Abstract - Since more than 30 years the sandy rectilinear, WSW-ENE running Belgian coast between Bredene and De Haan with its ridge and runnel beach and which is only partly defended by groins, is attacked by beach erosion over a distance of several kilometer. The erosional wave gradually extends from the west to the east, in the same direction as the residual tidal current. In 1976, the erosion peak was situated at Bredene-Vosseslag where the mean annual retreat of the dune foot reached 4.5m. Since 1980, the erosion advanced to the east, attacking the beach at De Haan. Recently, residual beach erosion and dune face retreat progressed even more to the east over a distance of about 2 kilometer. Meanwhile erosion slackened at the western edge of the erosional section.

In 1978 and 1980, important beach nourishments with Longard armouring were put on the beaches between Bredene and De Haan. Moreover since 1980 spring beach bulldozering has been carried out at De Haan itself over a length of about 800m in order to install a practicable high beach for tourist activities at the De Haan waterfront itself. The beach nourishment has been accompanied by an extensive high beach fencing for fixation of the long shore net eolian sand transport, directed to the east in direction of the prevailing winds.

The behaviour of the beach has been monitored using a 20 year lasting visual inspection and a 12 year lasting detailed sequential half monthly beach profiling. The absolute unit volume of the beach between the dune front convexity and the neap low water line has been used as a basic parameter. The absolute unit volume difference in relation to the volume at a fixed date and the relative volume unit which is related to a mean value over an initial period of one year provide the final data output. The ensuing volumetric time series form an objective registration of the residual beach evolution and a valuable base form statistical treatment of the data.

Key-words - North Sea Coast, Beach erosion, Beach nourishment, Coastal defense, Coastal evolution, Coastal megaprotuberances, Coastal monitoring.

Résumé - Depuis près de 30 ans, la côte belge entre Bredene et De Haan est atteinte par l'érosion sur une distance de plusieurs kilomètres. L'estran y est sableux, de type à rides et sillons pré littoraux, rectiligne, orienté de l'WSW à l'ENE et partiellement pourvu d'épis. Graduellement, la vague érosive s'y déplace d'ouest en est, direction correspondant à celle du courant de marée résiduel. En 1976, le maximum d'érosion se situait à Bredene-Vosseslag. Depuis 1980, l'érosion est devenue particulièrement active à De Haan situé plus à l'est. Plus récemment encore, l'érosion s'est particulièrement intensifiée sur deux kilomètres à l'est de De Haan. Entretemps, l'activité érosive diminuait à la limite occidentale de la section érosive.

En 1978 et 1980, d'importants réhaussements avec armature Longard ont été effectués sur les plages à l'ouest de De Haan. En plus, à De Haan et à partir de 1980, chaque printemps, des sables ont été poussés vers le haut de plage afin d'en faire un espace continuellement accessible aux touristes ; des fascines ont été posées à l'ouest de De Haan, azfin de capter le transit éolien résiduel vers l’est, direction des vents dominants.

La côte fait l'objet d'un suivi ; suivi visuel sur une vingtaine d'années, suivi topographiques par profils séquentiels sur une douzaine d’années. On a utilisé le volume unitaire de la plage entre la convexité majeure du front dunaire et la laisse des basses mers de mortes-eaux comme paramètre de base. La différence de volume unitaire calculé par rapport à une valeur initiale et le volume unitaire relatif, établi par rapport à un volume de référence correspondant au volume moyen pour une période initiale d'une année fournissent les paramètres finaux. Ces valeurs forment une série numérique, enregistrement objectif et qualitatif de l'évolution littorale et base pour une analyse statistique.

Une attention particulièrée a été accordées aux effets de l'interruption et de la stabilisation du transit éolien longitudinal sur la haute plage. Son rôle dans l'intensification de l'érosion vers l'est est, malgré un certain impact positif mais local, mis en évidence. Le rôle éventuel d'autres phénomènes, comme les mégaprotubérances, les tempêtes et l'impact de certains types d'intervention de défense côtière et de gestion du littoral ont également été prises en considération.

Mots-clés - Mer du Nord, érosion côtière, rechargement de plage, évolution du littoral, suivi du littoral, mégaprotubérances côtières, défense côtière.
1. COASTAL MORPHOLOGY

The Belgian coast is 65 km long and forms a part of the Southern North Sea coast between Calais and the Dutch Rhine-Meuse-Scheldt delta (fig. 1). It runs from the SW to the NE and comprises a megatidal, linear and sandy beach of runnel and ridge type. It stretches out at the foot of a dune belt reaching elevations of 15 up to 25 m and consisting partly of coast-transversal parabolic dunes whose seaward arms merge with a linear seafront dune ridge. At low tide the beach width reaches a 500 m in the western part. To the east the width decreases while the beach becomes a little steeper. In summer time an eolian sand accumulation develops on the high beach along the dune foot. It forms a sand buffer against dune retreat due to scarping during winter storms.

Fresh water seepage from the dune foot is only important in some eroded zones especially during winter storm scarping. Seepage on the beach hampers eolian transport, provokes low tide sheet erosion and helps to invigorate wave action at high tide. Hence it presents locally a possible factor for a beach and dune erosion that lowers the groundwater table in the dunes, decreasing the outflow and stimulating cyclic new eolian supply.

More than 70% of that coastline shows soft or hard defence structures, mostly longitudinal dikes, groynes and beach nourishments. Some of the longitudinal structures have initially been built for touristic purposes. The coast is breached by a few harbour approach channels. At Zeebrugge two breakwaters protrude up to 3 km offshore since 1980. Both these structures interrupt the longshore sediment transport causing local erosion or accretion.

There are no rivers of any importance debouching along the Belgian coast. To the east the coastline slightly curves toward the entrance of the Scheldt estuary which is more tidal than river dominated. Most coastal sediments are reworked from the sea floor where they originally were deposited by fluvio-periglacial activity during the low upper
pleistocene sea level stands and before the holocene marine transgression.

That beach and dune belt is backed by a flat and low area of reclaimed intertidal flats of Dunkerquian age (polders mostly reclaimed during the 9-10th and the 12-13th century). Initially it corresponded to an island barrier cut by tidal inlets which have been closed mostly for reclamation purposes.

The foreshore zone very gradually deepens in a seaward direction. The MLLW-isobath of -5 m is situated at several kilometer off the low water line. More off shore the coast is preceded by large off shore sand banks, the most in shore ones running parallel to the coastline. Those situated at larger distance off shore (20 km) are more or less oblique to the coast.

2. HYDRODYNAMICS AND WIND ACTION.

The mean tidal range is about 4.2 m, slightly decreasing to the east. Spring tidal range is more important than neap tide range. At spring tide periods the high water mark stands distinctly higher and more duneward, and the low water mark more seaward.

Tidal currents are bidiurnal and continuously changing their orientation and velocity. In the fore shore area flood peaks reach velocities of 2 to 3 kts and are ENE oriented. Eb peaks reach velocities of 1 to 2 kts and are more or less WSW directed. Elongated and asymmetric current ellipses suggest a net longshore water displacement to the east and a residual, flood dominated displacement of sand to the east. This is confirmed by the development of sand accumulations at the west side of the Zeebrugge breakwater, of silt deposition at its eastern side, by eastward spit development in the approach channels (Blankenberge) and by beach erosion at their eastern side, as well as by the eastward shift of beach ridges, beach pads and ridge-transversal channels. Strong runnel currents accompanied by rip activity can develop. Longshore wave induced drift currents develop during periods of longshore winds or obliquely incoming waves, possibly in opposite directions.

Wave action depends on wind force and on wind direction. The fetch from northerly directions is more important than that from any other one. The most severe storms blow from the NW; the most frequent ones from SSW to W.

Eolian sand transportation on the beach is mainly conditioned by wind force, wind direction and beach humidity: prevailing winds and highest storm wind frequencies are from the SSW to W. They provoke sand transportation slightly oblique to the dune front and sand accumulation at the dune foot itself. Dry northeasterly winds may as well provoke sand accumulation at the dune foot.

Wind and wave action depend on the passage of mid-latitude depressions in the Southern North Sea area, and especially on their exact track and distance in relation to the Belgian coast. In the coastal area sea level upheaval due to wind pushing and to barometric depression severely enhances the effects of storms, the more that such rise generally is linked to the development of seaward bottom currents in the nearshore zone. During storms of NW direction the combined effect can provoke sea level rise of more than 1 m.

Eustatic sea level rise in Ostend is estimated at a mean value of 0.8 mm per year over the last 30 years. There are strong geologic and altimetric indications for a tectonic stability in this area during the Upper Quaternary.

figure 3 - Schematic outline of the displacement of the front of residual accretion and erosion of beach and dune face in the coastal section Bredene - De Haan during 1955-1990 (De Moor - 1991).
3. COASTAL EVOLUTION

Coastal morphodynamics are extremely complex as they are simultaneously
commanded by processes of erosion, transport and deposition of current, wave, tide,
wind and seepage origin, each of them varying locally and temporarily in intensity and
direction, so that direct and residual effects over varying time spans may be quite
different. Moreover they are characterized by a combination of different short term,
medium term and "long term" components. We do not intend to discuss them at length
nor to treat geological aspects of coastal genesis and evolution.

The results of a detailed but qualitative assessment of shoreline behaviour
during the period 1982-1987 are shown in figure 2. This map of the residual shoreline
displacement, used as criterion for beach erosion, shows that along the Belgian coast
several sections of residual erosion or residual accretion are succeeding each other.
Some of them are related to coastal management; some however are undoubtedly of a
natural origin. G. De Moor (1979) advanced that since the 60's the section Bredene -
De Haan corresponds to an erosive megaprotuberance. Such long term coastal
dynamics component consists of a coastal section of a few kilometer length,
characterized by a residual erosion continuing over several decades, changing in
intensity and sweeping slowly the coastline in the direction of the residual current, so
that it locally presents a longer term cyclic character (estimated in that case at about 50-
70 years) and is slowly replaced by an accretional phase. Inside the erosive
megaprotuberance storm effects seem to be more devastating. Continuing visual
observation of the coastal evolution in the Bredene - De Haan area during the period
1987-91 proved that the erosion meanwhile intensified toward the east, reaching De
Haan itself and progressing since 1990 over another 2 km to the east of De Haan, while
at its western tail stabilization and even accretion started, burying parts of defence
structures (fig. 3).

4. COASTAL MONITORING.

Objective description of the local beach evolution, comparison of beach
behaviour in different locations and research for causal relationships and prognosis of
further evolution cannot be fulfilled without the use of a numerical parameter for the
beach condition and its follow up by a sequential monitoring with an adequate
frequency, yielding a numerical time series signal available for a statistical analysis.
Moreover erosion means loss of material within a morphological entity and is not
necessarily indicated by shoreline displacements or merely by surface lowering.

The basic numerical parameter is the absolute unit volume of the beach
measured by detailed beach profiling in a fixed station. This geomorphological
approach assesses beach dynamics not by direct monitoring of particle or bedform
motion, but using residual effects of their multidirectional displacements during
successive phases of erosion and deposition. Time series are obtained by sequential
profiling with a frequency which can be fit to causal conditions (e.g. storms).

The absolute unit volume (AUV in $m^3/m$) of a beach or a beach section in a
profiling station corresponds to the volume defined by the vertical cross section along
the rectilinear transversal beach profile delimited by a vertical at the begin and another at
the end of the profile (or one of its section) and by its intersection with an horizontal
plane situated at a fixed depth below a local elevation datum, and further by an equal
cross section at 1 m parallel to the former. Limits of the total beach are defined by the
SLW line and by the dune front convexity at a fixed date. Beach profiling was carried
out with a 3 m step. Volumetric computations were performed with the programme
SPEV (G. De Moor, 1987). As the size of the beaches is varying, comparison of UV
data is only meaningful after normalization of the AUV in relation to a reference volume
specific for each profiling station. It corresponds to a mean value. This yields the
Figure 4 - Evolution of the relative unit volume difference (RUVd) of the total beach and of the high beach at Oostduinkerke (KP 12) in 1979-1991.

Figure 5 - Evolution of the relative unit volume difference (RUVd) of the total beach and of the high beach at Klimskerke - Vosseslag (KP 37) in 1978-1991.
relative unit volume (RUV in $\theta_{wd}$).

The absolute unit volume difference (AUVD) accounts for the value of the reference volumes themselves. This parameter corresponds to the difference between the momentaneous AUUV, and that at a former reference date or corresponding to a mean value for a fixed period. For similar reasons as mentioned before, a relative unit volume difference (RUVd) is to be calculated.

Figures 4, 5 and 6 show UVd time series for Oostduinkerke (KP 12)(*), a station in an accretional zone; for Klemserkerke-Vosseslag (KP 37), a station in an erosional zone with defence structures; and for Vlissegem (KP 42), a station without defence structures in a zone that recently became erosive. They confirm the simultaneous occurrence of different morphodynamical beach types along a uniform coast and the shifting of the megaprotuberance. These time series allow to formulate short term perspectives by trend analysis (G De Moor, 1991).

5. COASTAL DEFENSE AND ITS EFFECTS

Since 1976 the erosion in the area Bredene-De Haan became severe. In the period 1976-78 a series of winter storms caused a mean annual retreat of the dune face estimated at 4-5 m. In the period 1970-78 numerous groynes were constructed over a distance of 4 km west of Klemserkerke-Vosseslag. These the west of KP 36 reach the SLW line. East of KP 36 unto KP 37 they become shorter. They did not stop the erosional attack.

In 1978 an important beach nourishment (of about 1,000,000 m³ sand) with Longard armouring was put on the high and medium parts of the beach over a distance of 2 km between KP 35 and KP 37 (G. De Moor, 1979(b)). In the first months there was a quick reinstalment of the runnel and ridge morphology, followed up by a gradually decreasing erosion and lowering of the central part of the beach, by the exhumation of the sandtubes and deep pitting of the beach, and by the development of a high water line cliff that gradually advanced by wave attack. Meanwhile, more to the east, between KP 37 and KP 39, erosion continued as well, causing the exhumation of old defence structures (dating from an earlier 1910 erosional megaprotuberance, meanwhile covered by accretion) and, for the first time, provoking dune face cliffing in KP 39 in 1979.

In 1980, the beach nourishment was extended to the east over a distance of about 2.5 km between KP 37 and the west side of the De Haan waterfront, necessitating another sand supply of about 1,000,000 m³, mostly dredged on offshore sandbanks. Since 1980 erosion of the nourishment went on, although the highest part remained more save, with the exception of the section near KP 39.

In 1980 an extensive beach fencing was put on the higher part of the beach nourishment between KP 36 and De Haan over a distance of 3.5 km. It caused a quick fixation of the eolian sand transport and the formation of an artificial lower fore dune edged by a dune rim at its seaward side as shown by UVd-time series (fig. 5) and by beach profile matching (fig. 7). It did not change the beach behaviour, but caused a slow down of the retreat rate of the high water line cliff. Simultaneously the eolian sand supply east of the fenced area decreased and the high beach along the De Haan waterfront became very vulnerable to winter storms, despite residual currents dragging nourishment sands to the east.

Since 1980 residual erosion intensified at the De Haan waterfront itself, partly due to the shifting megaprotuberance and to lee side effect of the groyne field west of KP 37, but as well because of loss of eolian sand supply ensuing the beach fencing on its weather side in relation to prevailing coast parallel winds. Up to 1980 local winter fencing was sufficient to keep a high beach practicable for touristic summer activities.
figure 6 - Evolution of the relative unit volume difference (RUVd) of the total beach and of the high beach at Vissegem (KP 42) in 1978-1991.

eolian dune foot accumulation
decrease of eolian sand supply due to hedging in KP 37

figure 8 - Evolution of the relative unit volume difference (RUVd) of the high beach at De Haan (KP 40) and at Vissegem (KP 42) in 1988-1991. The time series shows the impact of the February 1990 storms and that of the high beach nourishments in KP 40.
Since 1980 spring time beach bulldozering and later on external sand supply became necessary to keep a practicable summer high beach. The impact of such sand supply on the high beach after the February 1990 storms is shown by the UVd-time series for KP 40 at De Haan (fig. 8).

Meanwhile the erosional attack shifted further to the east. Since 1980 the beach at De Haan (KP 40) was attacked with increasing severity. In February 1990, storm attack at the KP 39 site, inside the erosional megaprotuberance, became so important that the nourishment on the high beach disappeared despite the armouring and the artificial foredune. The original dune face was again laid bare, steepened and sliding along the dune face started. In February 1990 as well important residual erosion reached KP 42, east of De Haan, as shown by UVd-time series (fig. 8). The dune front between De Haan and Wendoine retreated markedly. Due to steep cliffing, sand slabs slid down the dune face towards the dune foot where they were eroded by waves and the sand spread out over the beach, weakening the storm effects on the beach surface. This worsening is partly due to longshore current deviation by the westward situated groyne protrusion as the current is hitting the coast in this section under a sharper angle.

5. STORM IMPACTS.

UVd-time series for stations inside and outside the Bredene-De Haan section, prove that direct and residual storm effects were much more important inside the erosional megaprotuberance. UVd-time series for KP 37, KP 40, KP 42, all situated inside the megaprotuberance, show severe losses and a slow or merely a partial recovery even after more than 1 year (fig. 9). UVd-time series for KP 12 and KP 51, both situated outside an erosive megaprotuberance, show little direct storm damage, quick beach restoration and resumption of the accretion (fig. 10).

The effect of the winter storms of February 1990 illustrate the areal differentiation of the immediate and the residual storm impact along that relatively short and uniform coast. Tide and wave data show equality of hydrodynamic conditions along the coast during the storm (G De Moor, 1991). Changes neither in storm characteristics, nor in defence structures, could be considered as a main cause for the differentiation.

6. CONCLUSIONS

Erosional and accretional megaprotuberances are alternating along the Belgian coast. They are slowly shifting to the east, in the direction of the dominant flood peak current. Various small scale and short term beach processes are acting within the megaprotuberance. Storm events seem to be one of the short term events that discontinuously enhance the evolution of the erosional megaprotuberance and its coast sweeping displacement.

On a local scale the beach nourishment in the Bredene-De Haan area was a defendable way of local soft defence against dune front retreat during the last 10 years. Nevertheless beach erosion went continuously on, high water line cliff retreat persisted, the armoured beach was strongly deteriorated by deep pitting and exhumation of the sandtubes and it became a dangerous section.

Eolian sand fixation by fencing of the high beach proved to be of good local help. Its impact was better than that of groynes. At some longshore distance however, in places situated at the lee of the fencing in relation to the prevailing (in fact the most effective) winds, it contributed, due to the interruption of the natural eolian sand supply, to the non restauration of the dune foot sand buffer and therefore to an increase of the winter storm damage and the residual erosion. The effect of such measures depends highly on wind direction relative to the orientation of the coastline and the position of the station. Uncomplete or uneven coverage by groynes intensifies erosion.
figure 9 - Evolution of the absolute unit difference (AUVD) of the high beach at Oosduinkerke (KP 12) and at Zeebrugge-West (KP 37) at De Haan (KP 40) and at Vlissegem (KP 42) in 1988-91. The three stations are located inside the Bredene - De Haan megaprotuberance. The impact of the February 1990 storms is striking. Partial recovery in KP 40 is mainly due to spring high beach nourishment.

figure 10 - Evolution of the absolute unit difference (AUVD) of the high beach at Oosduinkerke (KP 12) and at Zeebrugge-West (KP 51) in 1988-91. The two stations are located outside a megaprotuberance. In both stations, the high beach is partly hedged for eolian sand transport fixation. In Zeebrugge, the accretion is mostly conditioned by breakwater effect upstream flood peak current direction.
The use of the numerical UV-parameter proved to be a useful way for objective description and analysis of beach behaviour. Its simplicity, low budget requirements and flexibility present numerous practical and scientific advantages.

REFERENCES


