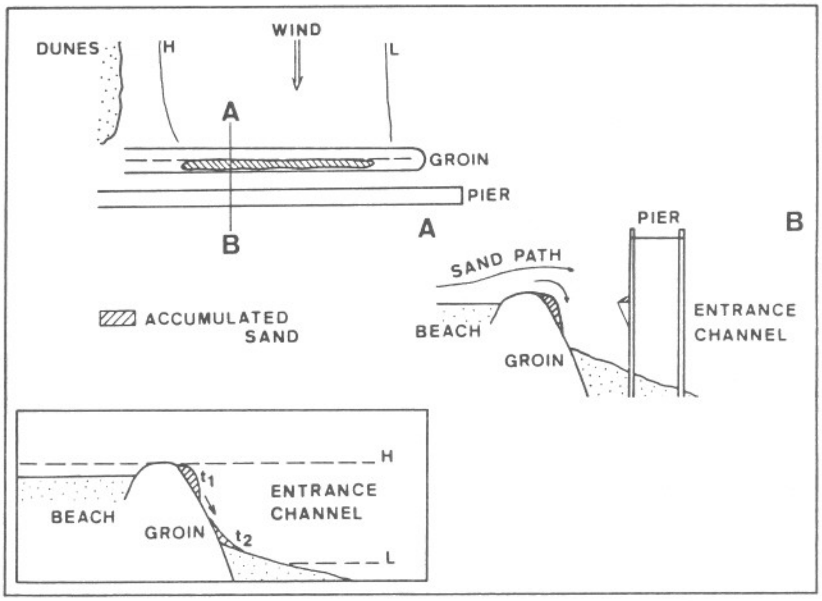


Fig. 23. Mechanism of stepwise eolian-sand supply to the channel.
Mekanisme van stapsgewijze eolische zandaanvoer naar de geul.
Mécanisme du transport de sable au chenal. Le sable s'est déplacé en étapes de la plage au fond du chenal.

G5 and G9, fig. 16) is especially pronounced during winds from the SSW (fig. 20 series 2.1). There is no accumulation at this point.

Once the sand has been carried onto the channel surface, it is locally reworked by wave action and gravitational processes. Under calm hydrodynamical conditions (little or no wave action) the edge accumulation sinks away as a whole to the central axis of the entrance channel (fig. 22 series 5.1; fig. 17 series 1.1 to 1.2). At extremely low-water levels, this process is accelerated considerably due to slumping of large sand masses from the steep accumulation slope to the channel bottom.

Because of its shallowness, the sand surface is nearly constantly subject to wave action. Incoming waves are reflected on the groin and move further inland alongside it, thus causing a pronounced landward sediment transport (fig. 24). This is particularly true under strong northerly winds which causes high waves to enter the channel from the north. Under such circumstances a continuous landward migration of sand ridges is noticed. The crests are oblique to the groin and their direction coincides with those of the crests of the reflected waves (fig. 19 series 3.7 to 3.10; fig. 20 series 4.1 to 4.3). As soon as wave action falls to a lower level, gravitational action gets the upper hand again (fig. 19 series 3.10 to 3.11). The landward sediment movement by wave action along the groin is noticed to occur very rapidly during northwestern storms (fig. 20 series 4.3), causing the rapid increase in sand volume at GO. This landward end of the edge accumulation grows very rapidly both vertically as well as horizontally (fig. 20 series 4.1 to 4.4). Volumetric analysis of the edge accumulation between G2 and G12 on 4 February '88 yields a sand volume of about 4.800 m³.

5. CONCLUSION

The shallowing of the Blankenberge harbour entrance channel is caused by a complex of interacting coastal processes with different intensities at different places within the coastal zone. The entrance channel which is perpendicular to the shore forms an obstacle to longshore eolian and longshore aquatic sediment movement. There is a clear interaction between the choking of the channel and nearby beach dynamics, each of them mutually influencing the other.

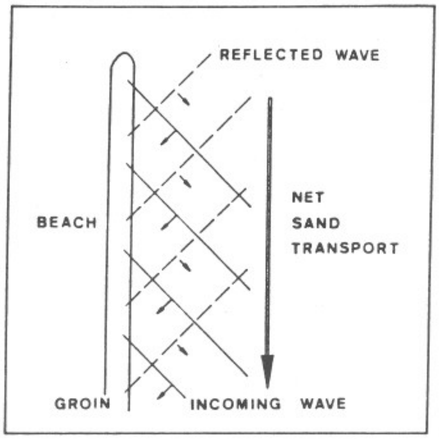


Fig. 24. Mechanism of net landward sand movement by wave action. The crest lines of incoming and reflected waves are drawn.
Mekanisme van residueel landwaarts zandtransport door golfwerking. Op de figuur zijn de golfkammen en de -dalen aangegeven.
Mécanisme du transport de sable résiduel vers la côte. Les crêtes et les creux des lames sont indiqués.

This case study illustrates the concept of a coastal system. The dune, beach, nearshore zone and artificially created channel subsystems evolve individually within the greater coastal system, influencing each other and determinated by sedimentological processes and meteorological and hydrodynamical conditions.

The filling in of the channel shows the self regulating capacity of the coastal system which compensates a disruption of the normal equilibrium state to restore the original balance. The results point out that without dredging, restoring of the original situation would take place very rapidly, with finally the reappearance of a non-interrupted beach.

Detailed morphodynamical research not only showed the interruption of longshore transport but also the local reworking of accumulated material within the channel.

The spit, growing longshore in an eastern direction as a consequence of longshore drift, fills the entrance channel starting from the western nearshore bar. This shallowness creates a zone of low wave energy landward of it, thus facilitating deposition between the two piers.

The sand supplied to the central part of the channel mainly originates from the intertidal beach. Beach drift and especially the sediment transport increasing runnel effect are the sand moving processes. At the high-beach zone, eolian sediment transport plays an important and often underestimated role.

Once the sand has been deposited in the channel, wave action and graviational action compensate the sand supply on the edges by moving it to the central channel axis. The supply of sand to the channel, as well as the reworking of the sediment on the channel bottom, does not happen continuously at the same rate. Both processes are accelerated during stormy periods and under rougher hydrodynamical conditions.

As to sediment dynamics, the research highlights the existence of important net longshore eolian as well as aquatic sediment transport in this part of the Belgian coast. Moreover, the study shows that important quantities of sand are moved in relatively short periods of time.

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