COASTAL EROSION CONTROL BASED ON THE CONCEPT OF SEDIMENT CELLS
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1. Introduction

Nearly all coastal states have to deal with the problem of coastal erosion. Coastal erosion and accretion has always existed and these processes have contributed to the shaping of the present coastlines. However, coastal erosion now is largely intensified due to human activities. Presently, the total coastal area (including houses and buildings) lost in Europe due to marine erosion is estimated to be about 15 km^2 per year. The annual cost of mitigation measures is estimated to be about 3 billion euros per year (**EUROSION** Study, European Commission, 2004), which is not acceptable.
Although engineering projects are aimed at solving the erosion problems, it has long been known that these projects can also contribute to creating problems at other nearby locations (side effects). Dramatic examples of side effects are presented by Douglas et al. (*The amount of sand removed from America's beaches by engineering works, Coastal Sediments, 2003*), who state that about 1 billion m^3 (10^9 m^3) of sand are removed from the beaches of America by engineering works during the past century.
The EUROSION study (2004) recommends to deal with coastal erosion by restoring the overall sediment balance on the scale of coastal cells, which are defined as coastal compartments containing the complete cycle of erosion, deposition, sediment sources and sinks and the transport paths involved. Each cell should have sufficient sediment reservoirs (sources of sediment) in the form of buffer zones between the land and the sea and sediment stocks in the nearshore and offshore coastal zones to compensate by natural or artificial processes (nourishment) for sea level rise effects and human-induced erosional effects leading to an overall favourable sediment status.
In the CONSCIENCE Project the coastal cell concept to deal with coastal erosion is further explored by identifying and analyzing the sediment volumes accumulated in large-scale and small-scale coastal cells at various pilot sites. Mechanisms causing chronic erosion and fluctuation erosion related to coastal variability are identified and discussed. The effectiveness of soft and hard remedial measures for sandy beaches are assessed based on laboratory, field and modelling experiences.

The basic objectives of the present study are:

- definition of coastal cells, sediment budgets and processes involved;
- definition of coastal variability and coastal erosion;
- mitigation of coastal erosion by soft nourishment (short and long term): options, consequences and guidelines;
- mitigation of coastal erosion by hard structures (seawalls, groynes and detached breakwaters): options, consequences and guidelines.

Information on the erosion of gravel/shingle beaches and barriers is presented in another paper (**Van Rijn, 2010**)

2. Coastal cells

Many coasts consist of relatively straight and flat (low-gradient) beaches. These simple, flat beach coasts may differ greatly from the originally submerged coasts. The most basic coastal form is an indented coast (bay-headland coast or embayed coast) resulting from subsidence or from submergence due to sea level rise and which has not been modified by marine processes (waves and currents). Wave attack on an indented bay-headland type of coast will result in concentration of wave energy on the headlands (due to refraction) and reduction of wave energy in the bays, which may lead to headland erosion and bay deposition, if these coastal forms consist of erodible material. Longshore currents accelerating along headlands and decelerating in the bay area will enhance headland erosion and bay deposition. Thus, headlands are cut back and bays are filled up. In case of uneven resistance against erosion, the 'softer' headlands will erode more rapidly and the more erosion-resistant headlands remain present as promontories along the coast. Rock-type and cliff-type coasts consisting of variable erodibility retain as irregular crenulate coasts.
When a coast is very irregular with large bays and pronounced headlands; the evolution of each bay will be independent of that of adjacent bays, because the sediment can not easily pass the headlands (each bay is a closed cell). If the headlands are equally erosive, the coastline will be straightened. This can be demonstrated by considering an undulating sandy shoreline under wave attack from a constant direction, see Figure 1. The longshore transport depends on the angle between the nearshore wave crest (based on refraction) and the coastline. The longshore transport rate is maximum on the downdrift flank of the protruding headland resulting in erosion on the updrift flank and accretion on the downdrift flank and coastal straightening on the long term.

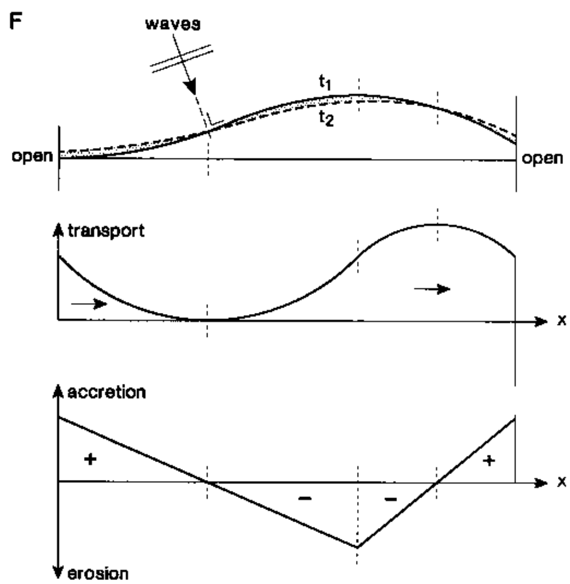


Figure 1 *Coastal straightening by longshore transport gradients*

On larger spatial scales this process, dominated by littoral drift, will continue until the coastline consists of a series of smooth beach curves (arcs with curvatures between 1 and 100 km, depending on wave climate and erodibility). The end points of the arcs may be associated with old, more erosion-resistant headlands, with outlets and deltas of rivers, with ebb deltas of tidal inlets or with man-made structures. The dominant waves will turn the beaches to face the direction of the dominant wave approach by moving sediment to the downwave end of the arc resulting in a (hollow) arc-type coast. The formation of smooth arc-type barrier beaches is the most basic element of coastal straightening and is the ultimate stage of wave-dominated coastal evolution.
Headlands present along a sandy shoreline act as natural groynes and compartmentalize the shoreline into sediment cells. One large isolated headland usually causes an embayment to form on its downdrift shoreline. A series of two or more headlands spaced closely generally causes the formation of embayments that are semi-circular in shape. Headlands with broad faces block significant amounts of wave energy sheltering the beaches in the lee zone. The

most important characteristics of headlands are: convergence points for wave energy; obstruction to longshore tide- and wind-induced currents, convergence of currents; large-scale circulation zones downstream of headland; obstruction to littoral drift; fixation points for seaward rip currents promoting offshore transport; fixation points for spit formation and shoals originating from headland erosion.
A sandy coast between two erosion-resistant points (headlands or groynes) will readjust its orientation to arrive at a beachface as much as possible perpendicular to the main wave direction. Sand will be eroded at the updrift end of the beach and carried to the downdrift end of the beach. This process is known as bay or cell development. A crenulate-shaped bay or cell formed under oblique incident waves is stable (static or dynamic equilibrium), if the littoral transport is zero (on average) or constant everywhere along the beach. Storm waves or swell waves from one dominant direction are the most effective agents in bay formation. A stable bay consists of three parts: an almost circular section behind the upcoast headland, a logarithmic-spiral curve, and a nearly tangential straight beach segment at the downcoast end. The upcoast headland is the point at which diffraction takes place.

Whatever the initial form of a relatively soft erodible coast, the ultimate equilibrium coast of sandy materials should be one of simple wide curves (arcs) and relative straightness. Small-scale morphological features developing along these smooth beaches are: berms, terraces, scarps, beach cusps, sand waves, parallel/transverse bars and rip channels. Straight beaches may be interrupted by outlets of small isolated rivers.

A straight coast consisting of various coastal arcs can be considered as a geomorphic system consisting of various coastal cells, each with its own spatial and temporal scale. Cells are self-contained units within which sediment circulates with cycles of erosion and deposition including sources, transport paths and sinks. In each cell the morphology is driven by water and sediment motions, based on energy input from the incoming wind, waves and currents. Gradients in sediment transport result in morphological changes, which in turn influence the water motion in a continuous cycle.
Cell and sub-cell boundaries can be defined by identification of discontinuities in rate or direction of sediment transport.

The following types of alongshore cell boundaries are defined:

- *fixed absolute boundaries*; barriers to all sediments (hard rock headlands, long jetties, deep inlets, canyons, navigation channels; long harbour breakwaters);
- *fixed partial boundaries*; bypassing or periodic (often storm-related) throughput of sediments take place, (soft rock/ compound cliff type headlands and shallow inlets);
- *transient partial boundaries*; generally, have a more diffusive character and have limited stability (spits, sand banks, shallow channels, short headlands, short breakwaters).

In cross-shore direction the coastal cell system between the shore and the shelf may be subdivided in the following three zones: upper shoreface between waterline and -8 m depth contour, middle shoreface between the -8 m and -20 m depth contours and the lower shoreface between -20 m contour and the shelf. These cross-shore zones of coastal cells are linked by sediment transport processes. In the lower and middle shoreface zones the (bed load) transport rates are relatively small and hence the response time of the morphology is generally slow (passive behaviour). In the surf zone the transport rates are relatively large and the response time of the morphology is faster, almost on the scale of the events (active behaviour).

Possible sources of sediment within a cell are (see also **Figure 2**): sediment input by rivers and estuaries, cliff and dune erosion, onshore transport due to wave asymmetry from the shelf, artificial nourishment, biogeneous deposition (shell and coral fragments). The most important sinks are: offshore transport due to undertows and rip currents during storms, trapping in local depressions (canyons) and mining. Sources and sinks are herein identified as phenomena of an irreversible nature; a sediment particle eroded from a cliff system cannot return to this system and a particle deposited in a canyon is a permanent loss for the coastal zone.
Besides sources and sinks, stores or accumulations can be distinquished. Stores can be sand/gravel bars and banks migrating or resting in the coastal system. Sediment particles may be stored for a certain period in these features, but later the sediments may be mobilised again to take part in the transport process.

Coastal evolution and hence coastal sediment budgets are strongly related to long term sea level rise (relative to the land). Shoreline response to relative sea level rise can be broadly divided into two main categories: erosional transgression and depositional regression (**Van Rijn, 1998**).
Erosional transgression refers to a net landward movement of the shoreline in the case of rising relative sea level. The well-known concept relating shoreline recession to water level rise is the geometric shift concept of **Bruun** (**1962, 1988**), which is based on the idea that the (dynamic) equilibrium profile of the beach and surf zone moves upward and landward in response to sea level rise (Bruun-rule; see **Figure 2**). Using this concept, the required annual input of sediment (accomodation space) to the nearshore zone is equal to the area (m^2) of the nearshore zone times the annual rate (m/year) of relative sea level rise. Assuming that relative sea level rise is 2 mm/year and that the width of the nearshore zone is in the range of 1 to 10 km, the required sediment supply to the nearshore zone per unit length of shoreline is about 2 to 20 m^3/m/year to keep up with sea level rise. This volume of sediment will be eroded from the coast, if nothing is being done. This type of coastal erosion can be prevented (compensated) by coastal nourishment of the same amount (2 to 20 m^3/m/year). Examples of eroding coasts due to sea level rise are: Mississippi delta coast, USA; Egypt coast.
Depositional regression refers to seaward shoreline evolution by the formation of a series of beach and dune ridges due to abundant sediment supply by longshore and onshore transport processes exceeding the erosional effects associated with relative sea level rise. Examples are: geological development of Holland coast (5000 years BC to 1000 years AC; see **Mulder et al., 2008**) and South-East Australian coast.

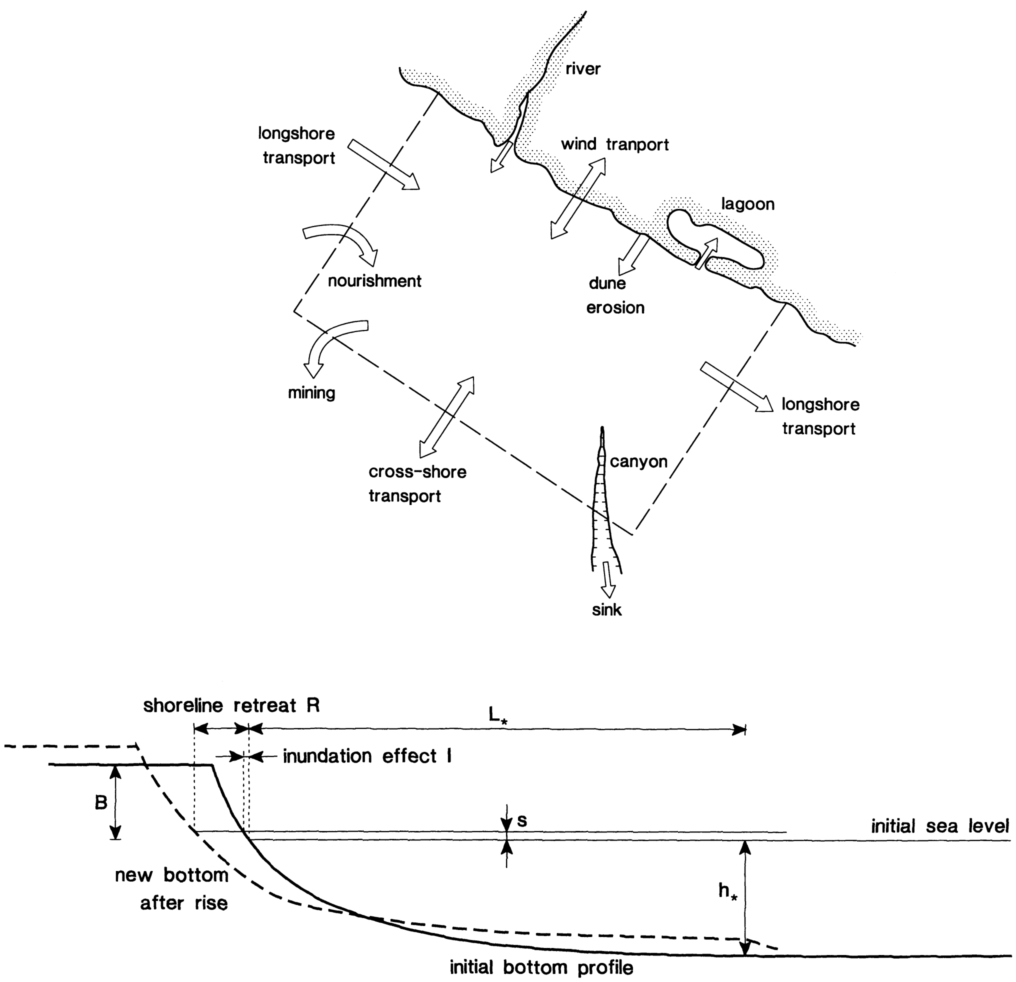


Figure 2 *Coastal sediment budget and effect of sea level rise*

The analysis of the sand budget (mass balance of inputs and outputs) for a predefined cell gives insight in the relative importance of the various sediment sources and losses. Sediment transport estimates across the cell boundaries are important in assessing the morphological development of coastal cells. Net longshore transport rates may be estimated from depositional forms near (man-made) obstructions like groynes, breakwaters, submerged offshore breakwaters, headlands or from sediments accumulated in depositional forms like spits, tombolos, etc. Contributions in cross-shore direction (on-offshore transport) usually are neglected.
An excellent example of coastal sediment budget analysis is the Coastal Regional Sediment Management Plan of California, USA (www.dbw.ca.gov/csmw).

Conclusions coastal cells

- smooth-arc type beaches and dunes are the most basic elements of coastal straightening and are the ultemate stages of wave-dominated coastal evolution; headlands act as natural groynes and compartmentalize the coast into sediment cells;
- sandy coasts between two erosion-resistant points (headlands or groynes) will readjust in orientation in response to the local wave and current climate; sand will be eroded at updrift end of the beach and carried to the downdrift end of the beach (cell development);
- cells are self-contained micro, meso or macro units within which sediment circulates with cycles of erosion and deposition including sources (input by rivers, estuaries, cliffs, dunes, shelf, artificial nourishment), transport paths and sinks (dead zones, depressions, canyons, mining);
- coastal sediment budgets are strongly related to relative sea level rise.

3. Mechanisms of coastal erosion and variability

3.1 Coastal erosion

The erosion of sandy beach-dune systems and soft cliff systems (see **Figure 3**) due to storm waves has been studied by many researchers. Reviews are given by **Komar (1976)**, **Vellinga (1986)** and **by Van Rijn (1998)**. Most of the studies involve the analysis of experimental results in small-scale and large-scale flumes. Detailed and complete field data sets are scarce, because usually the pre-storm bed profiles are missing.
Coastal erosion strongly depends on the type of coast (exposure, wave climate, surge levels, sediment composition, beach slope). Factors favouring coastal erosion are:

- *exposure*: wave and current attack will be concentrated on headlands, capes and other protruding coastal forms (promontories); wave exposure is strongly related to the beach grain size; in the case of a fine sandy beach (0.2 to 0.3 mm) the wave exposure generally is assumed to be low for an annual mean significant wave height $H_s < 0.75$ m at edge of surf zone (say, depth of 6 m); moderate for H_s between 0.75 and 1.5 m; and high for $H_s>1.5$ m;
- *high tides (spring tide), high storm surge levels and severe storm intensity*: flooding, wave overtopping and breaching may occur;
- *persistent oblique wave attack*; wave-induced currents increase with increasing wave angle; net littoral drift will be relatively large in case of one dominant wave direction;
- *unconsolidated sediments*: low sandy coasts can be relatively easily eroded (1 to 10 m/year); bluff and cliff type coasts are more erosion resistant (0 to 1 m/year);
- *absence of nearshore bars/banks/shoals*; relief is important for offshore dissipation of energy (wave breaking);
- *presence of nearby sinks*; trapping of sediment by inlets, back-barrier basins (lagoons), ebb shoals, offshore sand banks, harbour basins, deep navigation channels, offshore canyons, etc.

Coastal erosion has both cross-shore and longshore components. Dune and soft cliff erosion during extreme events mainly is a cross-shore process bringing the sediments from the immobile dune front into the mobile littoral system. Beach erosion also is an alongshore process due to the presence of eroding longshore currents including tidal currents.
Sea level rise may also contribute to chronic erosion of straight sandy beaches in wave-dominated areas (Bruun rule, see **Figure 2**). Coastal erosion related to relative sea level rise is in the range of 2 to 20 m^3/m/year, see **Section 2**.

Dune and soft cliff erosion erosion are mainly caused by hydrodynamic and soil-related processes during major storm events with surge levels above the dune toe level. The basic mechanisms are:

- erosion and undercutting from swash uprush during initial stages; the swash uprush behaving as a bore (characterized by the leading edge velocity and height) reaches the toe of the dune, scoures sand and is reflected down the beach; the swash may also cut a slot of 0.2 to 0.3 m in the dune foot after which the upper dune sand slides down; the retreat can be as large as 1 m per tide; the swash may be superimposed on long-period waves (surf beat, infragravity waves);
- erosion and undercutting by the impact of breaking waves at increasing surge levels in combination with high tide levels; soaking of the sediment mass decreases resistance; often locally a vertical scarp (steep vertical face) is formed depending on soil conditions (especially in somewhat consolidated soil, see **Figure 3**); slope and scarp failure (layer separation, slumping or overturning, avalanching) will follow undercutting; scarps mainly occur when the upper dune face has some internal coherence or is covered by vegetation; the retreat can be as large as 5 m per tide;
- wave overtopping (water surface lower than crest) and wave overwashing (water surface higher than dune crest).

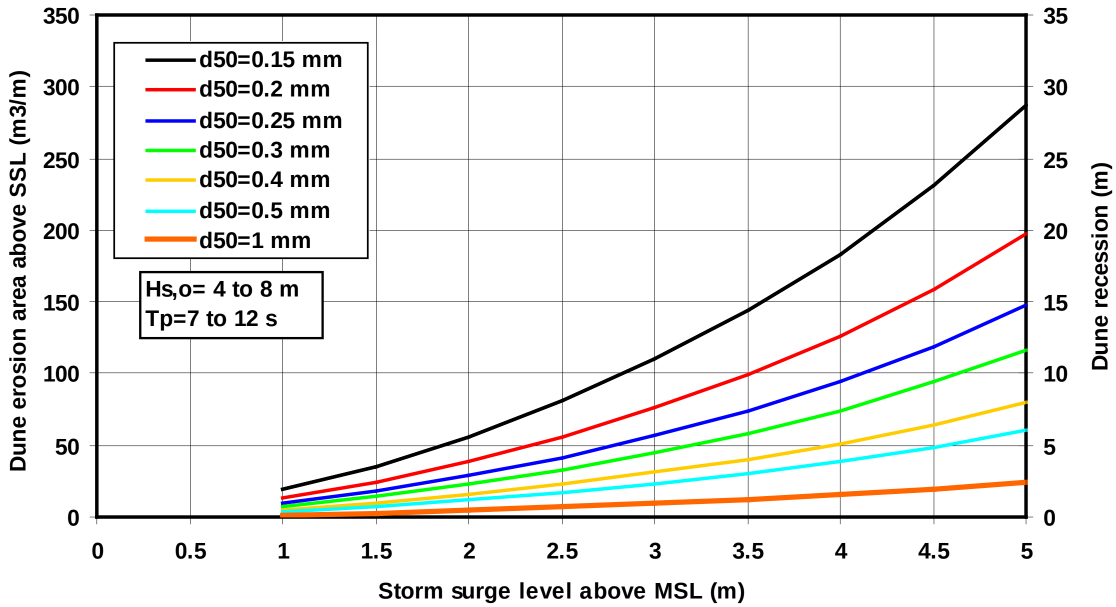
Dune erosion is most strongly related to high storm surge levels (SSL). Dune erosion generally leads to beach accretion and bar development when the beach and surf zone slopes are relatively flat (dissipative conditions). In case of a steep surf zone slope the dune and beach zone are eroded simultaneously and the sediments are carried away to deeper parts of the profile.

Various empirical models are available to estimate dune erosion. A semi-empirical model (S-beach) has been proposed by **Larson and Kraus (1989)**. This model is based on equilibrium theory with limited description of the physical processes. A beach profile is assumed to attain an equilibrium shape if exposed to constant wave conditions for a sufficiently long time. An equilibrium profile ($h=Ax^{2/3}$ with x=cross-shore coordinate and A= shape paramer depending on bed material diameter) dissipates incident wave energy without significant net change in shape. The transport rate is related to the difference between the actual wave energy dissipation and the equilibrium wave energy dissipation along the equilibrium profile. The transport direction is determined from an empirical criterion. **Steetzel (1993), Van Thiel de Vries (2009), Van Thiel de Vries et al. (2008)** and **Van Rijn (2009)** have used process-based mathematical models based on cross-shore wave propagation, wave shoaling, wave refraction and wave breaking. The output of the wave model is used to compute the local cross-shore sand transport rate. Bed level changes are determined from cross-shore gradients of the transport rate in a numerical loop system.

Figure 3 *Examples of soft cliff erosion, near Mar del Plata, Argentina*

Figure 4 shows plots of the dune erosion area (above the storm surge level) after 5 hours as a function of the sediment size and the storm surge level for two wave climates (North Sea and Mediterranean) based on the simplified cross-shore model of **Van Rijn (2009)** for the case of waves normal to the coast. The effect of the wave climate is very small. **Vellinga (1986)** has found that the most effective duration of a storm along the North Sea coast is about 5 hours. The significant offshore wave height in the North Sea is assumed to vary between 4 and 8 m for surge levels between 1 and 5 m above mean sea level (MSL). Dune erosion after 5 hours is largest for relatively fine sediments (0.15 mm) and reduces rapidly for coarser sediments. Dune erosion of gravel (1 mm) is only 15% of that of fine sand (0.15 mm). The shoreline recession (E) due to dune erosion can be estimated from E=A/h with A= dune erosion area above storm surge level SSL and h= dune height above the storm surge level. **Figure 4** shows dune recession values (axis on right side of plot) based on a dune height of 10 m above SSL. Dune recession values are twice as large for dune height of 5 m.
The simplified model of **Van Rijn (2009),** applied to compose **Figure 4**, produced fairly good results using measured dune erosion data of Inch Beach (sand of 0.24 mm) in Ireland (pilot site of CONSCIENCE project). The data represent accumulated dune recession values in the range of 14 to 28 m over the period December 2007 to May 2008 with offshore wave heights in the range of 2.5 to 5.5 m (periods of 12 to 16 s). The computed total dune recession value for this period is about 20 m (accumulation of various storm events, each with duration of 5 to 6 hours). This confirms that **Figure 4** yields realistic results.

Dune erosion is very much related to extreme events with high surge levels including tidal effects. Extreme storms have a large return period. For example, a North Sea storm with a surge level of 5 m above mean sea level has, on average, a return period of about 10,000 years (so once in 10,000 years), but it can happen tomorrow. The return period of a surge level of only 2 m is 1 year; so, once every year. The computed dune erosion values after 5 hours are of the order of 20 m^3/m for a surge level of 1 m and up to 300 m^3/m for a large surge level of 5 m, see **Figure 4**. To withstand an extreme event with a surge level of 5 m above mean sea level, the dune row fronting the sea should have a minimum width of the order of 50 m. In 'normal' conditions with two or three events per year with surge levels between 1 and 2 m per year, the total annual dune erosion may be as large as 50 m^3/m/year locally along the sandy North Sea coasts. Most of the eroded dune sand will be deposited on the beach from where it can be returned to the dune front by wind-induced forces or carried away by cross-shore and longshore currents. Dune accretion at the dune front due to wind effects is of the order of 10 to 20 m^3/m/year (**Van der Wal, 2004**) and is generally not sufficient to compensate dune erosion on the annual time scale by natural processes. Thus, dune erosion generally leads to a permanent loss of sand which can only be compensated by artificial nourishment (dune restoration).



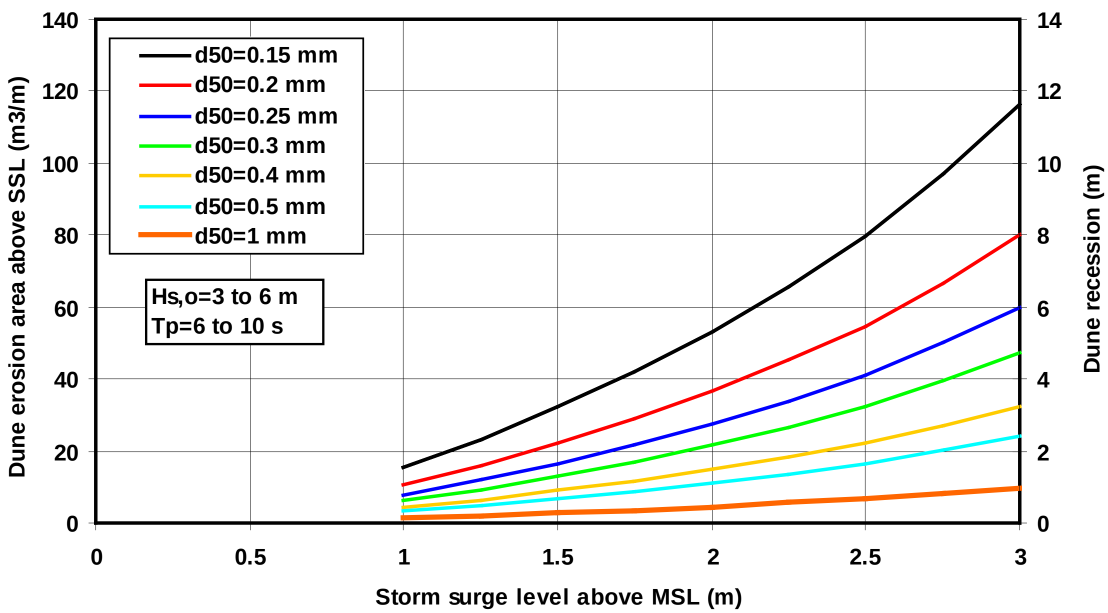


Figure 4 *Dune erosion after 5 hours during a storm event as function of sediment size and storm surge level for two wave climates: North Sea (upper) and Mediterranean (lower); dune recession based on dune height of 10 m above SSL*

Beach erosion during minor storm events with surge levels below 1 m and offshore waves up to 4 m is of the order of 10 to 20 m^3/m per event (5 to 10 hours or so). Beach build-up during daily fairweather waves is of the order of 1 to 2 m^3/m/day (**Van Rijn, 1998**). Thus, beach erosion can easily be compensated by natural processes on the time scale of weeks to months depending on the type of post storm wave climate (North Sea or Mediterranean).

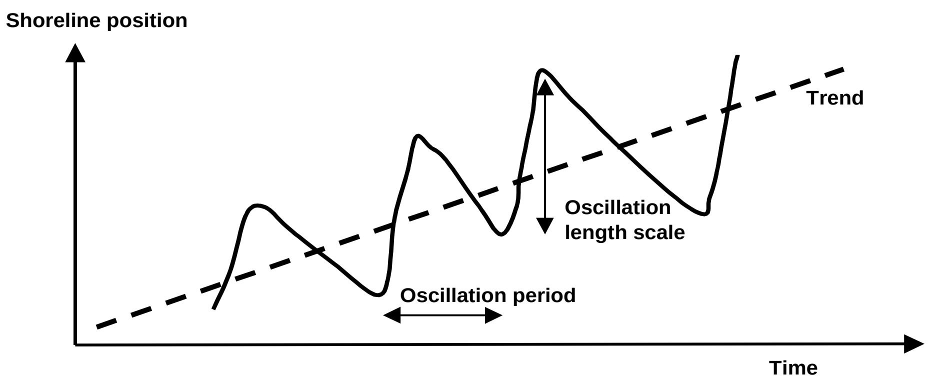


Figure 5 *Shoreline position as function of time*

3.2 Coastal variability

Coastal variability (shoreline variations) is not the same as coastal erosion, which is herein defined as the permanent loss of sand from the system. Shoreline variations (LW-line, HW-line, dunefoot-line) generally are variations around a systematic trendline (chronic erosion or deposition; see **Figure 5**); the trendline may be caused by natural (autonomous) processes or related to man-made structures. Several time scales can be identified:

- long-term variations (centuries): changes in relative sea level; changes in tidal range and wave climate, availability of sediment; long-term shoreline changes are in the range of 100 to 1000 m/century;
- medium-term variations (years, decades): changes in wave climate and hence in wave-current conditions, migration of tidal channels and flats, sand bank migration, migration of inlets, closure of inlets, effects of coastal structures; shoreline changes can be up to 100 m over a period of 10 years near tidal inlets (attachment and detachment of shoals and banks; **Stive et al., 2002**); shoreline changes due to migrating sand waves (length of 1000 to 2000 m; longshore migration rates of 50 to 200 m/yr) or other rhythmic features along an open coast are in the range of 10 to 100 m over 10 years;
- short term fluctuations (seasons; days to months): bar migration, sand wave migration, rip channels, beach fills, effects of coastal structures; the maximum local shoreline changes on the storm time scale (days) and on the seasonal time scale (summer-winter response) of the open shoreline are generally in the range of 1 to 50 m.

Shoreline variations due to natural forcings are manifest at all time scales; shoreline variations due to human forcings typically operate at decadal and centennial time scales. Often, the oscillating component of the shoreline change (expressed in m/day) is much larger than the long-term change of the trendline.
Spectral analysis (**Stive et al., 2002**) of time series over a period of about 10 years for three typical ocean-fronted beaches (Duck, USA; Ogata, Japan and Ajigaura, Japan) shows pronounced peaks corresponding to a 1-year cycle indicating the effects of seasonal (summer-winter) changes. Higher frequencies are also present in the data sets associated with the typical return period of storm events. Peaks at lower frequencies (2 to 4 years) are also present, most probably associated with migrating sand waves.

List et al. (2003) have found that the regionally-averaged beach slope becomes a few degrees (1^o to 3^o) flatter (classic berm-bar profile response) during storm events for three sites along the east coast of the USA. Profile recovery (steepening) did occur during post-storm conditions. These locations were defined as short-term reversible hotspots (STRH). The maximum local shoreline change (erosion) over a coastal stretch of 70 km during pre-storm and storm conditions over 3 to 5 days was about 20 m; the maximum local shoreline change (accretion) during post-storm conditions was also about 20 m. However, this type of symmetrical response did not always occur because many exceptions (non-STRH) were observed along the three sites with either no slope response or even a steepening response during storms (**List et al., 2003**).

Beach behaviour usually is expressed by the temporal position of the high water line (HW), low water line (LW) or dune foot line (DF), but spatial beach variations due to alongshore migrational features such as sand waves, crescentic bars, rip channels, etc can also be observed. Temporal and spatial variations of the shoreline are closely related and often are manifestations of the same phenomena. Temporal variations generally show a mean component (time-averaged trend) and an oscillating component (variability), see **Figure 5**. The mean component can be a linear trend (erosion or accretion), but most often it is a long term oscillation cycle (erosion followed by accretion or vice versa) and generally the shoreline recession or accretion is of the order of 1 m per year for straight coasts. Near inlets these mean (trend) values may be somewhat larger (up to 10 m/yr) due to the interaction of the beach with large scale shoals detaching from or attaching to the coast.

At many natural beaches the cyclic beach behaviour is strongly related to the cyclic breaker bar behaviour. The typical beach-bar behaviour on the time scale of the seasons is the offshore-onshore migrational cycle with offshore migration of the bar system during the winter season and onshore migration and beach recovery during the summer season (low waves). Seasonal variation resulting in so-called winter and summer profiles is a general characteristic of nearshore morphological behaviour, but the degree of seasonality varies widely. Along Pacific coasts the nearshore bars often disappear during the summer period (bar welding to beach); along many other coasts the nearshore bars are permanent features. The knowledge of the seasonal variability of nearshore bars has increased considerably during recent years due to the use of video remote sensing techniques (**Lippmann et al., 1993; Van Enckevort, 2001**). Lippman et al. studied the onshore and offshore migration cycle of the breaker bar (cross-shore bar length L of about 100 m; defined as crest to crest length) at the Duck site (USA) and found offshore migration rates up to 100 m and onshore migration rates up to 50 m on the seasonal time scale. Van Enckevort analysed seasonal variations of bar crest positions (cross-shore bar length of about 150 to 200 m) at the Noordwijk site in the Netherlands. Based on analysis of alongshore averaged (over 2 km) bar crest positions, the cross-shore variability on the seasonal time scale was found to be about 20 m for the outer bar migration and about 10 m for the inner bar migration at the Noorwijk site. Both onshore and offshore migration was observed on the seasonal time scale at both sites, but offshore migration (during storm conditions) was found to be dominant. These results show that the nearshore bars can migrate over a distance up to their own cross-shore length scale (0.2 to 1 L) on the seasonal time scale of a few months up to a year. The alongshore variability (planform) of the inner bar at Noordwijk was found to have an amplitude of about 0.1 to 0.2L and a length scale of about 5 to 10L on the seasonal time scale. Hence, the alongshore bar variability is of the same order as the net cross-shore bar movement on the seasonal time scale expressing a typical 3D behaviour.
On the decadal time scale the bars often show a migrational cycle in offshore direction over several bar length scales (up to 5L) with decay of the outer bar at the outer edge of the surf zone and generation of a new bar at the foot of the beach (**Wijnberg, 1995**). During storm conditions, the outer bar decays due to erosion of sand at the bar crest and transport of the eroded sand to the seaward flank of the inner bar, resulting in offshore migration of the inner bar. During (minor) storms, the conditions are also favourable for generation of a new bar at the foot of the beach. These phenomena have clearly been observed at the Duck site and at the Dutch coast (**Hoekstra et al., 1996; Van Rijn, 1998; Shand et al., 1999**). The cycle time of the bars at the central Dutch coast and at the US-Duck site is in the range of 5 to 15 years depending on the size of the bars. Realizing that these time scales are closely related to spatial scales, it can be stated that the behaviour of the outer and inner bars generally is 2-dimensional on long term (years) and on large alongshore scale (10 km), in the sense that the bars are continuous and of the same form in alongshore direction and show the same overall migrational pattern (onshore and offshore migration). On short and medium time scales of storms and seasons, the bars are not completely straight or linear, but alongshore non-uniformities are present as local disturbances superimposed on the overall straight

base pattern yielding a 3-dimensional morphological system. Examples of these local disturbances are the development of depressions (rip channels), crescentic and meander patterns, introducing an alongshore wave length of the bar system of the order of 100 to 1000 m (**Lippmann and Holman, 1990; Van Rijn, 1998; Ruessink et al., 2000; Van Enckevort and Ruessink, 2001 and Van Enckevort, 2001**). The cross-shore amplitude of the planform was found to be about 15 to 20 m for the outer bar and 10 to 15 m for the inner bar at the Noordwijk site. Residence times of the 3D features were found to be on the time scale of months to a year, but no distinct seasonal trend was observed at the Noordwijk site. The 3D features of the outer bar were more persistent than the inner bar features. These 3D features have been observed to migrate along the shore under the direct influence of the wave-induced longshore currents. The mean longshore migration rates were of the order of 20 to 40 m/day for the outer bar (mainly meander type features) and 10 to 20 m/day for the inner bar (mainly rip channel features) at the Noordwijk site. No consistent relation between the amplitude and the wave conditions was found. The alongshore migration of the planform of the bars yields an onshore-offshore behaviour superimposed on the overall offshore migration of the bars.

3.3 Conclusions coastal erosion and variability

- coastal erosion is the permanent loss of sand from the active coastal zone (dunes, beach and surf zone) due to wind, wave and current-induced forces;
- coastal variability is the variation of the coastline around a systematic trendline and is strongly related to the cyclic onshore-offshore breaker bar behaviour with dominant offshore migration in the stormy winter season and onshore migration and beach recovery in the summer season;
- beach and dune erosion increases strongly with increasing storm surge level and decreasing sediment size; dune erosion values are in the range of 50 to 250 m^3/m (recession rates of 5 to 25 m) for surge levels larger than +3 m (above MSL) and sediments in the range of 0.2 to 0.3 mm as present on most beaches;
- dune erosion during storm events cannot easily be compensated by natural processes (wind transport); hence, artificial dune restoration often is necessary for reasons of coastal defence;
- beach erosion can be compensated by natural processes (onshore transport by post-storm waves) on the seasonal time scale.

4. Controlling coastal erosion by soft nourishments

4.1 Available methods

The available options of shoreline management to deal with erosion problems, are:

- to accept retreat in areas where beaches and dunes are wide and high;
- to maintain the coastline at a fixed position by of hard structures and/or by soft nourishments;
- to bring the coastline at a more seaward position by reclaiming land from the sea.

To distinguish between long-term chronic erosion and short-term fluctuation erosion (natural coastal variability), cross-shore profile data should be available covering at least 10 to 20 years in the area of interest. Based on the profile data, the total volume of sediment within the active zone (say landward of the -8 m depth contour) of the problem area (length scale of 5 to 10 km) can be determined and plotted as a function of time (see **Figure 5**) to reveal erosional or depositional trends. If there is a substantial loss of sediment over a period of 5 years or so , it may considered to nourish the area with a sediment volume equal to the observed volume loss, either as shoreface nourishment or as beach nourishment or both, see **Figure 6**.

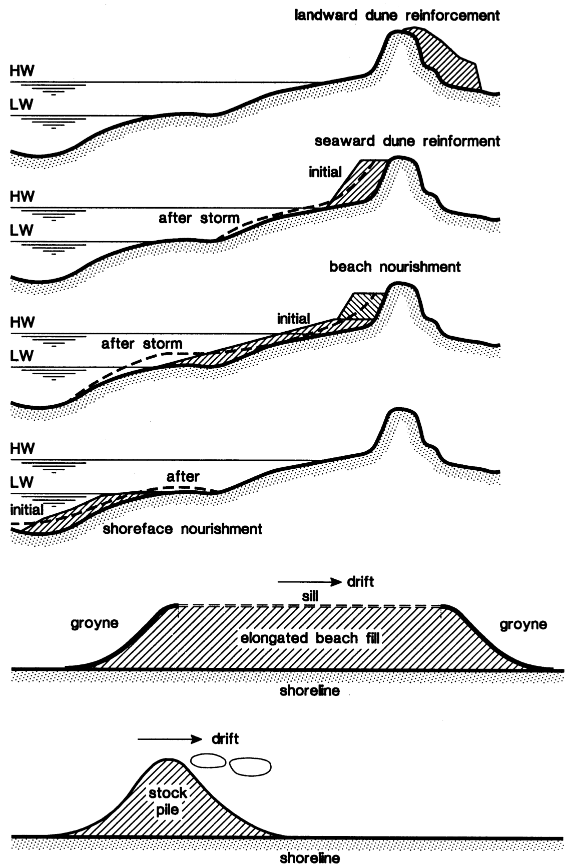


Figure 6 *Dune, beach and shoreface nourishments: cross-shore profiles (upper) and planforms (lower)*

Shoreface nourishments are most simple because the sediment can be placed at the seaward edge of the surf zone where the navigational depth is sufficient for hopper dredgers and if compatible sand is economically available (nearby borrow area <10 km). Shoreface nourishments mainly contribute to the sediment balance of the active surf zone, but are not very efficient for immediate beach widening. Beach nourishments are about twice as expensive as shoreface nourishments, and are of direct benefit to beach erosion problems (immmediate beach widening).

Although, sand nourishment may offer significant benefits, it may also be a costly method if life spans are fairly short at very exposed beaches or if the long-term availability of adequate volumes of compatible sand at nearby (economic) locations is problematic. For example, sand material suitable for beach nourishment cannot easily be found at most Italian and Spanish sites along the Mediterranean.

Sand nourishment is the mechanical placement of sand in the nearshore zone to advance the shoreline or to maintain the volume of sand in the littoral system. It is a soft protective and remedial measure that leaves the coast in a more natural state than hard structures and preserves its recreational value.
Sand nourishment can be carried out at various locations in the profile and along the shoreline (**Figure 6**), as follows:

- *beach and surf zone*: sand is dumped as high as possible on the beach as an elongated buffer layer of sand on the beach or as a continuous source at one or more specific locations (stock pile); typical volumes are in the range of 30 to 150 m^3/m;
- *shoreface zone*: nearshore berms or mounds are constructed from dredged material as a feeder berm in shallow water at the seaward flank of the most offshore bar or as a reef berm in deeper water to act as a filter for storm waves; typical volumes are in the range of 300 to 500 m^3/m;
- *dune zone* (landward and seaward above dune toe level): dune is reinforced/protected against breaching due to storms.

Beachfills are mainly used to compensate local erosion in regions with relatively narrow and low dunes (in regions of critical coastal safety) or when the local beach is too small for recreational purposes. Practical beachfill volumes per unit length of coast are: 10 to 30 m^3/m/yr for low-energy coasts (Mediterranean); 30 to 75 m^3/m/yr for moderate-energy coasts (North Sea); 75 to 150 m^3/m/yr for high-energy coasts (Atlantic/Pacific Ocean). Practical life times are of the order of 1 to 5 years. An elongated beach fill should be placed as much as possible landward of the high tide line in a layer of 2 to 3 m thick (volumes of 50 to 100 m^3/m) with a berm of about 20 to 30 m wide (if required) at the dune foot level; the length of the fill should be larger than about 3 km to minimize the sand losses at both alongshore ends due to dispersion effects under normal wave attack. The initial lower slope of the beachfill should not be too steep (not steeper than 1 to 20). Stockpiling concentrating the beach fills in triangular-shaped patterns (see **Figure 6 bottom**) may be attractive for economical reasons (lower construction costs).
Ideally, the beach fill material should be slightly coarser than the native beach material in the beach/swash zone. Fine fill materials will require a relatively large overfill volume to compensate the losses during construction. The sand size largely depends on economically available sand in the borrow area. The effectiveness of beachfills increases considerably for sand larger than 0.3 mm. Beachfills are relatively expensive as a pumping line to the beach generally is required.

Shoreface nourishments (also known as feeder berms) are used in regions of relatively wide and high dunes (relatively safe coastal regions) to maintain or increase the sand volume in the nearshore zone with the aim to nourish the nearshore zone on the long term by natural processes (net onshore transport). The nourishment volume is of the order of the volume of the outer breaker bar (300 to 500 m^3/m). The length scale (alongshore 2 to 5 km) of a shoreface nourishment is of the order of several times the width of the surf zone. Shoreface nourishment is relatively cheap as the sand can be dumped during sailing in shallow water (5 to 10 m). Relatively large nourishment volumes are required as only part of the nourishment volume (approximately 20% to 30%) will reach the beach zone after 5 years. Shoreface nourishments have both longshore and cross-shore effects (see **Figure 7**). The shoreface nourishment acts as a wave filter (larger waves are reduced by breaking), resulting in a decrease of the longshore transport landward of the nourishment location; updrift sedimentation and downdrift erosion. The cross-shore effect is that the large waves break at the seaward side of the shoreface nourishment and the remaining shoaling waves generate onshore transport due to wave asymmetry over the nourishment resulting in an increase of the onshore sediment transport. Both effects result in the trapping of more sand behind the shoreface nourishment area. Basically, a shoreface nourishment behaves in the same way as a low-crested, submerged breakwater as discussed by **Sánchez-Arcilla et al. (2006)**. However, the wave filtering effects will reduce in time as sand will be eroded from the shoreface and carried away in both cross-shore and longshore directions.
Overall nourishment volumes in Europe are about 30 million m^3 per year (about 10 million m^3/yr in The Netherlands and 3 million m^3/yr in Denmark). A similar volume is nourished in the USA. Most countries have

no long-term strategy and no performance evaluation programme. Often, the nourishment scheme is remedial rather than preventive (**Hamm et al., 1998; Van Rijn, 1998**).

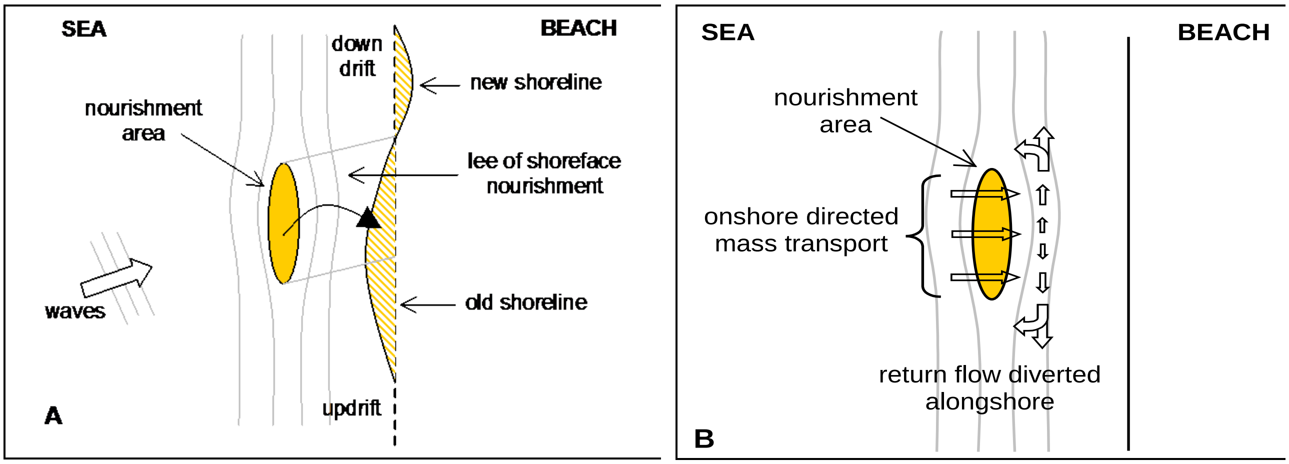


Figure 7 *Effects of a shoreface nourishment*

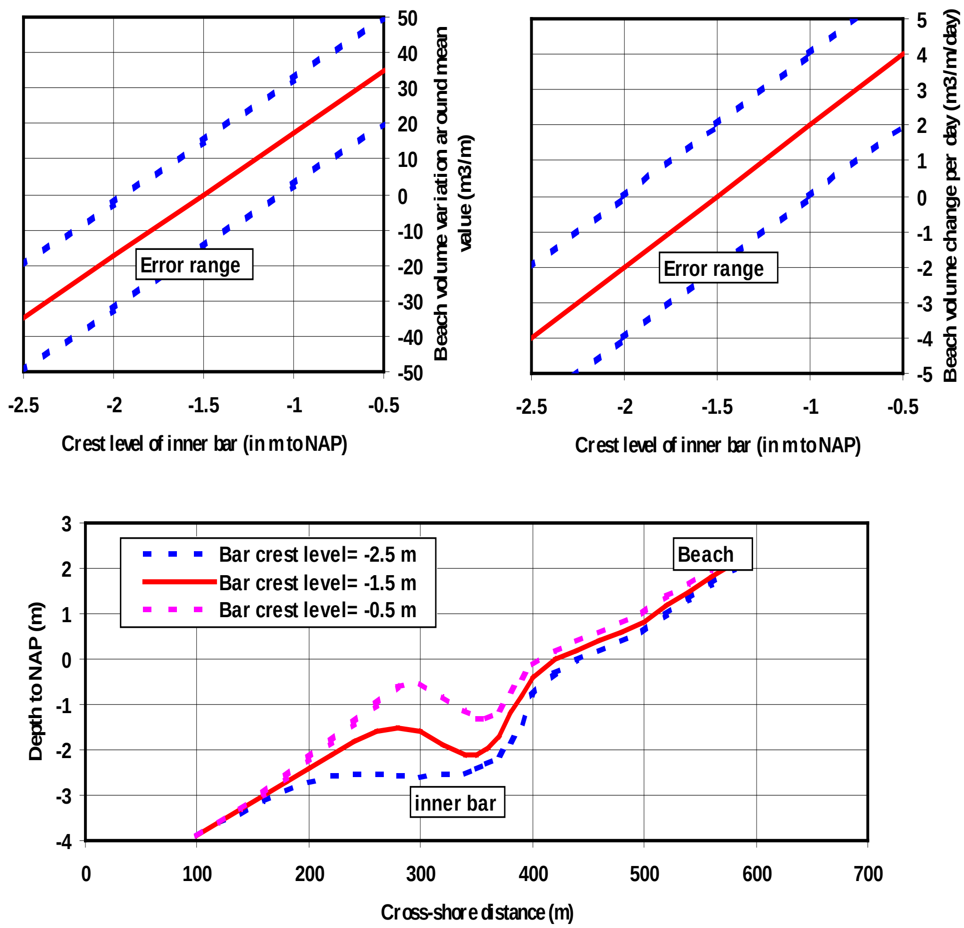


Figure 8 *Beach volume variations; Main Experiment October-November 1998; COAST3D-project*
Top left: *volume variation around mean value (equilibrium volume) as function of crest level*
Top right: *volume change per day as function of bar crest level*
Bottom: *Beach profiles for different crest level positions (NAP ≃ mean sea level MSL)*

4.2 Cross-shore morphology of beach and shoreface nourishments (physical processes involved)

Beach nourishment generally results in a largely disturbed beach profile. The natural beach profile is covered by a thick layer of sand (1 to 2 m) with relatively straight slopes. The beach slope may be in the range between 1 to 50 and 1 to 100, but the slope of the seaward flank of the fill usually is quite steep (1 to 10). Relatively steep beach profiles are very vulnerable to erosion. The initial losses of beach nourishments are largely determined by the initial slope of the seaward flank of the fill. Practical experience at Sylt beach (Germany; **Raudkivi and Dette, 2002**) shows an initial beach loss of about 120 m^3/m in about 4.5 months (winter period) or about 1 m^3/m/day for a beach nourishment at 28 September 1992 with an intial toe slope of 1 to 5 and 1 to 2 above the +2 m line. Experience at Egmond beach (The Netherlands) also shows relatively large initial losses and relatively short beachfill lifetimes of about 1 to 2 years. Peferably, beach nourishments should have a relatively flat initial slope (1 to 20 or flatter). If possible, an underwater berm at about -1 m should be included to minimize the intial sand losses.
To better understand the erosional behaviour of beach fills, it is of crucial importance to understand the erosion/accretion processes at natural beaches (without nourishment). Data from two beaches along the central Holland coast are available: Egmond beach and Noordwijk beach. The tidal range at both beaches is of the order of 2 m; the beach sediment is sand with a median particle diameter of about 0.25 mm. Field experience at Egmond beach along the Holland coast (**Van Rijn et al., 2002**) clearly shows that high and low areas on the beach co-vary with high and low levels of the crest of the inner surf zone breaker bar. The beach volume per unit width increases/decreases with increasing/decreasing crest level of the inner bar, as shown in **Figure 8Bottom**. The beach volume (above -2.5 m NAP; NAP ≅ MSL) in a situation with the crest level of the inner bar at -1.5 m NAP is found to be the (time-invariant) equilibrium volume of the beach. The beach volume per unit width increases by about 30 m^3/m if the crest level of the inner bar increases from -1.5 m to -0.5 m NAP (**Figure 8Top left**); and decreases by about 30 m^3/m if the crest level decreases from -1.5 m to -2.5 m NAP (**Figure 8Top left**). Given a beach width of about 100 m, this means a maximum vertical change (increase/decrease) of the beach level near the waterline of about 0.5 m assuming a triangular accretion/erosion pattern. The daily beach volume changes (erosion/accretion) vary between 1 and 3 m^3/m/day in a storm month with wave heights up to about 5 m (**Figure 8Top right**); the daily accretion is maximum if the crest level of the inner bar is at -0.5 m NAP; daily erosion is maximum if the crest level of the inner bar is at -2.5 m NAP. The beach volume changes of about 30 m^3/m can occur over a period of about 10 to 15 days in a storm month (maximum storm surge level SSL of about +2 m above NAP); the beach volume is almost continuously adjusting to a new equilibrium, if the bar crest level is continuously changing. The variation around the trend line represents the response time of the beach morphology to the time-dependent equilibrium value. Assuming a maximum beach volume variation (erosion) of about 20 to 30 m^3/m due to a storm event and a net daily onshore transport rate of about 1 to 3 m^3/m/day due to fairweather processes, the restoration time of the beach morphology to the changing inner bar morphology is of the order of 10 to 30 days (a few weeks) after a storm period.
Similar volume variations have been observed over a period of three years at the beach of Noordwijk along the Holland coast (**Quartel et al., 2008**). The mean beach width is about 120 ±15 m; the mean beach volume (above MLW) is about 190 ± 25 m^3/m. Thus, the maximum beach volume variation over a period of 3 years is about 25 m^3/m or about 15% of the total beach volume above the mean low water line (MLW; about -0.7 m below mean sea level MSL). The volume variations are largest (± 15 m^3/m) in the lower beach zone with the inner bar between the MLW (at 1.3 m above MSL) and MSL and smallest (± 5 m^3/m) in the zone between MHW and MSL and in the upper beach zone above MHW (± 5 m^3/m). The beach volume is found to be largest at the beginning of the winter season and smallest at the end of the winter season (storm waves). The maximum volume variation of about 25 m^3/m (above MLW≅ -0.7 m to MSL) at Noordwijk beach is somewhat smaller than that at Egmond beach, which is about 30 to 50 m^3/m (above -2.5 m to MSL) including the inner bar volume variation at that location.

The erosion of nourished beaches with straight slopes has been studied extensively by performing small-scale and large-scale tests in wave tanks/flumes. **Figure 9** shows beach profiles for an initial slope of 1 to 10, 1 to 20 and 1 to 40 based on experimental results in a small-scale laboratory flume with sand of 0.13 mm and approaching (irregular) waves of about $H_{s,o}$= 0.17 m (**Deltares, 2008**). Similar tests have been done in the large-scale Hannover wave flume with $H_{s,o}$= 1 m and d_{50}= 0.27 mm (**EU SANDS Project**). The small-scale test results have been upscaled to the Hannover flume (length scale =depth scale; $n_l = n_h$= 5.5). The erosion volume can be determined by multiplying with 5.5^2. Assuming a grain size scale of n_{d50} = 2 and using the proper scaling laws (**Van Rijn, 2008**), the morphological time scale is equal to n_{tm}= n_{d50}= 2. Based on this upscaling approach, **Figure 10** shows the beach erosion volumes as a function of time. The upscaled results represents prototype erosion by waves of about 1 m at the toe of the beach (minor storm events; offshore waves of 3 to 4 m). The steepest initial slope of 1 to 10 yields an erosion volume after 1 day of about 12 m^3/m. The beach erosion is of the order of 6 to 9 m^3/m/day for milder slopes between 1 to 20 and 1 to 40.

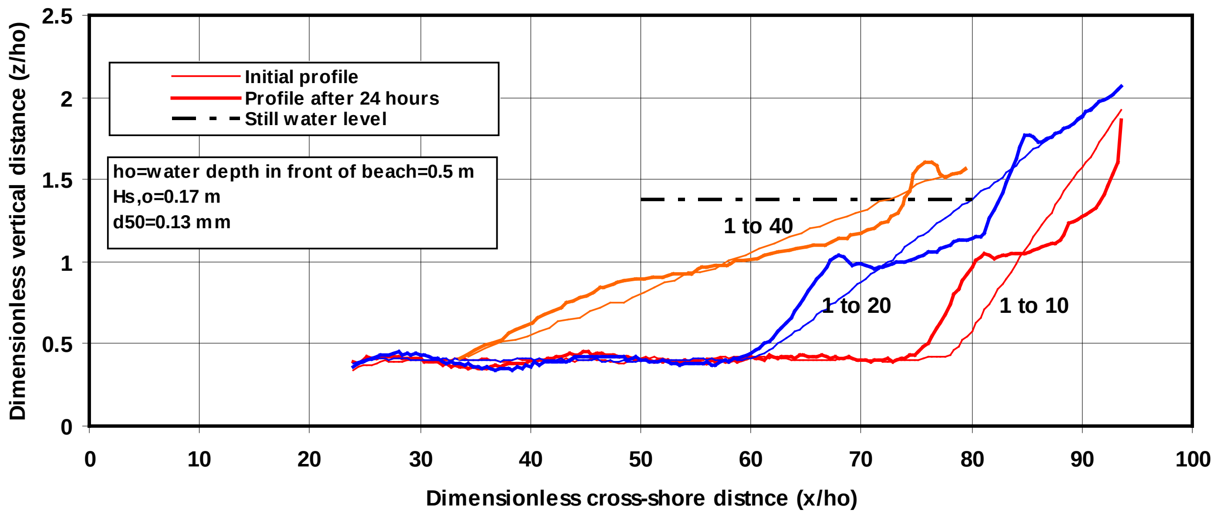


Figure 9 *Beach profile development for intial slopes between 1 to 10 and 1 to 40 (laboratory tests).*

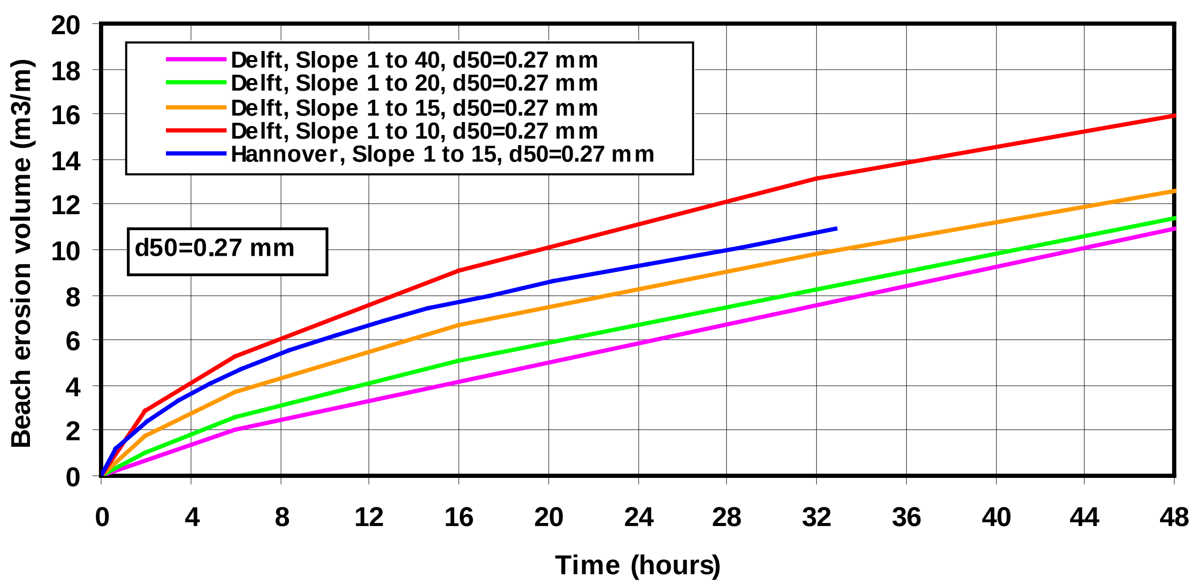


Figure 10 *Beach erosion volumes for plane sloping beaches in nature with daily waves of about 1 m at toe of beach; slopes between 1 to 10 and 1 to 40, d_{50} = 0.27 mm*

The large-scale experimental results show that a prototype beach profile of fine sand (0.2 to 0.3 mm) with an initial constant slope (between 1 to 10 and 1 to 40) landward of the -1 m depth contour is not stable and will be transformed into a profile with an underwater terrace at the lower beach end (see also **Dette et al., 2002**). Sand will be eroded at the upper beach and deposited in the underwater zone around the -1 m depth contour.

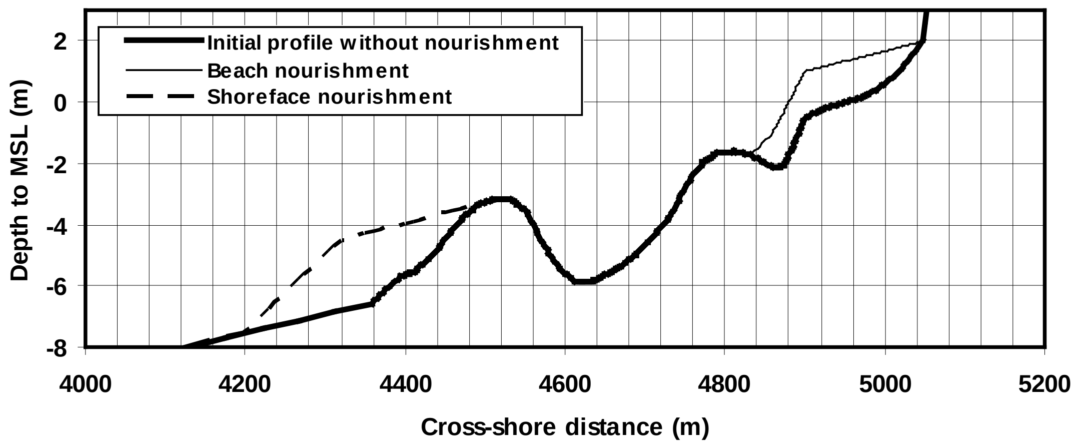


Figure 11 *Schematized beach and shoreface nourishment profiles along Dutch coast (Egmond profile)*

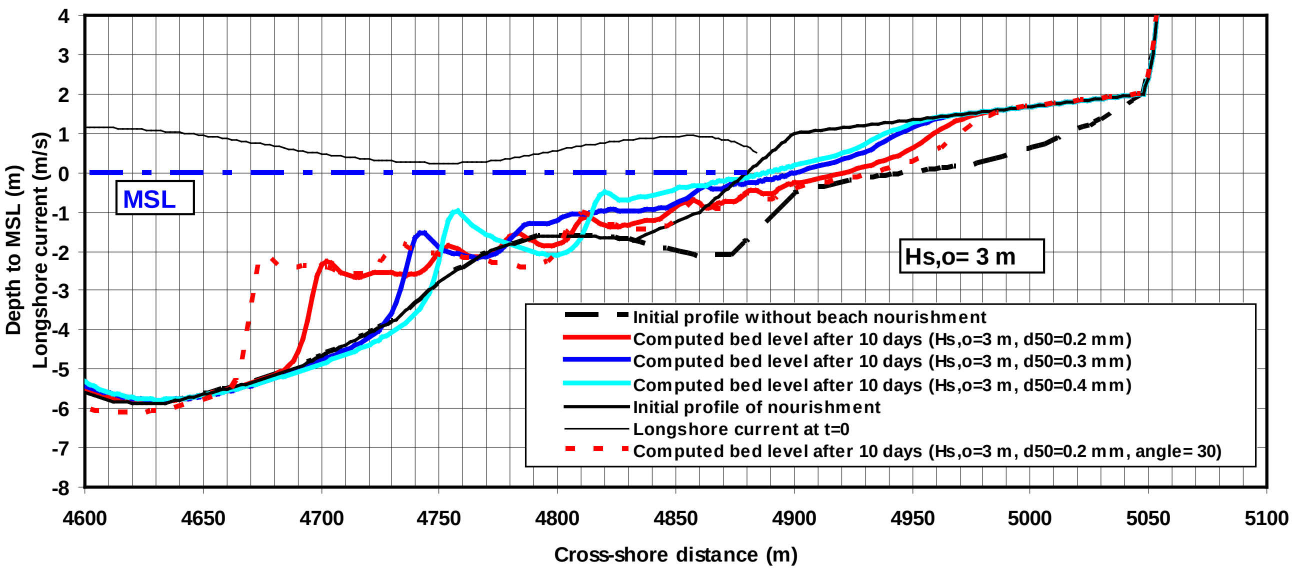


Figure 12 *Erosion of beach nourishment;* $H_{s,o}$*= 3 m; sediment* d_{50}*= 0.2, 0.3 and 0.4 mm*

To determine the overall efficiency of beach nourishments, the process-based CROSMOR-model (**Van Rijn, 2009**) has been used to compute beach erosion volumes for various schematized cases (see **Figure 11**) along the Dutch coast (North Sea wave climate). The initial beach nourishment volume is about 220 m^3/m. The slope of the upper beach is set to 1 to 150; the initial slope of the lower beach is 1 to 20. The North Sea wave climate along the Dutch coast can be characterized as: $H_{s,o} < 1$ m during 50% of the time, $H_{s,o}$= 1 to 3 m during 45% of the time and $H_{s,o} > 3$ m during 5% of the time. Three wave conditions have been used: $H_{s,o}$ = 0.6 m and wave period of T_p = 5 s over 100 days normal to the beach, $H_{s,o}$ = 1.5 m and wave period of T_p = 7 s over 30 days normal to beach and $H_{s,o}$ = 3 m and wave period of T_p = 8 s over 10 days normal to beach representing a standard winter season. The tidal range is set to 1 m. The peak flood tidal current to the north is set to 0.6 m/s and the

peak tidal ebb current to the south is set to -0.5 m/s. These values apply to the offshore boundary. Nearshore tidal currents are computed by the model and are much smaller due bottom friction (decreasing depth). A storm set-up of 0.5 m has been used during offshore waves of $H_{s,o}$ = 3 m. Three types of beach material have been used: d_{50}= 0.2, 0.3 and 0.4 mm. The offshore boundary conditions were applied at a depth of 15 m to MSL.
Figure 12 shows computed results for the wave height of H_s= 3 m over 10 days and three types of beach materials (0.2, 0.3 and 0.4 mm). Erosion mainly occurs in the beach nourishment section above the water line (0 to +1.5 m). The eroded sand is deposited at the toe of the beach nourishment between the 0 and -1.5 m depth contours. The deposition layer in front of the beach nourishment slows down the erosion in time by reducing the wave height. The cumulative erosion volumes (in m^3/m/day) are shown in **Figures 13, 14** and **15**. The large-scale Hannover flume data are also presented in **Figures 13** and **14**, showing reasonably good agreement with the computational results for waves of about 1.5 m. **Figure 13** shows that the cumulative beach erosion volume stabilizes after about 30 days due to the generation of an equilibrium beach profile. Erosion values after 100 days are only 10% larger. Runs without tide show similar values, as the nearshore tidal currents are not very strong and are smaller than the wave-induced longshore currents. Runs with a combined shoreface and beach nourishment show almost no reduction of the beach erosion due to the presence of the shoreface nourishment (crest level is too low to act as a reef).

The initial erosion volumes (after 1 day) for waves<1.5 m are about 6 m^3/m for sand of 0.4 mm to 10 m^3/m for sand of 0.2 mm. These values are in line with the initial erosion volumes of the upscaled laboratory data (**Figure 10**) yielding values of about 6 to 8 m^3/m after 1 day for sand of 0.27 mm (slopes between 1 to 15 and 1 to 20).
Over a month these values are significantly smaller. Monthly-average erosion volumes (cumulative erosion divided by total duration) are in the range of 1 m^3/m/day for sand of 0.4 mm to 2.5 m^3/m/day for sand of 0.2 mm and waves with H_s<1.5 m (based on **Figure 14**). For waves of H_s= 3 m these values increase to 4 m^3/m/day to 10 m^3/m/day.
The computed bed profile of a run with $H_{s,o}$= 3 m and an offshore wave angle of 30^o has also been plotted in **Figure 12**, showing a slight increase of the total erosion volume by about 20%. The cumulative erosion is plotted in **Figure 15**. The wave-induced longshore current at initial time is also shown in **Figure 12**. The maximum longshore current is of the order of 1 m/s just in front to the beach nourishment, which enhances the transport capacity and hence the erosion power of the system. The eroded sediments are deposited at the seaward edge of the inner breaker bar. This wave angle effect is a typical storm feature, as it is hardly noticeable for an offshore wave height of 1.5 m (see **Figure 14**).
The cumulative erosion is slightly reduced, if a shoreface nourishment is present due to additional wave breaking at the shoreface nourishment location, see **Figure 15**.

These computational results with daily-average erosion values of the order of 1 to 10 m^3/m/day show that a beach nourishment volume of the order of 100 to 200 m^3/m can be easily eroded away in one to two winter seasons in line with observations at the Dutch coast where beach fills have, on average, to be repeated at two year intervals. The trough (depression) beyond the inner breaker bar acts as a sink to the erosion of beach sediments. Therefore, the presence of a trough in front of the beach nourishment should be avoided (trough between inner bar and beach should be filled with sand). **Figure 16** shows the computed bed level after 1 winter period with a sequence of waves, as follows: 100 days with $H_{s,o}$ = 1 m, 30 days with $H_{s,o}$= 1.5 m and 10 days with $H_{s,o}$= 3 m for three sediment diameters (d_{50} = 0.2, 0.3 and 0.4 mm). The beach erosion is approximately 150 m^3/m for d_{50} = 0.2 mm; 100 m^3/m for d_{50} = 0.3 mm and 90 m^3/m for d_{50}= 0.4 mm. As can be seen, the beach nourishment volume of 0.2 mm sand is almost completely removed after 1 winter season. At the landward end of the beach a typical scarp-type erosion front is present, which is often observed in nature. Beach nourishment of relatively coarse material of 0.3 mm has a lifetime which is about 50% larger than that of 0.2 mm material. The eroded beach sediment is deposited as a new breaker bar beyond the -4 m depth line.
Using the data of **Figures 13, 14** and **15** and adding the results of each wave class (H_s = 0.6, 1.5 and 3 m) linearly, yields beach erosion volumes of 210, 130 and 120 m^3/m for d_{50} = 0.2, 0.3 and 0.4 mm. This approach leads to an overestimation of about 30%, as the time history effect of the beach profile is not taken into account.

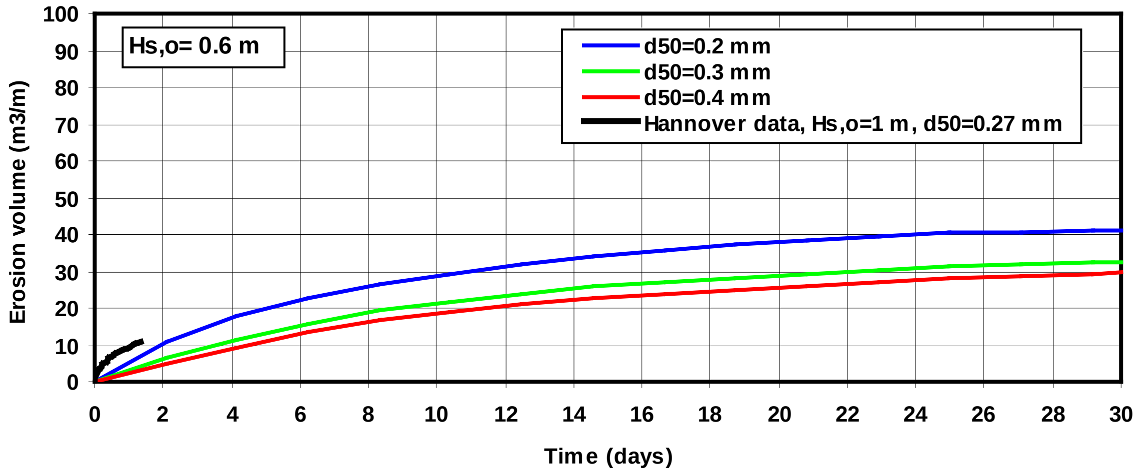


Figure 13 *Cumulative erosion of beach nourishments;* $H_{s,o}$*= 0.6 m; sediment* d_{50}*= 0.2, 0.3 and 0.4 mm*

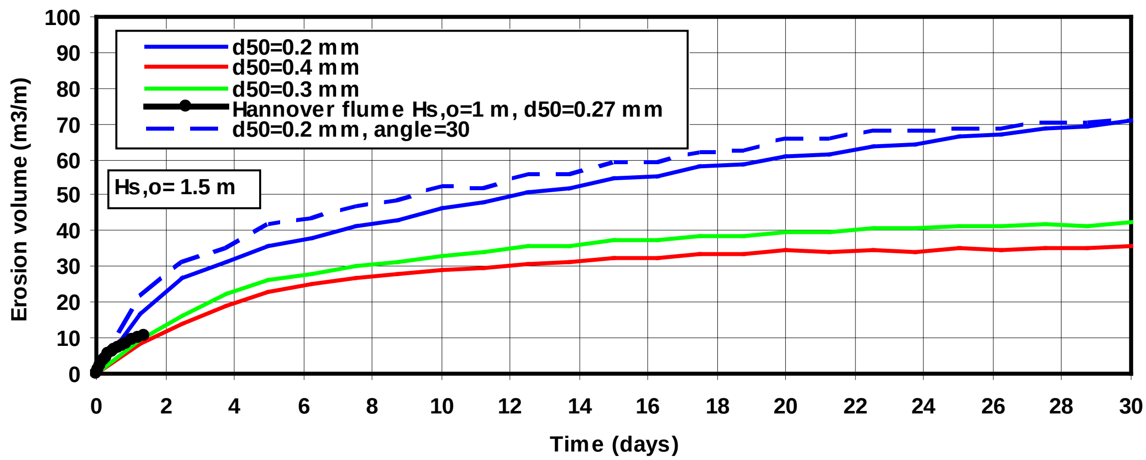


Figure 14 *Cumulative erosion of beach nourishments;* $H_{s,o}$*= 1.5 m; sediment* d_{50}*= 0.2, 0.3 and 0.4 mm*

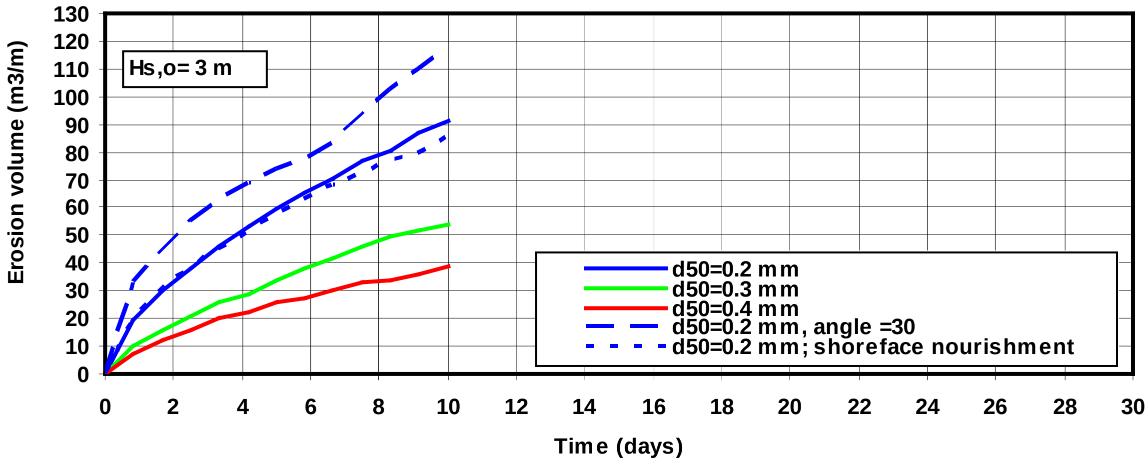


Figure 15 *Cumulative erosion of beach nourishments;* $H_{s,o}$*= 3 m; sediment* d_{50}*= 0.2, 0.3 and 0.4 mm*

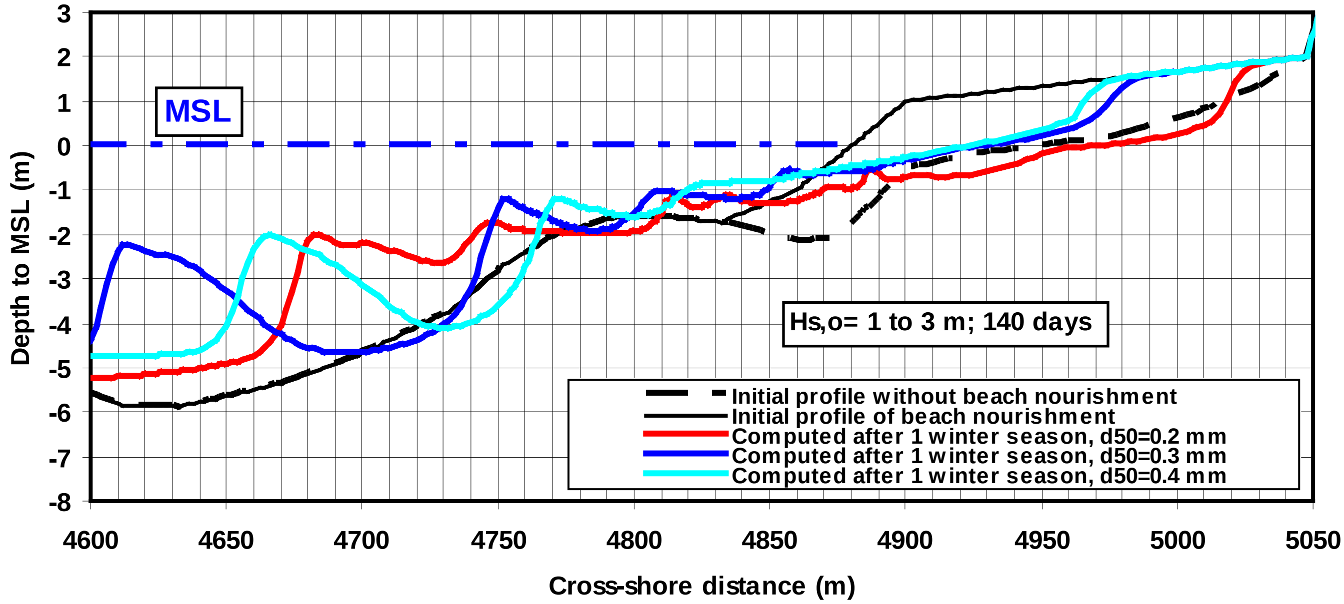


Figure 16 *Erosion of beach nourishment after 1 winter season (d_{50}= 0.2, 0.3 and 0.4 mm)*

The CROSMOR-model has also been used to evaluate the efficiency of shoreface nourishments beyond the -6 m depth line. **Figure 17** shows the morphological changes of a shoreface nourishment at the seaward flank of the outer breaker bar for a wave height of $H_{s,o}$=1.5 m (post-storm waves and fair-weather waves) for d_{50}= 0.2 mm and 0.4 mm. Onshore sand transport in the range of 20 to 100 m^3/m over 100 days can be observed for waves of 1.5 m depending on the bed material diameter and the modelling of the suspended transport due to wave asymmetry. The largest values occur for relative coarse sediment and inclusion of the suspended transport due to wave asymmetry. The migration distance varies between 10 and 40 m over 100 days. The nourishment profile shows a slight tendency to grow due to the shoaling wave of 1.5 m as has been observed in nature (see **Figure 16**). As the beach zone (-3/+3 m) is situated at about 200 m shorewards from the shoreface nourishment, it will take at least 5 years of low wave conditions (which occur during about 75% of the time; $H_{s,o}$<1.5 m) before the nourishment can migrate to the beach zone (-3 to +3 m). Hence, it is rather difficult for the sediments to pass the deep trough landward of the outer bar.

Figure 18 shows the morphological changes (offshore migration) of the shoreface nourishment at the seaward flank of the outer breaker bar for storm events with $H_{s,o}$ in the range of 2.25 to 5 m (which occur during about 25% of the time) and d_{50}=0.2 mm. As can be observed, these conditions result in offshore-directed migration of the nourishment. The sediment (in the range of 50 to 100 m^3/m) is eroded from the crest region and deposited at the seaward flank over a period of 5 to 50 days.

On the seasonal time scale with low and high waves, the shoreface nourishment will be gradually spread out in both onshore and offshore direction. The annual transport from the crest region to both flanks (seaward and landward) of the bar is of the order of 50 to 100 m^3/m/year yielding a lifetime of the order of 5 years (as observed along the Dutch beaches in North Sea conditions) given an initial volume of about 400 m^3/m. The computed net onshore transport over one year is of the order of 25 to 50 m^3/m/year. Practical experience (see later) shows that about 25% of the initial shoreface nourishment volume will eventually (after 5 years) be transported to the nearshore zone. Assuming an initial shoreface nourishment volume of about 400 m^3/m, the net onshore transport involved will be about 0.25x400/5= 20 m^3/m/year, which is somewhat smaller than the computed value of 25 to 50 m^3/m/year. These values refer to Nort Sea wave conditions. The onshore feeding potential of a shoreface nourishment will be much smaller in milder wave climates (Mediterranean).

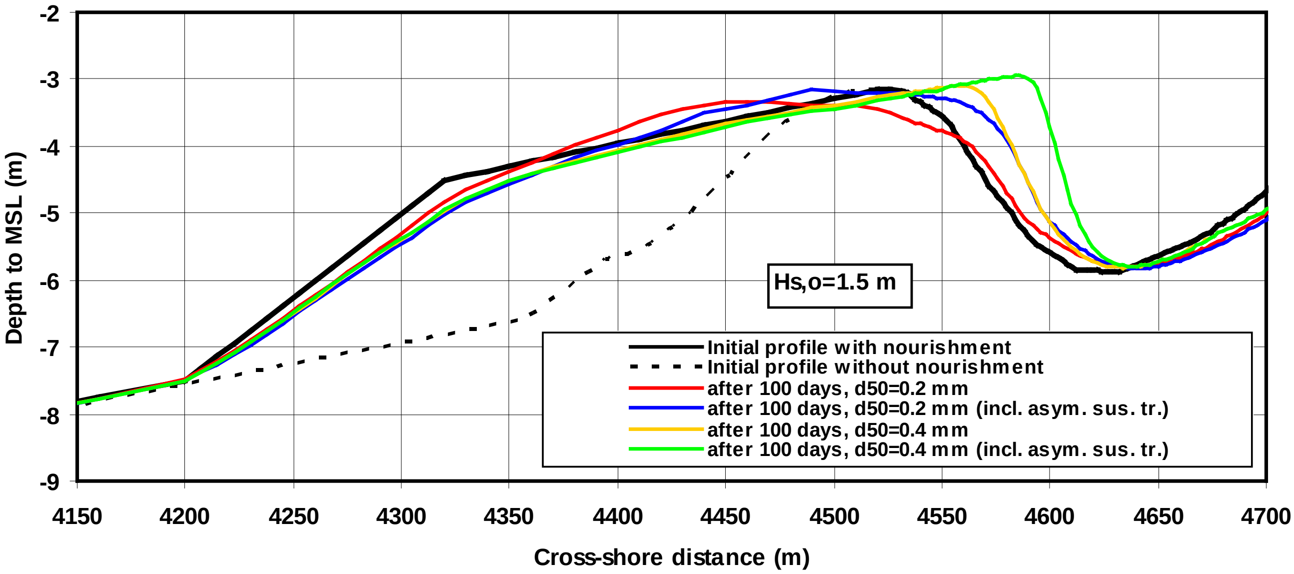


Figure 17 *Onshore migration of shoreface nourishment; $H_{s,o}$=1.5 m, sediment d_{50}=0.2 mm and 0.4 mm*

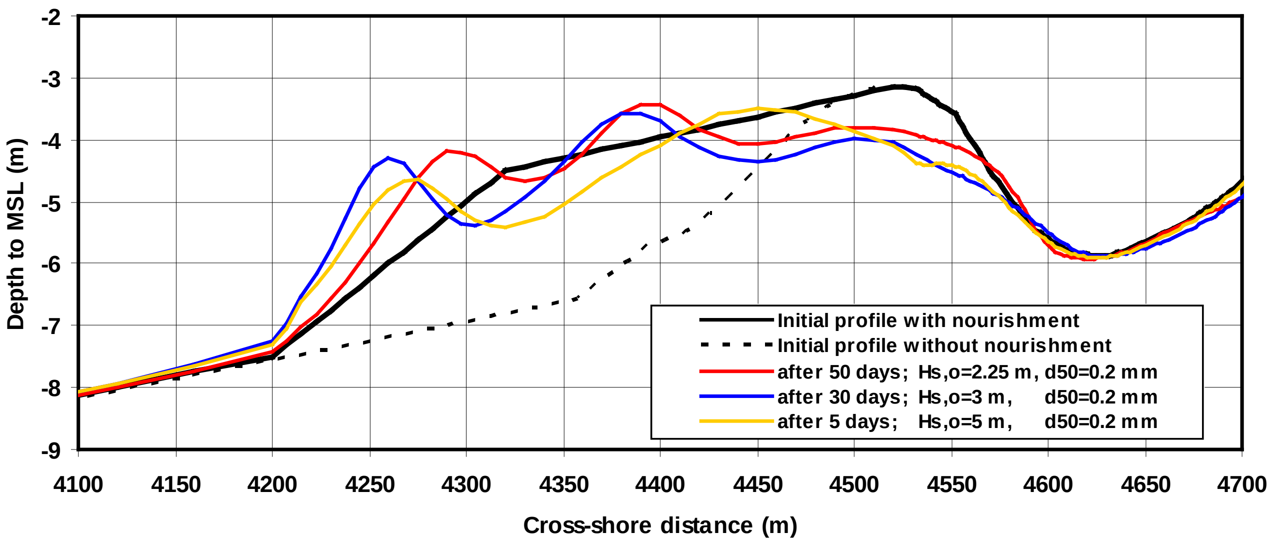
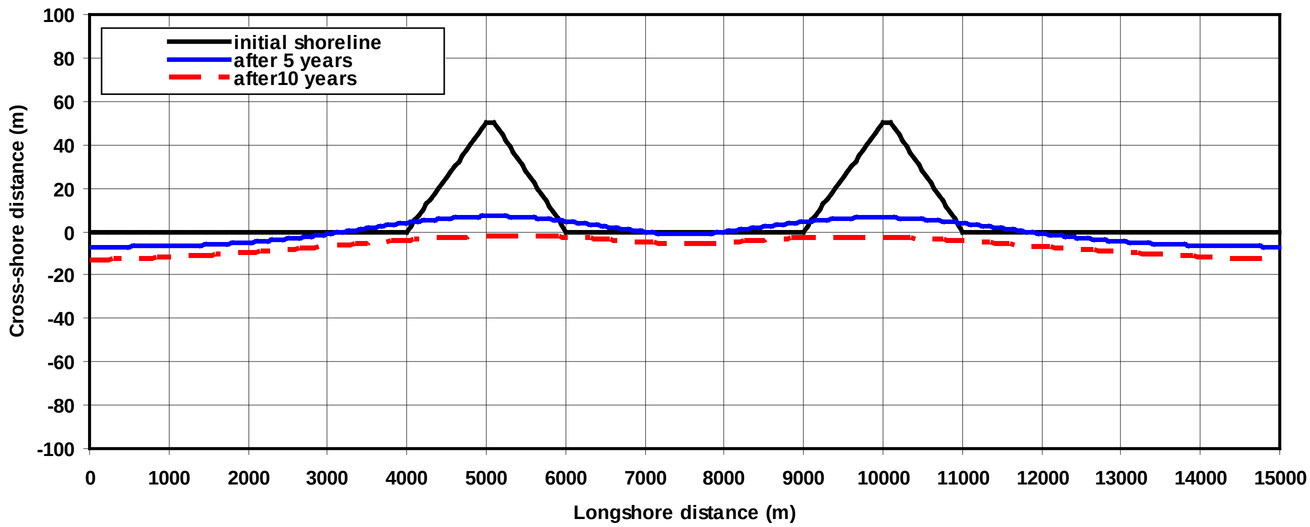


Figure 18 *Offshore migration of shoreface nourishment; $H_{s,o}$=2.25 to 5 m, sediment d_{50}=0.2 mm*

4.3 Longshore morphology of nourished beaches (physical processes involved)

In planform two types of beach nourishments are designed: rectangular, elongated beachfills or a triangular, headland-type beachfills (stockpiles), see **Figure 6**. The latter are more attractive from economical point of view (lower construction costs). Using headland-type fills, the nourished beach is divided into a series sediment stocks and cells (compartimentalization) in which the sediments are supposed to be spread out by natural processes. This idea will hereafter be explored by example computations for an eroding coastal section in a severe wave climate (North Sea) with a length of 15 km using the LONGMOR-model (see Equation 1, Section 5).
The local wave climate (offshore waves of 0.5 to 4 m and incidence angles of 30^o and -15^o with respect to the coast normal) is assumed to generate a net longshore transport of about 375,000 m^3/year at x = 0 and about 500,000 m^3/year at x=15 km. Hence, a significant longshore transport gradient of 125,000 m^3/year is assumed to be present to

impose a chronic coastal erosion of about 7 m in 5 years along this coastal section (see **Figure 19**). The LONGMOR-model has been used to determine the consequences of creating coastal cells by means of headland-type beach fills with a cross-shore length of 50 m and a spacing of 5 km. The active layer thickness of the coastal profile is assumed to be 6 m. The beach sediment is sand with d_{50}= 0.2 mm and d_{90}= 0.3 mm. The local beach slope is assumed to be tanβ= 0.05 (slope of 1 to 20 from waterline to 6 m depth contour). The local wave breaking coefficient is assumed to be 0.6. The longshore grid size is 50 m and the time step is 0.01 days. The shoreline changes over a period of 5 and 10 years have been determined using the schematized wave climate yielding a net longshore transport gradient of 125,000 m^3/year based on the method of **Van Rijn (2002, 2005)**.



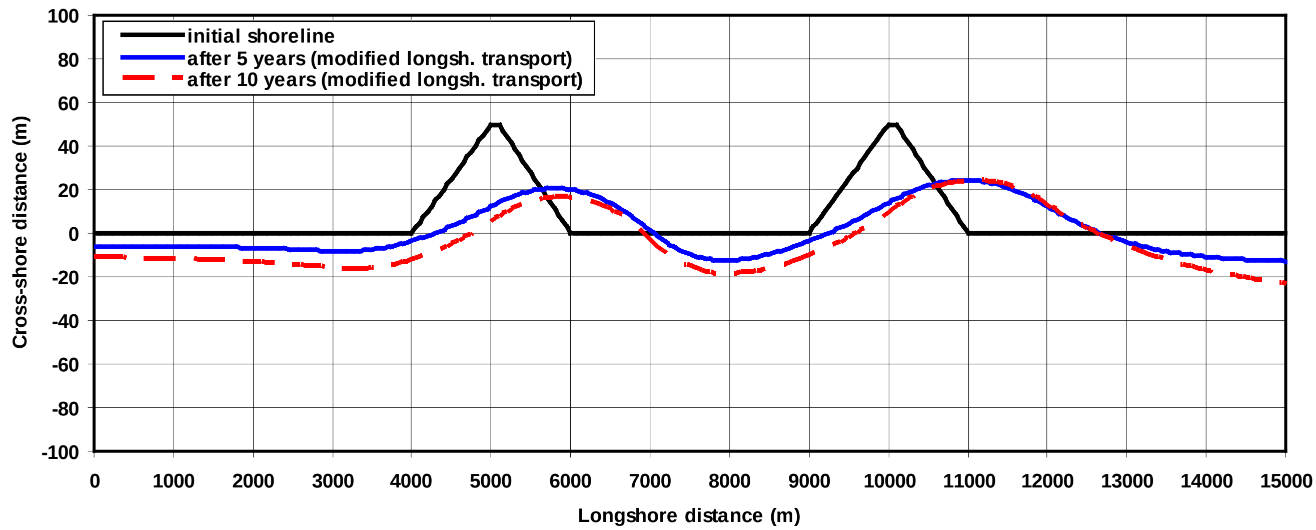


Figure 19 *Shoreline behaviour after 5 and 10 years of headland-type beach fills (net longshore transport from left to right); spacing of 5000 m.*
Top: standard longshore transport
Bottom: longshore transport on updrift flank is 20% larger than on downdrift flank of headland

Figure 19Top shows the typical shoreline behaviour with gradual decay of the beach fills and a shoreline erosion of 7 m in 5 years (and 14 m in 10 years) on both ends of the beach due to the imposed longshore transport gradient. These results are based on the assumption that the longshore transport is symmetric with respect to the shoreline angle; a positive angle of +15 degrees yields the same results as a negative angle of -15 degrees. When the longshore transport is modified by assuming that the transport rate on the updrift flank of the headland is about 20%

larger than that on the downdrift side, the shoreline shows a migrational behaviour of the sandy headlands, see **Figure 19Bottom**. The beach in the middle between the two headlands even shows significant erosion of about 20 m after 10 years. Thus, a side effect of headland-type beach fills may be the generation of local erosion spots due to (minor) alongshore variations of the net longshore transport, which is not attractive from a management perspective as it will require remedial measures. This example for an exposed coast in a severe wave climate (see **Figure 19**) shows that the introduction of artificial alongshore variations by headland-type beach fills is extremely triggy and should be avoided as much as possible. These effects will be less, but not absent in conditions with milder wave climates (Mediterranean, Baltic). The creation of sediment cells seems attractive from a management perspective, but it may enhance alongshore variations of the longshore transport resulting in extra local erosion which may need additional mitigation.

4.4 Practical experiences of nourished beaches

4.4.1 Behaviour of short-term beach and shoreface nourishments

Various shoreface nourishment projects have been carried out along the Holland coast with a length of about 100 km in the central part of The Netherlands. The main objective of these shoreface nourishments is the maintenance of the local nearshore sediment volume above a critical minimum value (local basal minimum value). When the actual nearshore sand volume (approximately between +3 and -4.5 m to MSL) based on the trend line over 10 years is below the minimum required volume (defined as the value present in 1990), either beach or shoreface nourishment is required (by law) at that location.

Data of five typical cases (period 1995 to 2005) are presented in **Table 1**. Two cases (Ter Heijde 1997-2001 and Noordwijk 1998-2001) are situated along the coast of South Holland and two cases (Egmond 1999-2002 and Egmond 2004-2006) are situated along the coast of North Holland. All these locations have a chronic beach erosion of the order of 10 to 20 m^3/m per year. The spring tidal range is about 2 m. The beach sand is about 0.2 to 0.25 mm. The net longshore transport is in the range of 100,000 to 300,000 m^3/yr depending on the actual annual wave climate and location along the coast (**Van Rijn, 1997**).

The shoreface nourishment volume (about 850,000 m^3 or 500 m^3/m) at location Ter Heijde was placed in the zone between -5 and -7 m over a length of 1700 m (alongshore) during the summer and autumn of 1997 (**Rijkswaterstaat/RIKZ, 2002**). At that location the cross-shore profile is quite smooth without any breaker bars. The middle section (nourishment area) shows a loss of about 300,000 m^3 (about 35% of initial value) after 4 years. The nearshore zone (between +3 and -4.5 m to MSL) shows a volume increase of about 150,000 m^3 (about 100 m^3/m) after 4 years, which is about 20% (efficiency) of the initial nourishment volume. The beach zone (between +3 and -1 m) shows a volume increase of about 20,000 m^3 (about 15 m^3/m) after 4 years which is about 2% (efficiency) of the initial nourishment volume. At this location the shoreface nourishment (feeder berm) moved gradually onshore as a bar. **Figure 20** shows this typical behaviour of the cross-shore profile at Ter Heijde between 1998 and 2006. The downdrift (south) and updrift (north) section show relatively small net accretion values, which is an indication that the longshore processes are quite small along this coastal section in the lee of the large harbour breakwater at Hoek van Holland. Overall, the erosion and accretion values are of similar magnitude (closed balance).

The shoreface nourishment volume (about 1.2 million m^3) at location Noordwijk (**Table 1**) was placed in the zone between -5 and -7 m over a length (alongshore) of 3500 m during the winter period between January and April 1998 (**Rijkswaterstaat/RIKZ, 2002**). The middle section (nourishment area) shows a loss of about 300,000 m^3 (about 25% of initial value) after 3.5 years. The nearshore zone (landward section) between the +3 m and -4.5 m (with respect to MSL) shows a volume increase of about 600,000 m^3 (about 200 m^3/m) after 3.5 years which is about 60% of the initial nourishment volume. The beach zone above the -1 m line shows a volume increase of about 50,000 m^3 (about 15 m^3/m) after 3.5 years, which is about 4% of the initial nourishment volume. The volume increase in the nearshore zone is about twice as large as the loss from the nourishment zone, which means that the nearshore zone traps sediment from longshore (updrift and downdrift) sections.

Both shoreface nourishments (Ter Heijde and Noordwijk) along the South Holland coast have liftetimes of the order of 5 years,

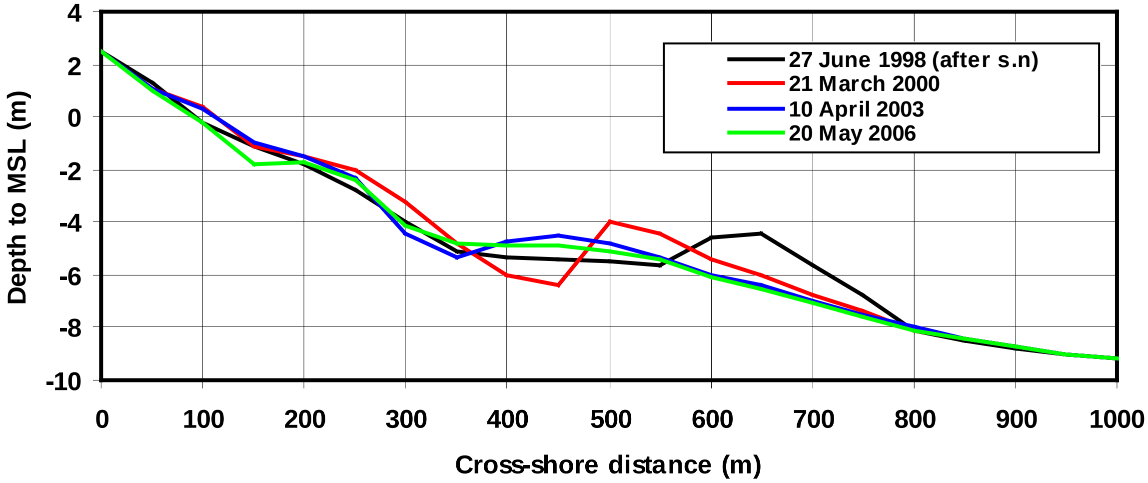


Figure 20 *Profile Ter Heijde (113.94) in period of 27 June 1998 (after shoreface nourishment) to 20 May 2006*

Section	**Ter Heijde (1.7 km) Sep. 1997-Nov. 2001** **(after 4 years) initial volume= 850,000 m3 (500 m^3/m)**	**Noordwijk (3 km) March 1998-Nov. 2001** **(after 3.5 years) initial volume= 1,200,000 m^3 (400 m^3/m)**	**Egmond 36.9-39.1 km (2.2 km) Sep 1999-April 2002 (after 3 years) initial volume= 900,000 m^3 (410 m^3/m) and 200,000 m3 beach fill**	**Egmond 36.1-40.3 km (4.2 km) Nov 2004-July 2006 (after 2 years) initial volume= 1,800,000 m^3 (430 m^3/m) and 500,000 m^3 beach fill**	**Terschelling (4.4 km) Nov 1993-Nov 1997 (after 4 years) initial volume= 2,100,000 m^3 (480 m^3/m)**
Downdrift section	net accretion of 75,000 m^3	net erosion of 100,000 m^3	net erosion of 150,000 m^3; (autonomous erosion of about 30,000 m^3)	net accretion of about 100,000 m^3 (after 2 years)	net accretion of 100,000 m^3
Middle section (nourishment section)	Nourishment zone shows decrease of 300,000 m^3 Nearshore zone (+3/-4.5 m) shows increase of 150,000 m^3 (eff.=20% after 4 years) Beach zone (+3/-0.7 m) shows increase of 20,000 m^3 (15 m^3/m); (eff.=2%)	Nourishment zone shows decrease of 300,000 m^3 Nearshore zone (+3/-4.5 m) shows increase of 600,000 m^3 (eff.=50% after 3.5 years) Beach zone (+3/-0.7 m) shows increase of 50,000 m^3 (15 m^3/m) (eff.=4%)	Nourishment zone shows erosion of about 350,000 m^3 (after 3 years); Nearshore zone landward of nourishment area shows increase of 225,000 m^3 (eff.=25% after 3 years)	Nourishment zone shows no erosion or accretion; volume remains constant (after 2 years); Nearshore zone landward of nourishment area shows increase of 1,100,000 m^3 after 2 years); (eff.=60% after 2 years)	Nourishment zone shows net accretion of 700,000 m^3 (after 4 years) mainly in beach and inner surf zone (eff.=30% after 4 years)
Updrift section	volume increase of 150,000 m^3	volume increase of 100,000 m^3	net erosion of 120,000 m^3; (autonomous erosion is estimated to be of the order of 30,000 m^3)	net accretion of about 100,000 m^3 (after 2 years)	net accretion of 1,300,000 m^3 due to incoming longshore transport

Table 1 *Volume data of four shoreface norishments along the Dutch coast*

The shoreface nourishment at location Egmond 1999-2002 (**Table 1**) was studied by **Van Duin and Wiersma (2002)**. The nourishment volume (length of about 2 to 2.5 km; total initial volume of about 900,000 m^3) was placed in the summer of 1999 at the seaward side of the outer surf zone bar (offshore distance of about 500 m) between the -6 and -8 m depth contours (below MSL). A beach fill of 200,000 m^3 was placed in September 2000 (middle section). Sand volumes were determined in three alongshore sections over a period of 3 years: south

section with a length of 1 km, middle section of 3 km (including feeder berm) and north section of 1 km. The cross-shore boundaries are +3 m and –8 m to MSL (cross-shore length scale of about 900 m).
The shoreface nourishment area shows a total loss of about 350,000 m^3 after 3 years, which is about 40% of the initial volume. Hence about 60% of the nourishment volume is present in the middle section resulting in a lifetime of the order of 6 to 7 years. Both the updrift and downdrift sections do not benefit from this as both sections show erosion (of the order of 150,000 m^3 after 3 years).
The second shoreface nourishment at location Egmond 2004-2006 (**Table 1**) is situated at approximately the same location as that of Egmond 1999-2002 (**Delft Hydraulics, 2008**). The shoreface nourishment (length of about 4 km; total initial volume of about 1,800,000 m^3) was placed in the summer and autumn of 2004 at the seaward side of the outer surf zone bar (offshore distance of about 300 m) between the -5 and -8 m depth contours (below MSL). A beach fill of 500,000 m^3 was placed in the summer of 2005 (middle section). After 2 years the middle section (nourishment area) shows no losses; the volume still is about 1,800,000 m^3.
Both shoreface nourishments at Egmond beach have lifetimes of at least 5 years. Both the updrift and downdrift sections show minor changes (erosion or accretion of the order of 50,000 m^3 per year), which is marginal compared with the initial nourishment volumes. If the nourishment volume is placed on the seaward flank of the outer bar, a typical feature is the splitting of the outer bar in two new bars. The most landward bar grows in height and moves slowly onshore. In both Egmond cases the beach zone did not benefit much from the presence of the shoreface nourishments, as beach nourishments were necessary in both cases to maintain a sufficiently wide beach (for recreation). Hence, it can be concluded that the Egmond beach is not positively affected by the presence of shoreface nourishments on the lifetime scales (about 5 years).
Finally, a shoreface nourishment along one of the northern barrier islands (Terschelling site; 1993-2000) is discussed (**Table 1**). This location is much more dynamic with large net longshore transport in north-eastern direction. This case was studied by **Hoekstra et al. (1996), Spanhoff et al. (1997) and Grunnet (2002)**. The spring tidal range is about 2.8 m; the peak tide- and wind-driven longshore currents are between 0.5 and 1 m/s. The wave energy climate is moderate to high. The bed material consists of sand with median diameter between 0.24 mm (beach) and 0.16 mm (outer surf zone). About 2.1 million m^3 (450 to 500 m^3/m; 0.2 mm) of sand was dumped in the trough between the middle and outer longshore bars between -4.5 and -7 m over a length of 4400 m. The dumping of sand was completed in October 1993. The most important morphological features are: rapid adjustment of disturbed bar-trough morphology (in about 6 winter months) to former patterns; splitting of outer bar in two new bars; growth of the most landward bar (increase of height by about 1.5 m) and landward migration of this bar and migration of nourishment volume (cross-shore area of about 400 m^2) in dominant alongshore drift direction (north-eastwards) at a rate of about 350 m/yr, yielding a net longshore transport of 1.5 million m^3/yr. Analysis of the sediment volumes over the first 2 years shows an erosion volume of about 0.6 million m^3 at the nourisment area; about 0.15 million m^3 is lost in offshore direction (across -7 m), about 0.3 million m^3 in alongshore direction and about 0.15 million m^3 in onshore direction. The nearshore (landward) zone shows a volume increase of about 1.2 million m^3 in 2 years, which is much larger (8 times) than the value of the onshore migrated volume (0.15 million m^3). Thus, about 1 million m^3 sand has entered the beach area by longshore transport processes (lee effect). All three sections show a significant increase of the sand volume after 4 years, especially the middle section (nourishment section). The nearshore (landward) zone shows a volume increase of about 700,000 m^3 after 4 years, which is an efficiency of 30% of the initial nourishment volume During the period November 1993 to May 2000, a layer of sand with a thickness of about 1 m has accumulated in the inner beach and bar zone ($0<x<500$ m) due to onshore transport processes (feeding effect) and longshore trapping processes (lee effect). Based on these results, the lifetime of the feeder berm at the Terschelling site is of the order of 5 to 10 years.
Overall, it is concluded from field practice that shoreface nourishments have an efficiency (defined as the ratio of volume increase of the nearshore zone and the initial nourishment volume) of 20% to 30% after about 3 to 5 years; the nearshore zone is defined as the zone between -1 and -4.5 m NAP (landward of the nourishment area). Similar values are reported by **Witteveen and Bos (2006)** based on the analysis of 8 shoreface nourishments along the Holland coast. The efficiency with respect to the beach zone between -1 m and +3 m is extremely low (about 2% to 5% after 3 to 5 years). Given a typical shoreface nourishment volume of 400 m^3/m, the potential increase of the beach volume after 3 to 5 years is not more than about 10 to 15 m^3/m or a layer of sand with thickness of about 0.1 m to 0.15 m over a beach width of 100 m. Beach nourishments have extremely low life times of 1 to 2 years along the Holland coast.

4.4.2 Coastal response to long term nourishments

A massive programme of large scale and long term beach and shoreface nourishments is being executed along the Holland coast to mitigate the chronic long term erosion. The Holland coast is the central coastal section of the Netherlands bordering the North Sea. It consists of two large-scale cells (compartments), each with a length of about 55 km, see **Figure 21**. The southern cell is situated between two long harbour jetties; the Hoek van Holland jetty (south) and the IJmuiden jetty (north). The northern cell is situated between Den Helder bordering the Texel inlet (north) and the IJmuiden jetty (south). Each cell is divided in two subcells (each with a width of about 0.5 to 1 km) covering the shoreface zone between the -8 m and -3 m depth contours (depth to MSL) and the nearshore zone or beach zone between the -3 m and +3 m depth contours. The landward boundary is situated at the dune toe line (+3 m to MSL).

Since many centuries the central coast of The Netherlands between Den Helder and Hoek van Holland behaves as a beach-dune system in a strong interaction with the barrier island coast in the north and the delta coast in the south. For hundreds of years the most northern and southern beaches are suffering from structural (chronic) erosion due to the sediment-importing capacity of the neighbouring tidal inlets and basins. During the period between 1600 and 1800 the retreat of the coastline in the eroding sections was of the order of 3 to 5 m/year caused by the eroding capacity of the flood and ebb currents near the tidal inlets in the south and in the north. From 1800 onwards coastal defence was improved by building stone groynes in the sections 0-30 km and 100-118 km.

As a result of these man-made structures, the retreat of the coastline in the eroding sections was considerably reduced to about 0.5 to 1.5 m/year. Long rubble-mound barriers (breakwaters) normal to the shore were built around 1870 near Hoek van Holland and IJmuiden to ensure a safe approach of vessels to the harbour of Rotterdam and Amsterdam. These man-made structures have compartimentalized the Holland coast into two large-scale sediment cells, each with a length of about 55 km. The annual loss of sediment into the Texel inlet is of the order of 1 million m^3/year.

The tidal range along the coast is between 1.4 m near Den Helder and 1.7 m near Hoek van Holland. Tidal currents are prominent along the coast; the flood currents to the north have maximum values of about 0.8 m/s during spring tide, whereas the ebb currents to the south have lower maximum values of about 0.7 m/s resulting in residual current velocities of the order of 0.1 m/s to the north. Wind waves offshore exceed 2 m approximately 10% of the time and 3 m approx. 2% of the time. Most waves arrive from southwest to northwest directions. The highest waves are from the northwest direction because of the longer fetches in this sector.

In 1990 a new coastal management policy was initiated aimed at compensating all coastal erosion by regular beach and shoreface nourishments using sand dredged from offshore borrow regions beyond the -20 m depth contour where large quantities of sand are available in the North Sea and the long-term effects of sand mining are minimum. This new policy is now in operation for more than 15 years and the effects on the overall sediment budget of the Holland coast can be evaluated based on analysis of measured long-term cross-shore profile data.

Figures 21 and 22 show the annual erosion and deposition volumes (in m^3/year) for various alongshore sections in both cells of the Holland coast focussing on the period 1964 to 1990 (with minor nourishments) and 1990 to 2006 (with major nourishments) to study the effect of the nourishment scheme (shown in Figure 20) set into operation since 1990.

Analysis of the 1964-1990 data shows (**Figure 21left** and **22left**) substantial erosion of the order of 100,000 m^3/year (or 20 m^3/m/year) and coastal recession of the order of 1 m/year along the northern sections (km 0 to 30) of the north cell. Large deposition values can be observed on both sides of the long harbour jetties in the middle of the Holland coast (IJmuiden sections, km 50 to 60) and erosion in the neighbouring sections in both cells (in line with the data presented by **Van Rijn, 1997**).

Analysis of the 1990-2006 data (**Figure 21right** and **22right**) shows substantial deposition at nearly all sections due to the massive nourishment programme, shown in **Figure 23**. Two methods have been used to determine the annual volume changes: 1) based on trend analysis using all annual data sets and 2) based on subtraction of the bathymetric data of 1 January 1990 and 1 January 2006 only. Given both results, the annual volume change in each subcell is of the order of 600,000±200,000 m^3/year in the period 1990-2006. The total nourishment volume (beach and shoreface nourishments) in the North cell was 1.3 million m^3/year (beach 0.8; shoreface 0.5) and 2.1 million m^3/year (beach 0.8 and shoreface 1.3) in the South cell. The total annual nourishment of 3.4 million m^3/year (between 1990 and 2006) is about 0.3% of the total sediment volume of about 1 billion m^3 in the littoral zone

between the -8 m and +3 m depth contours. Hence, the total potential increase (neglecting any sediment loss) of the sediment volume is of the order of 5% in the littoral zone on the time scale of 15 years.
Comparison of the volume data of both periods (1964-1990 and 1990-2006) shows that the erosive trend along the northern sections of the north cell has changed into an accretive trend due to the massive nourishment programme. Trends of (minor) erosion can only be observed in some isolated sections in the middle of the Holland coast.

Den Helder (km 0)

IJmuiden (km 55)

Hoek van Holland (km 118)

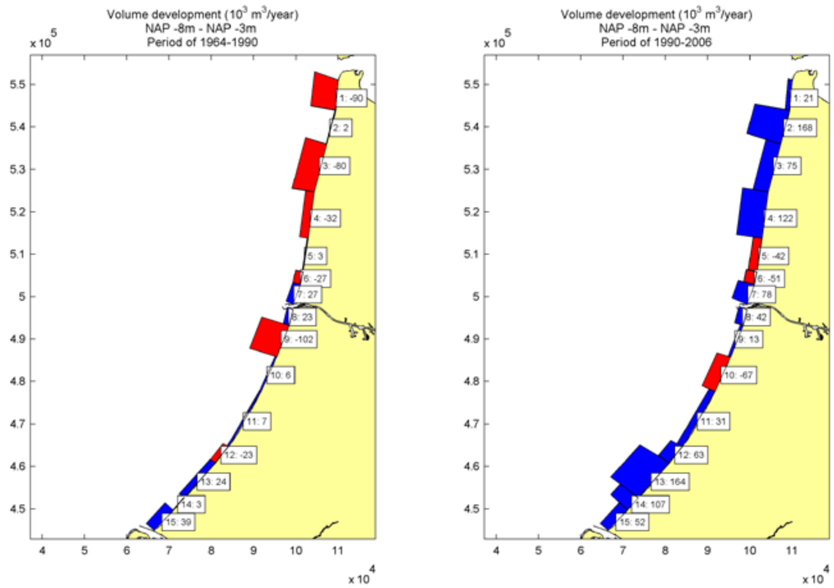


Figure 21 *Volume changes in zone between -8 m and -3 m (to MSL) depth contours (Red=erosion volume, -90,000 m³ in Section 1; Blue=deposition volume, 21,000 m³ in Section 1) Left: period 1964 to 1990 Right: period 1990 to 2006*

Den Helder (km 0)

IJmuiden (km 55)

Hoek van Holland (km 118)

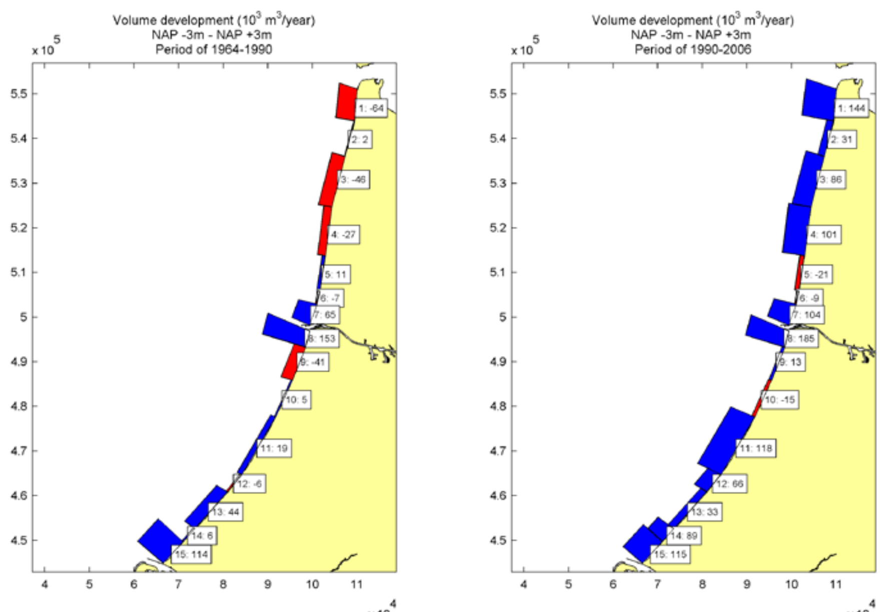


Figure 22 *Volume changes in zone between -3 m and +3 m (to MSL) depth contours (Red=erosion volume, -64,000 m³ in Section 1; Blue=deposition volume, 144,000 m³ in Section 1) Left: period 1964 to 1990 Right: period 1990 to 2006*

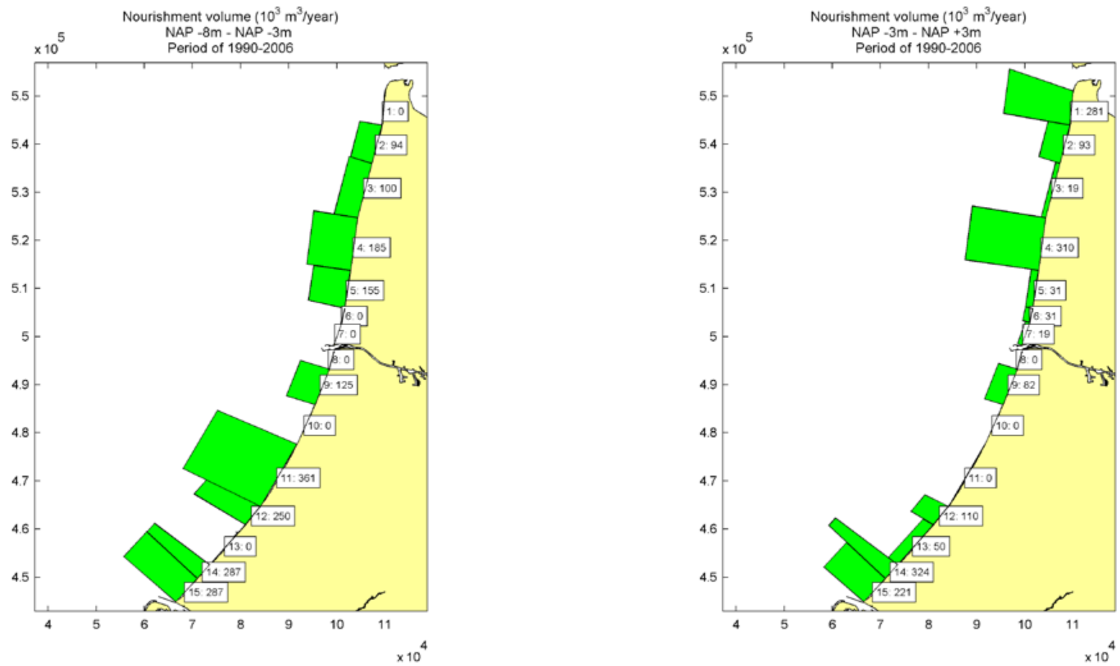


Figure 23 *Nourishment volumes in period 1990 to 2006*
Left: zone between -8 and -3 m depth contours *Right: zone between -3 and +3 m depth contours*

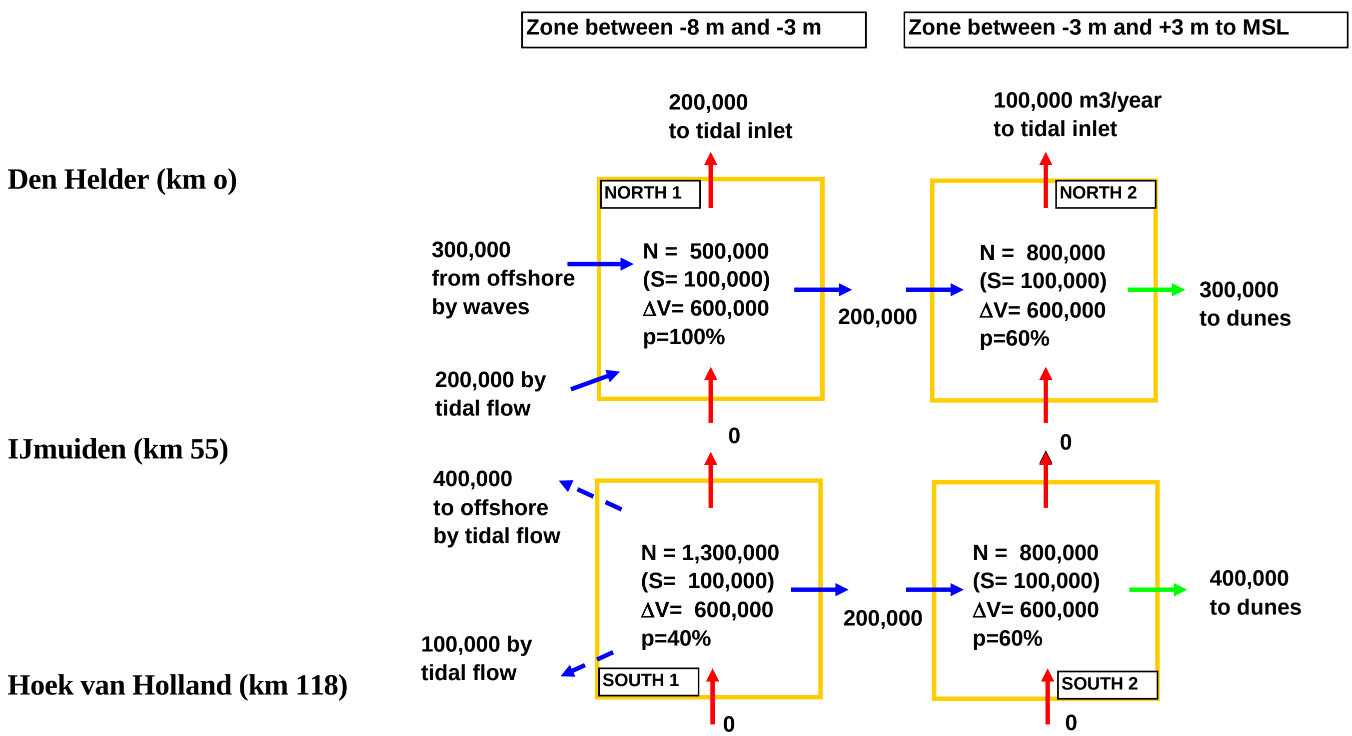


Figure 24 *Sediment budget for subcells of Holland coast; period 1990 to 2006 (15 years)*
N= nourishment volume (m^3/year); ΔV= measured volume increase (m^3/year),
S= compensation volume related sea level rise (m^3/year),
p=over-nourishment percentage (in %)

Cell		Period 1962-1990	Period 1990-2006
North cell (55 km)	In	Nourishments 0.18 Mm^3/year onsh. tr. across -8 m line 0.20 Mm^3/year	Nourishments 1.3 Mm^3/year tr. from offshore, south 0.5 Mm^3/year
	Out	across northern boundary -0.50 Mm^3/year across dune toe +3 m line -0.14 Mm^3/year	across northern boundary -0.3 Mm^3/year across dune toe +3 m line -0.3 Mm^3/year
	Net	-0.26 Mm^3/year	+1.2 Mm^3/year
South cell (63 km)	In	Nourishments 0.26 Mm^3/year onsh. tr. across -8 m line 0.15 Mm^3/year	Nourishments 2.1 Mm^3/year
	Out	across dune toe +3 m line -0.14 Mm^3/year	across dune toe +3 m line -0.4 Mm^3/year tr. to offshore, north, south -0.5 Mm^3/year
	Net	+0.27 Mm^3/year	+1.2 Mm^3/year

Table 2 *Sediment budgets in north and south cells of Holland coast in periods 1964-1990 and 1990-2006*

The sediment budgets including estimates of the annual transport volumes across the cell boundaries are shown in **Figure 24** and **Table 2**. The transport across the northern boundary into the Texel inlet was estimated to be about 0.5 million m^3/year (see **Van Rijn, 1997**), but is now estimated to be somewhat smaller at 0.3 million m^3/year (**Elias, 2006**). The transport volumes by wind across the dune toe line (+3 m) were estimated to be 100,000 m^3/year or about 2 m^3/m/year for the north cell and about 400,000 m^3/year or about 8 m^3/m/year for the south cell with two wide beach plains near IJmuiden and Hoek van Holland (**Van Rijn, 1995, 1997**). Now, these estimates are somewhat larger (0.4 and 0.3 million m^3/year; see **Arens, 2009**). These values are equivalent with a seaward dune migration of the order of 0.5 to 1 m/year (in line with observations). A closed balance of the North1 cell requires an input of about 0.5 million m^3/year by wave-induced and current-induced transport from offshore. A closed balance of the South1 cell requires an export of 0.5 million m^3/year to offshore by the north-going tidal current passing around the south jetty at IJmuiden. About half of this value is estimated to be deposited in the navigation channel seaward of the jetty and the other half is estimated to be deposited in subcell North1. The net volume increase per subcell is of the order of 0.6 million m^3/year (see **Figure 24**). The difference N-ΔV can be seen as an estimate of the real erosion loss, which has to be compensated. At three cells (North2, South1 and South2) this value is positive and varies in the range of 0.2 to 0.7 million m^3/year. In cell North1 the difference N-ΔV is negative (-0.1 million m^3/year), which means deposition in the absence of nourishment (volume increase is larger than the nourishment volume).

The value N+S-ΔV represents the value which has to be compensated to account for all losses (including that related to sea level rise). The total compensation volume for the Holland coast is about 1.4 million m^3/year for the period 1990-2006 (about 14 m^3/year per m coastline over a total length of about 100 km) and about 0.85 million m^3/year for the period 1964-1990. The total nourishment volume is 3.4 million m^3/year for the period 1990-2006, which means an over-nourishment of about 3.4-1.4 = 2 million m^3/year (about 60% of the nourishment volume). The over-nourishment percentage is defined as: p_{over}= (ΔV-S)/N with ΔV= volume increase, S = compensation volume related to sea level rise, N = nourishment volume. The over-nourishment values per cell vary between 40% and 100%. Ideally, these over-nourishment percentages should be approximately zero for each subcell. The over-nourishment in both beach cells (North2 and South2) are of the order 0.5 million m^3/year or about 10 m^3/m/year and will on the long term lead to seaward migration of the shoreline of the order of 0.5 to 1 m/year. These figures show that about 3.5 million m^3 sand nourishment per year is required to bring the coastline seaward over 0.5 to 1 m (average 0.75 m). So, roughly 5 million m^3/year of sand is required for coastal extension of about 1 m over a distance of 100 km. The sand should be placed at the weak spots, from where it can be spread out over the entire coastline by longshore processes. Using this approach of massive nourishment, the Dutch shoreline can be substantially extended and reinforced (50 to 100 m) in seaward direction over a period of the order of 100 years as an extra coastal buffer to better deal with sea level rise effects.

The overall permanent loss of sand from the Holland coast is about 0.3 million m^3/year (period 1990-2006) to the tidal inlet at the northern boundary (export to Wadden islands and Wadden Sea). The export of sand of about 0.7 million m^3/year across the dune toe is not a real loss for the Holland coast as it is kept within in the dune system of the Holland coast. The net exchange at the offshore boundary of -8 m is approximately zero and consists of 0.5 million m^3/year export in the southern cell and a similar import volume in the northern cell. Taking the loss of sand to the north as the only real loss for the Holland coast, the overall efficiency of the nourishment volume of about 3.4 million m^3/year is about (3.4-0.3)/3.4x100% = 90%. About 20% of the total nourishment volume is accumulated in the dune zone (across +3 m line); about 70% remains in littoral zone between the -8 m and -3 m lines and about 10% is lost from the Holland system (passing northern boundary to Texel inlet). The beach zone hardly benefits from the nourishment efforts; it functions as a transition zone between the shoreface and the dune zones.

This example of the Dutch coast shows that long-term and large-scale erosion can be stopped by massive beach and shoreface nourishment over long periods of time. This approach is only feasible if sufficient quantities of sand are available and the dredging and dumping costs are acceptable (about 10 to 15 million Euro per year or 100 to 150 Euro per m coastline for the Holland coast with a total length of about 100 km). Furthermore, the long-term impacts on nearby sediment sinks such as tidal bays, lagoons and back-barrier basins should be carefully assessed. In the Dutch case the trapping of fine sands carried away from the nourishment borrow and dumping locations by tidal currents may on the long term lead to excessive deposition in and gradual silting up of the Wadden Sea.

Although, sand nourishment may offer significant benefits, it is a costly method if life spans are fairly short at very exposed beaches. A recent study of nourishment projects along Californian beaches (USA) has shown that about 20% of the projects survived less than 1 year, 55% lasted only 1 to 5 years and about 20% survived over 5 years (**Leonard et al., 1990**). Another constraint is the long-term availability of adequate volumes of compatible sand at nearby (economic) locations. For example, sand material suitable for beach nourishment cannot easily be found at most Italian and Spanish sites along the Mediterranean. Hence, hard structures have often to be used to deal with erosion along these latter sites. This option will be explored hereafter focussing on groynes and detached breakwaters.

4.5 Conclusions nourishments

- coastal erosion including sea level rise effects can be mitigated by shoreface, beach and/or dune nourishments with sediments of comparable size or with slightly coarser sediments;
- dune and beachfills are mainly used to compensate local erosion in regions with relatively narrow and low dunes (in regions of critical coastal safety) or when the local beach is too small for recreational purposes; practical beachfill volumes per unit length of coast are in the range of 10 m^3/m/yr for low-energy coasts (Mediterranean) to 150 m^3/m/yr for high-energy coasts (Ocean coasts); practical life times are about 1 to 5 years depending on the wave climate; lifetimes of beach fills can be extended by using coarser sediments;
- field and laboratory data and modelling results show that the daily-average erosion rates of beach fills are of the order of 1 to 10 m^3/m/day which implies that beach fills of 100 to 200 m^3/m can be easily eroded away in one to two winter seasons depending on the local wave climate;
- shoreface nourishments (feeder berms) are used in regions of relatively wide and high dunes (relatively safe coastal regions) to maintain or increase the sand volume in the nearshore zone with the aim to nourish the nearshore zone on the long term by natural processes (net onshore transport); practical nourishment volumes are of the order of the volume of the outer breaker bar (300 to 500 m^3/m); practical alongshore length scales are 2 to 5 km; practical life times are 3 to 10 years depending on the wave climate;
- practical field experience shows that shoreface nourishments have an efficiency (defined as the ratio of local volume increase and initial nourishment volume) of 20% to 30% after about 4 to 5 years with respect to the nearshore zone between -1 and -4.5 m (landward of the nourishment area); the efficiency with respect to the feeding of the beach zone between -1 m and +3 m is extremely low (2% to 5%);
- the example of the Dutch coast shows that long-term and large-scale erosion can be stopped by massive beach and shoreface nourishment over long periods of time;
- sand nourishment is a costly method if life spans are fairly short at very exposed beaches and comparable sand is not easily available at nearby borrow sites.

5. Controlling erosion by hard structures

Generally, coastal structures such as groynes, detached breakwaters and artificial submerged reefs are built to significantly reduce coastal beach erosion and to maintain a minimum beach width for recreation. Preferably, these types of hard structures should be built at locations (downdrift of a protruding coastal section) where the transport gradient is almost zero at the transition from increasing to decreasing longshore transport to prevent lee-side erosion, **see Figure 1**.
Hard structures such as groynes and breakwaters are, however, no remedy for dune and soft cliff erosion during conditions with relatively high surge levels (+3 to +5 m above mean sea level). Seawalls and revetments have to be built to stop dune and cliff erosion completely. Usually, these latter structures are built in regions (along boulevards of beach resorts) where natural dunes are absent or have been removed for recreational purposes.
A modern approach along the coasts of major beach cities is the replacement of small-scale, cell-type groyne fields by wide pocket-type beaches consisting of one or two long terminal groynes and several submerged or low-crested detached breakwaters protecting large-scale beach fills and creating a relatively long uninterrupted and visually attractive beach (**Gomez-Pina, 2004**). Basically, this is the replacement of a series of small-scale cells by one large-scale cell.

5.1 Sea walls and revetments

Seawalls, dikes and revetments are shore-parallel structures armouring the shore to protect the land behind it against episodic storm-induced erosion and/or long-term chronic erosion by the sea, see **Figure 25**. These structures (vertical, concave or sloping) are built along a limited section of the shoreline as a last defence line against the waves, when natural beaches and dunes are too small or too low to prevent erosion due to high waves. It is the "end of the line" solution, if no other solution helps to solve the problem of erosion and/or flooding (high surge levels).

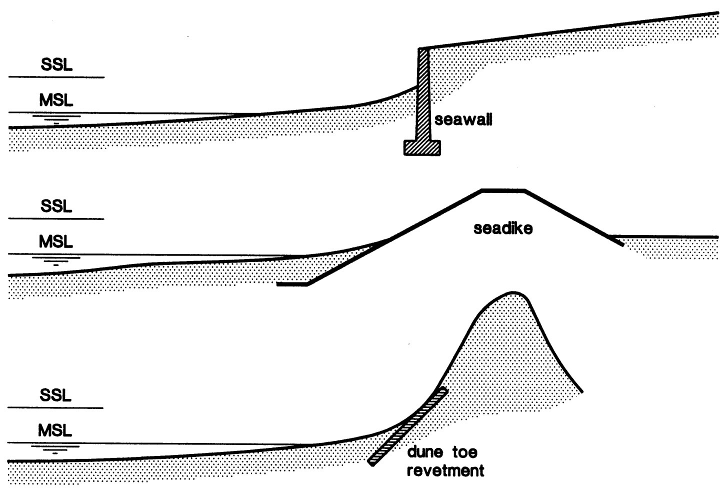


Figure 25 *Seawall, seadike and revetment*

A seawall is a vertical (or almost) retaining wall with the purpose of coastal protection against heavy wave-induced scour; it is not built to protect or stabilize the beach or shoreface in front of or adjacent to the structure. Thus, chronic erosion due to gradients of longshore transport will not be stopped or reduced.
A revetment (see **Figures 25 and 26**) is an armour protection layer (consisting of light to heavy armour layer, underlying filter layer and toe protection) on a slope to protect the adjacent upland zone against scour by current and wave action. To reduce scour by wave action and wave reflection at the toe of the structure, the slope of the revetment should be as mild as possible (not steeper than 1 to 3). The crest of the revetments should be well above

the highest storm surge level resulting in a crest level at +5 m above mean sea level along open coasts and upto +7 m at locations with extreme surge levels.

Seawalls and revetments are very effective in stopping local shoreline erosion (dunes and soft cliffs), but these types of structures hardly change the longshore transport gradient often being the basic cause of chronic erosion. Hence, erosion of the beach and shoreface in front of the structure will generally remain to occur. Downdrift erosion will usually occur at locations where no structures are present. Continuing shoreface erosion may ultimately lead to an increased wave attack intensifying the transport capacity and hence intensified erosion (negative feed-back system). Groynes (see **Figure 26**) are often constructed to reduce scour at the toe of the revetment by deflecting nearshore currents. Seabed protection may be necessary in case of strong tidal currents passing the structure (seadike protruding into sea).

Figure 26 *Coastal revetments and groynes at Caparica, South of Lisbon, Portugal*

5.2 Groynes

5.2.1 Types and hydraulic behaviour

Groynes are long, narrow structures perpendicular or slightly oblique to the shoreline extending into the surf zone (generally slightly beyond the low water line) to reduce the longshore currents and hence the littoral drift in the inner surf zone, to retain the beach sand between the groynes, to stabilize and widen the beach or to extend the lifetime of beach fills. A series of similar groynes (groyne field) may be constructed to protect a stretch of coast against erosion.

These structures are known as *beach groynes*. An overview of groynes is given by **Fleming (1990), Kraus et al. (1994), US Army Corps of Engineers (1994), Van Rijn (1998, 2005)** and many other authors (Journal of Coastal Research SI 33, 2004). Groynes can also be applied to deflect tidal currents from the shoreline and/or to stabilize relatively deep tidal channels at a more offshore position. These structures are known as *inlet groynes or current groynes*.

Two main types of groynes can be distinguished:

- *impermeable, high-crested structures*: crest levels above +1 m above MSL (mean sea level); sheet piling or concrete structures, grouted rock and rubble-mound structures (founded on geotextiles) with a smooth cover layer of placed stones (to minimize visual intrusion) are used; these types of groynes are used to keep the sand within the compartment between adjacent groynes; the shoreline will be oriented perpendicular to the dominant wave direction within each compartment (saw-tooth appearance of overall shoreline);
- *permeable, low-crested structures*: crest level between MLW and MHW lines to reduce eddy generation at high tide; pile groynes, timber fences, concrete units, rubble-mound groynes, sand-filled bags are used; permeability can increase due to storm damage; these types of groynes are generally used on beaches which have slightly insufficient supplies of sand; the function of the groynes is then to slightly reduce the littoral drift in the inner surf zone and to create a more regular shoreline (without saw-tooth effect); groynes should act as a filter rather than as a blockade to longshore transport.

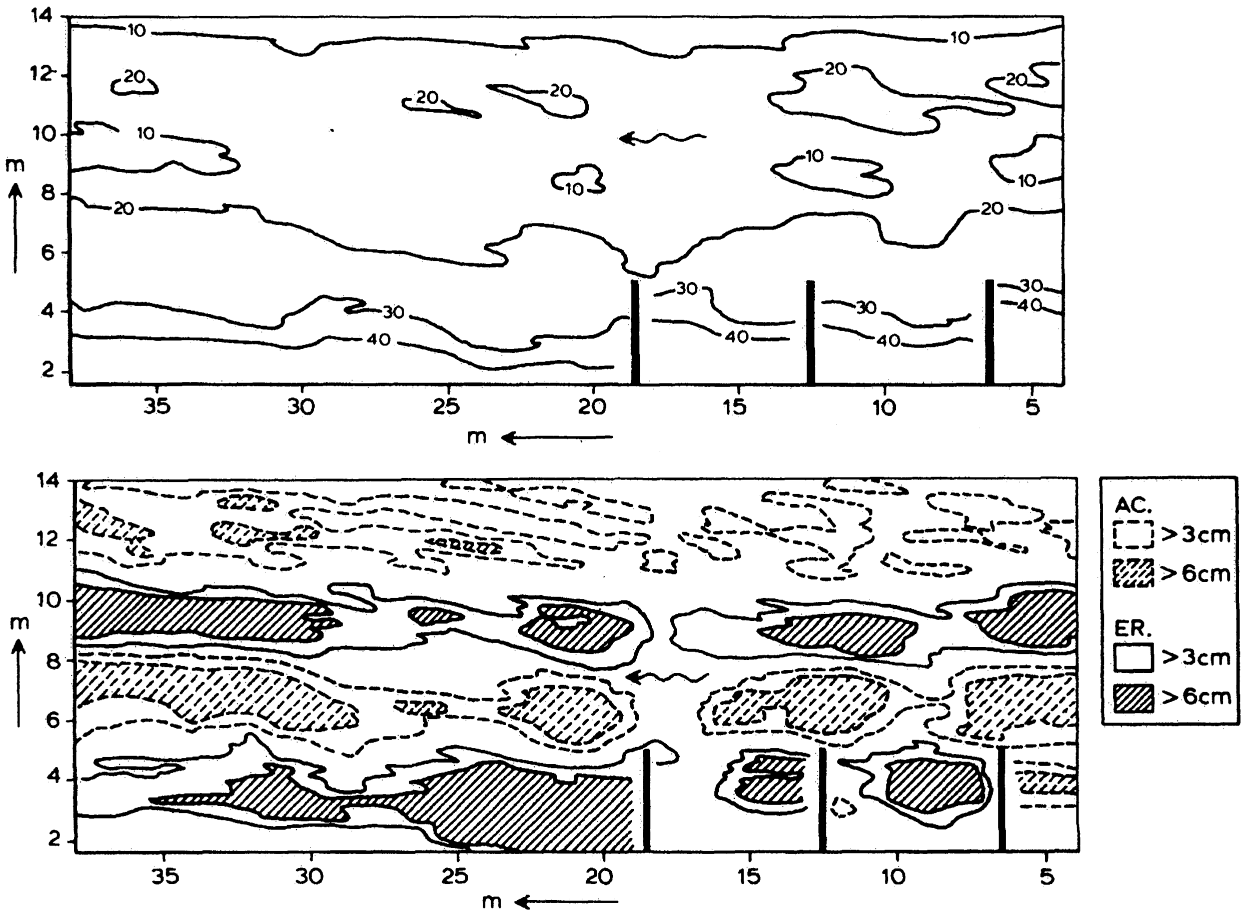


Figure 27 *Effect of groynes on coast, Test T23 (Hulsbergen et al., 1977)*
(longshore drift from right to left; 0= updrift; 35 m= downdrift)
Top: *contour lines (in cm above bottom of basin) after 50 hours*
Bottom: *bed level changes in cm after 50 hours (AC.= accretion; ER.= erosion)*

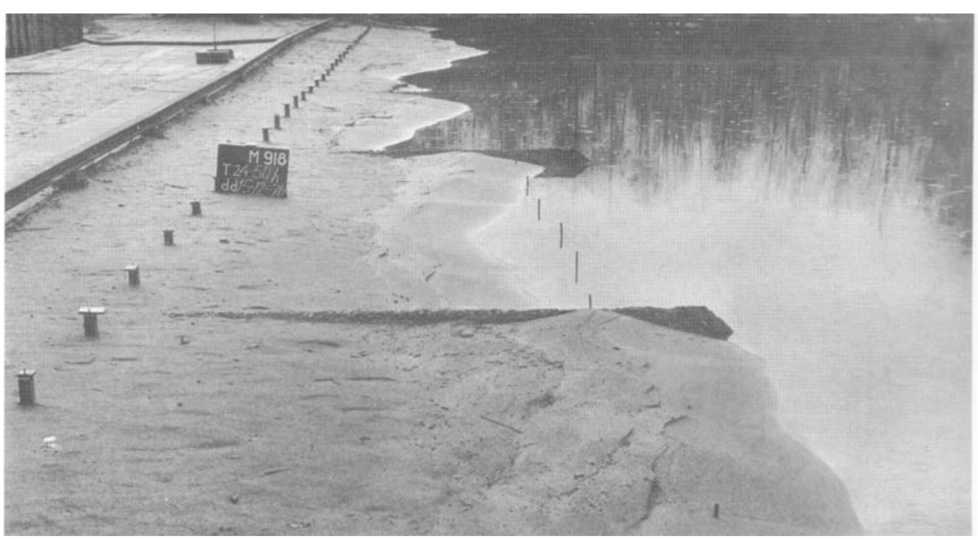


Figure 28 *Effect of three groynes on coast, Test T24 (Hulsbergen et al., 1977)*

Laboratory basin tests on the functioning of straight impermeable groynes have been performed by **Hulsbergen et al. (1976)** and by **Badiei et al. (1994)**. **Hulsbergen et al. (1976)** used an experimental set-up with 1 and 3 impermeable groynes (length of 4.2 m, spacing of 6 m) with their crest above the water level and perpendicular to the coast. The sand bed had a d_{50} of 0.22 mm. The beach slope between the groynes was about 1 to 12 and the shoreface slope beyond the tip of the groynes was about 1 to 25 over a distance of about one wave length. Regular waves with a period of 1.55 s were used. The wave heights were in the range of 0.075 and 0.14 m. The water depth in front of the wave board was about 0.38 m. The wave length in front of the wave board was about 2.7 m. The wave incidence angle at the breaker line was about 5^o. Water and sand were supplied upstream and trapped downstream to represent an infinitely long and straight beach. First, tests without groynes were done to establish a (dynamic) equilibrium beach and then the groynes were installed. The test results with 1 groyne (T22, length of 4.2 m; breaker line at approx. 3.5 m from shore) show regular accretion on the updrift side and erosion on the downdrift side of the groyne in the case of a low wave height of 0.075 m. In the case of a wave height of 0.1 m (T18) and hence a wider surf zone (groyne tip at edge of surf zone) the groyne was not able to block the bulk of the longshore transport, but most of it was moved around the tip of the groyne and was partly deposited in the lee area of the groyne. Accretion on the updrift side of the groyne was minimum with waves of 0.1 m. Erosion did occur at the tip of the breakwater and over some distance on the downdrift side of the groyne.

The test results with 3 groynes (T23, wave height of 0.075 m, breaker line at approx. 1 m beyond the tip of the groynes) shows the presence of accretion (after 50 hours) on the updrift side and erosion on the downdrift side, see **Figure 27.** The sand feed at the upstream boundary was in the range of 40 to 70 l/hour. The groynes were well inside the surf zone, because wave breaking occurred beyond the tip of the groynes. Inside the groyne cells there was re-orientation of the beach contours (parallel to wave crests) with accretion on the downdrift end (right) and erosion on the updrift end (left). Overall, erosion due to rip currents and circulations was dominant inside the cells. Bypassing of sediment did occur, but the cells did not trap sediment from the bypassing transport. In Test T23A the most upstream cell was filled with sand up to the tip of the groynes. The beach fill was quickly eroded after the start of the test.

In Test 24 the groynes were shortened by about 0.4 m to increase the width of the sand bypassing zone. The results (see **Figure 28**) are similar to that of test T23.

In Test T34 the wave height was 0.115 m and the water level was fluctuated over $\pm$ 0.025 m in a one-hour cycle to simulate tidal fluctuations resulting in a variation of the breaker line. The bed level changes after 45 hours showed opposite effects (to that of Test T23) with acretion on the updrift end of the cells and erosion on the downdrift end of the cells due to the generation of relatively strong circulation zones just downstream of the groyne tips (not shown). This mechanism prevented the contour lines inside the cells to become parallel to the wave crests. This behaviour may partly be caused by the use of regular waves, which produce relatively pronounced offshore bars and relatively strong rip currents.

Badiei et al. (1994) performed physical mobile bed tests to study th effect of groynes on an initially straight beach exposed to oblique incident irregular waves (Jonswap spectrum, T_p = 1.15 s). A straight beach (d_{50} = 0.12 mm) without groynes was tested for each set of variables, then 1 or 2 impermeable groynes with different lengths were installed.

At the beginning of each test the sandy beach was reshaped to a plane slope of 1 to 10. Then the beach was exposed to waves for 4 hours. At that time a clear offshore bar-trough formation had developed. Then, the groynes were installed and the tests were continued in cycles of 2 hours. The tests in the NRCC basin had a wave incidence angle of 11.6 degrees (at the wave board) to the coast normal. The deep water depth was 0.65 m near the wave board. Two tests with double groynes (spacing = 4.75 m, $H_{s,o}$ = 0.08 m) are herein described:

NT4: L_g/L_b = 1.4 with L_g = groyne length and L_b= width of surf zone ($\cong$1.7 m);

NT5: L_g/L_b = 0.8 with L_g = groyne length and L_b= width of surf zone ($\cong$1.7 m).

The results show accretion on the updrift side of the most updrift groyne and erosion on the downdrift side of the most downdrift groyne, see **Figure 29.** Two distinct shoals offshore of the groyne tips in the test NT4 with the long groynes were present due to blocking of the incoming longshore transport which could not bypass the tip of the groyne. Bypassing of sand was almost zero in the test NT4 with the long groynes. These shoals were absent in the test NT5 with short groynes due to bypassing processes. Inside the groyne cells there was re-orientation of the contour lines (paralllel to wave crests). Inside the groyne cell there was no significant trapping of sediment (see **Figure 29**) from the bypassing longshore transport due to the presence of circulation and rip currents. Small scour holes were generated near the tip of the groynes.

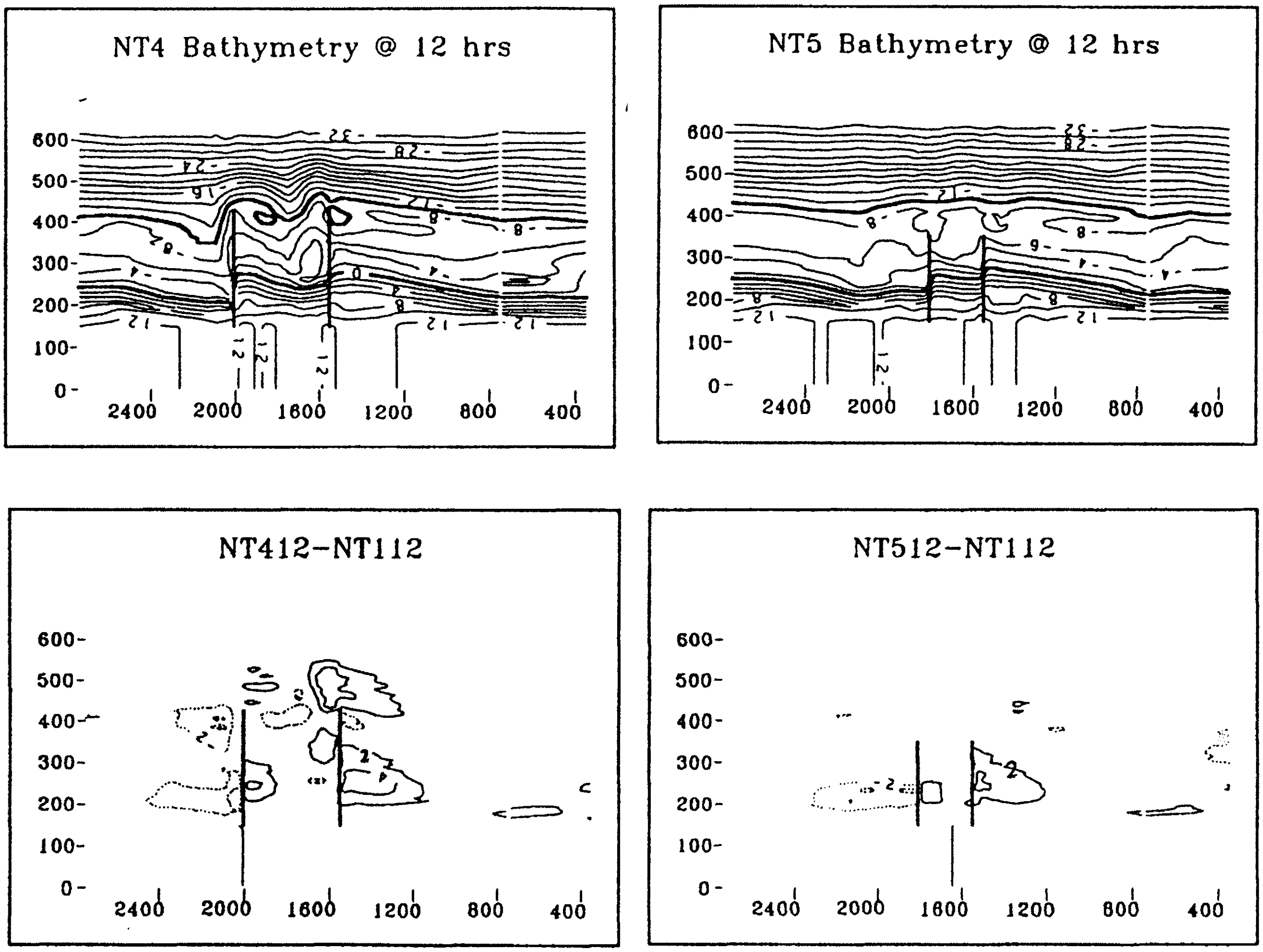


Figure 29 *Effect of groynes on coast, Tests NT4 and NT5 (Badiei et al., 1994)*
(longshore drift from right to left; 0 = updrift; 2400 = downdrift)
Top: contour lines (in cm below still water level) after 12 hours
Bottom: bed level changes in cm after 12 hours (solid= accretion; dashed.= erosion)

The differences in hydraulic behaviour of impermeable and permeable groynes have been elucidated by **Dette et al. (2004), Trampenau et al. (2004) and Poff et al. (2004)**, based on laboratory test results and field observations, see **Figure 30**. Impermeable groynes will tend to fully block the longshore current and transport over the entire length of the groynes, The longshore transport system is deviated seawards. Circulation and rip currents are generated due to set-up variations within the cell resulting in seaward transport of sediment on the updrift side of the groyne cells. The end result in a wave climate with one dominant wave direction is the typical saw-tooth bathymetry with scour channels near the groyne heads due to local rip currents. The saw-tooth effect increases with increasing groyne spacing.

In a severe wave climate with two dominant but adversary wave directions with respect to the shore normal, sediment erosion due to breaking waves, undertows and rips generally is dominant inside groyne cells along coasts consisting of fine sand (0.2 mm) resulting in narrow beaches (see **Figure 34**; northern groynes at Sitges, Spain). Scour holes may be generated at the tip of the groynes, which will lead to an increase of the wave height and associated sand transport capacity. Usually, large-scale erosion will develop downcoast of the terminal groin (lee-side erosion) if natural bypassing is absent. Erosion between the groynes and beyond the terminal groyne can only be mitigated by regular beach fills to stabilize the beach.

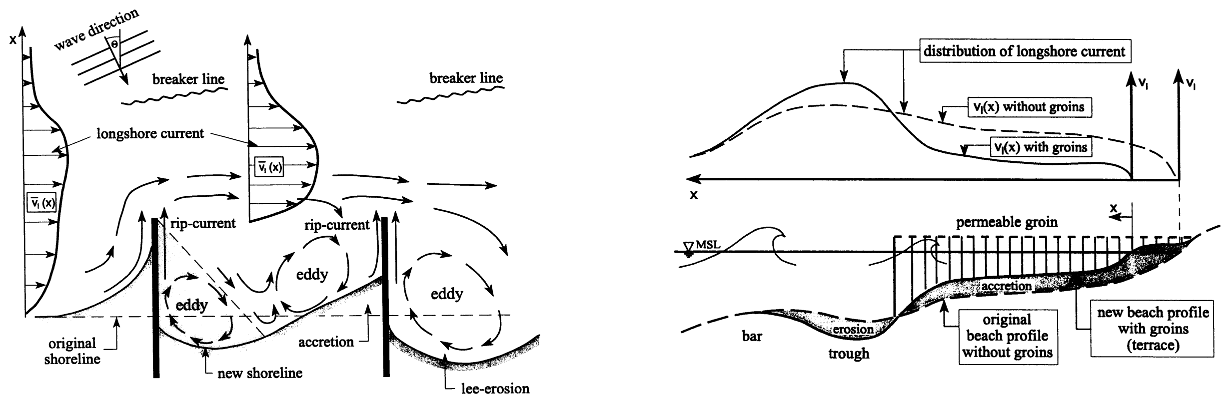


Figure 30 *Functioning of impermeable (left) and permeable groynes (right),* ***Trampenau et al. 2004***

Groynes with permeability <10% largely act as impermeable groynes. Groynes with a permeability of about 30% to 40% essentially act as resistance to flow through the groynes (**Figure 30**) without generation of circulation cells. Longshore velocities are reduced by about 50% over the entire length of the groynes. Velocities seaward of the groynes are much less than those with impermeable groynes. Natural bypassing of sediments is established resulting in a more continuous shoreline and large-scale lee-side erosion beyond the terminal groyne is suppressed. Wooden pile screens or pile clusters (single or double pile rows) offer an efficient solution with low construction and maintenance costs along micro-tidal coasts with mild wave climates (Baltic, Mediterranean, Florida Gulf coast). The highest groyne performance was found for a permeability in the range of 30% to 40%. The groyne length should be slighty larger than the surf zone width (up to the landward flank of the inner bar trough) and groyne spacing should be equal to groyne length (**Trampenau et al., 2004**). Groin height is about 0.5 m above mean sea level (minimum visual intrusion) in tideless basins and variable (sloping downward in seaward direction) in tidal basins. The maximum pile length above the sea bed is about 3 m. Initial beach fills should be used along relatively steep, eroding beach profiles. Using these types of permeable groynes, the longshore transport can be significantly reduced (factor 2 to 3). Favourable experiences are obtained along the German Baltic coast and along the West Florida coast (Naples Beach, **Poff et al., 2004**)

High-crested, impermeable beach groynes generally have lengths (L) between 50 and 100 m; crest levels beyond +1 m m above MSL (mean sea level); groyne spacing (S) between 1.5 and 3 times the length of the groynes (S = 1.5 to 3L), as shown by experimental research in a wave basin (**Özölçer et al., 2006**). If the groyne spacing is too large (>3L), the longshore current and transport will be re-established resulting in a very oblique or curved shoreline (saw-tooth shoreline, see **Figures 43 and 44**) between the groynes. The cover layer of armour units should be well placed to obtain a smooth, visually attractive scenery.

High-crested, impermeable groynes should only be considered along exposed, eroding coasts of fine sand (0.2 mm), if the recession rates are exceeding 2 m per year. The length of the groynes should be smaller than the width of the surf zone during storm conditions ($H_{s,o}$ > 3 m) to promote sufficient bypassing of sand. Along beaches of fine sand these types of groynes will only reduce beach erosion (factor 2 to 3), but not stop it completey, as the waves can easily propagate into the compartments. Regular beach fills are required to reduce the beach erosion to manageable quantities. At the north section of the Holland coast (The Netherlands) consisting of 0.2 mm sand, the beach groynes built around 1850 have reduced shoreline erosion from about 3 to 5 m/year to about 1 to 2 m/year. Since 1990, regular beach nourishments (between 200 to 400 m^3/m/year) are used to completely stop shoreline erosion along the Holland coast.

Groyne crest levels should not be much larger than about +1 m to allow bypassing of sediment during high tide and stormy conditions to reduce lee-side erosion. High crest levels prevent sediment bypassing and are unattractive for beach recreation. Groyne notching by creating openings along the groyne in the most active longshore transport zone (swash zone and inner surf zone) has been applied along USA beaches to improve the sediment bypassing of existing groyne fields in combination with beach fills between the groynes (**Rankin et al., 2004a,b; Donohue et al., 2004; Wang and Kraus, 2004**).

Figure 31 *Example of effective groyne design (small compartments) at Miramar beach, Argentina (beach sediments 0.3 to 0.6 mm; ratio of spacing and length $\leq$1 to 1.5; crest at +3 m above MSL)*

Figure 32 *Timber groynes at gravel beach of Eastbourne, East Sussex, UK*

Relatively long groynes at close spacing (narrow cells) may be very effective along ***swell dominated*** ocean coasts consisting of relatively ***coarse*** sand (0.3 to 1 mm) at the upper beach zone and finer sand in the lower beach zone. Regular onshore movement of coarse sand by near-bed transport may result in wide beaches between the groyne, as shown by the Miramar coast, Argentina, see **Figure 31**.

Figure 31 shows a groyne field with small spacings (S/L $\leq$1 to 1.5) at the Miramar beach (Argentina) consisting of relatively coarse sediments in the range of 0.3 to 0.6 mm. Bed load transport prevails under normal conditions causing onshore transport of sediments by wave asymmetry effects. The groynes with lengths of about 150 m and crests between +2 m (tip) and +4 m (root) above MSL are almost completely covered by sand; only the tip of the groynes is visible. Bathing along these coarse-grained beaches is problematic as the beach slopes are quite steep and swells are often present.

A similar example is the Keta Lagoon groyne field along the coast of Ghana (West Africa) facing the South Atlantic Ocean (**Nairn and Dibajnia, 2004**). Pre-project recesssion rates were between 2 and 7 m per year. The beach consists of a relatively steep beach face above the low tide level (1 to 7; 0.6 mm sand) and a nearshore slope of 1 to 20 with sand in the range of 0.15 to 0.2 mm. The project consisted of 6 major groynes (headlands) with average lengths of 190 m (spacing of 750 m) in combination with massive beach fills between the groynes (2 million m^3).

The positive groyne field performance in the case of relatively coarse beach sediments (>0.3 mm) is also illustrated by a small-scale project of 6 groynes in Greece (S/L $\cong$ 2, L = 85 m, sediments between 0.5 to 5 mm; **Moutzouris, 1992**).

Figure 32 shows short timber groynes at the beach city of Eastbourne on the south coast of England. The purpose of these groynes is to prevent that the gravel/shingle material gradually moves to one end of the beach (beach shifting/rotation) due to longshore transport processes in the swash zone and to the other end of the beach when the wave direction changes.

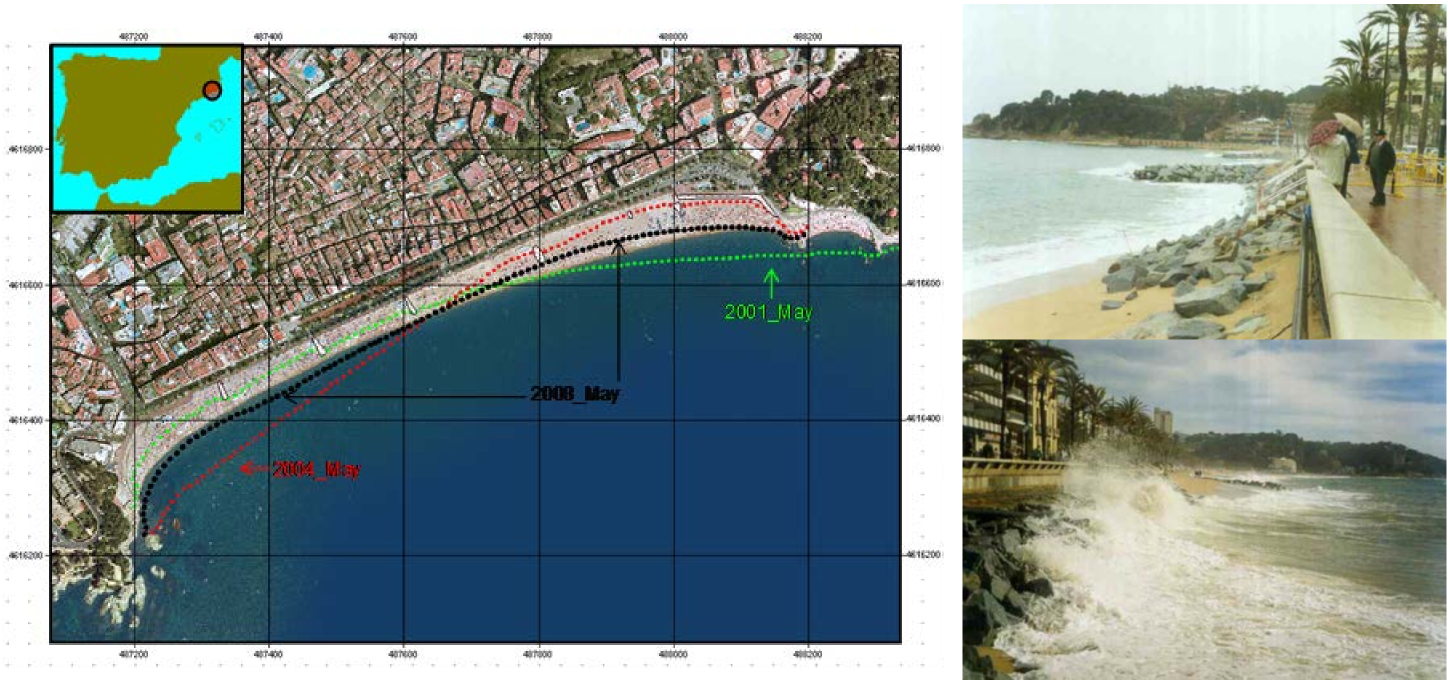


Figure 33 *Beach rotation (May 2001, 2004 and 2008) and storm impact at Lloret de Mar, Spain*

Figure 34 *T-head groynes at Longbranch-Bradley beach, North-Atlantic coast, USA (left)*
T-head and L-head groynes at South-Atlantic coast, Miramar, Argentina (right)

This type of beach behaviour (beach shifting/rotation) is a problem at many pocket beaches with relatively coarse sediments (coarse sand to shingle) between headlands. Generally, there are two main wave directions forcing the beach sediments along the beach depending on the wave direction. An early winter storm from another direction can cause major damage to the boulevard at the smallest beach end. Short beach groynes can be used to reduce the rotation of the beach. The beach at Lloret de Mar north of Barcelona (Spain) is a typical example of a coarse-grained (0.8 to 1 mm) beach with significant shoreline rotation (**Gracia et al., 2008**), see **Figure 33**. Another option here is to contruct one or more submerged detached breakwaters (see next section).

The effectiveness of straight groynes can be substantially increased by using T- or L- head groynes, which may be designed along very exposed, eroding coasts to reduce the wave energy into the compartments and to prevent/diminish the generation of rip currents near the groyne heads, see the beaches of **Figures 34** and **40** (Miramar, Argentina and Longbrach-Bradley, USA; Sitges, Spain). The length of the head should be of the same order of magnitude as the length of the groyne ($L_{head} \cong L$). Experimental research in a wave basin and field experience at a Turkish beach shows that T-groynes work well for S/L = 1.5 and $L_{head} \cong L = 60$ m (**Özölçer et al., 2006**). Measures should be taken to prevent wave reflection and the production of turbulence (vortex streets) near these types of groynes. Round headed groynes are more attractive in conditions with strong currents and low waves (inlets).

5.2.2 Numerical modelling results

A numerical study on the design of straight and T-head groynes using the DELFT3D-model has been performed by **Eslami Arab (2009)**. The model was operated in 3D mode using 11 layers. Waves were modelled using the SWAN-model including diffraction. The water level was constant (no tide). The results of tests NT4 and NT5 (two groynes) of **Badiei et al. (1994)** were used to validate the model. Qualitative agreement between measured and computed bed level changes was obtained. The validated model was used to compute the effect of various groyne fields on the nearshore morphology of a sandy coast (d_{50} = 0.2 mm), see **Table 3.** The offshore wave height (irregular waves) is $H_{s,o}$ = 1 m with T_p = 5 s and offshore wave incidence angle of 15°. The width of the surf zone is approximately 160 m (from the still water line). The initial cross-shore profile (without bars) was assumed to be a smooth equilibrium profile based on the Dean-method. The model was calibrated to represent this profile with only minor changes. The total run time was 45 days.

Run	**Number of groins**	**Length of groyne L_g (m)**	**Spacing S (m)**	**S/L_g**	**L_g/L_b**	**Wave angle offshore**	**Acretion/erosion inside cells (m^3 after 45 days**	**Acretion/erosion inside cells (as percentage of total total cell volume)**
O1	2	200	1000	5	1.2	15°	-2000	0.4%
O2	3	200	500	2.5	1.2	15°	-1000	0.2%
O3	5	200	330	1.25	1.2	15°	- 200	0.048%
B1	2	160	800	5	1	15°	+1000	0.4%
B2	3	160	400	2.5	1	15°	+1400	0.6%
B3	6	160	200	1.25	1	15°	+2000	0.8%
I1	2	130	650	5	0.8	15°	+ 120	0.06%
I2	4	130	325	2.5	0.8	15°	-1800	0.9%
I3	7	130	163	1.25	0.8	15°	- 800	0.4%
I21	4	130	325	2.5	0.8	25°	+4000	2 %

Table 3 *Basic parameters of model runs*

In all runs there was accretion at the updrift side of the most updrift groyne and erosion at the downdrift side of the most downdrift groyne, see **Figure 35B,C**. The volumetric changes inside the cells vary in the range of ±1% of the maximum accomodation volume between the groynes. Minor trapping prevails for the runs with a groyne length equal to the width of the surf zone. The volumetric changes inside the groyne cells are related to the amount of sand (both bed load and suspended load) passing the line through the tip of the groynes. Onshore-directed transport processes (wave-related bed load and suspended load transport) occur due to wave-asymmetry effects, see **Figure 35D** for Run B2. Offshore-directed transport processes occur due undertow velocities and due to the horizontal diffusive effect (see **Figure 35D**). This latter effect of horizontal diffusive transport is caused by the circulation velocities and the gradients of the sediment concentrations. The concentrations between the groynes generally are larger than those outside the groyne cells due the decreasing water depths and continuously breaking waves (fully saturated energy). Generally, this will result in diffusive transport from the zone with high concentrations inside the cells to low concentrations outside the cells. The actual suspended load passing the line through the tips of the groynes strongly depends on the magnitude and direction of the circulation velocities between the groynes and the concentration distribution. In **Figure 35A** it can be seen that the computed circulation velocities (and hence the suspended load) vary from case to case (wide cells to narrow cells). These processes cannot yet be computed with high accurary and thus the relatively small values of the computed accretion/erosion volumes inside the groyne cells are not very accurate. The computational results, however, do show that the potential trapping of sand inside the cells is extremely small. Hence, the capacity of the groyne cells to trap or retain sand is small. This is also evident from the results of the laboratory experiments of **Hulsbergen et al. (1976)** and **Badiei et al. (1994)**. **Figure 35C** shows the net bed level changes over 45 days. Acretion occurs on the downdrift (left) side of the cells and erosion on the updrift side. In the case of very narrow cells accretion can be observed on both sides of the cells. **Figure 35C** also show width-integrated longshore transport values (red arrows, in m^3/s).

The trapping of sand increases with decreasing width of the cells (narrower cells, see Runs B1, B2 and B3, **Table 3**). The trapping of sand also increases with increasing offshore wave angle (see last row of **Table 3**), because the wave shadow zone inside the cells (with lower wave heights and smaller sand concentrations) is more pronounced resulting in diffusive transport from outside to inside the cells.

A run with tidal water level variations and tidal velocities showed less trapping probably because the circulation velocities inside the cells were enhanced by the tidal velocities resulting in an increase of the offshore-directed diffusive transport. Furthermore, erosion is enhanced during ebb conditions with relatively small water depths between the groynes and relatively large circulation velocities.

Groynes will be more effective on beaches with coarser sand, where onshore bed load transport generally prevails. In that case the groynes usually are short (up to the low water line, see **Figure 32** of shingle beach) to prevent the longshore movement of the coarse sediment particles in response to the wave climate (beach rotation/oscillation).

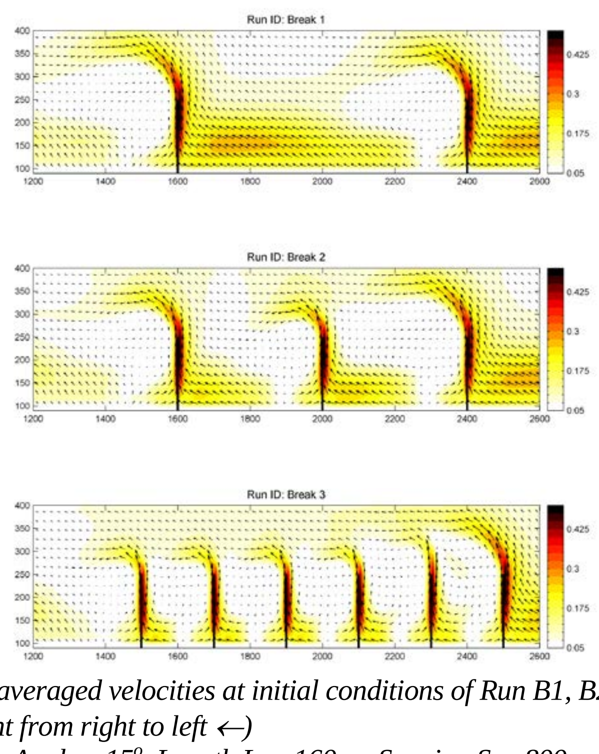


Figure 35A *Computed depth-averaged velocities at initial conditions of Run B1, B2 and B3 (see Table 3) (longshore current from right to left ←)*
Top: Run B1: Angle= 15^o. Length L_g= 160 m, Spacing S = 800 m, (S/L_g=5, L_g/L_b=1)
Middle: Run B2: Angle= 15^o. Length L_g= 160 m, Spacing S = 400 m, (S/L_g=2.5, L_g/L_b=1)
Bottom: Run B3: Angle= 15^o. Length L_g= 160 m, Spacing S = 200 m, (S/L_g=1.25, L_g/L_b=1)

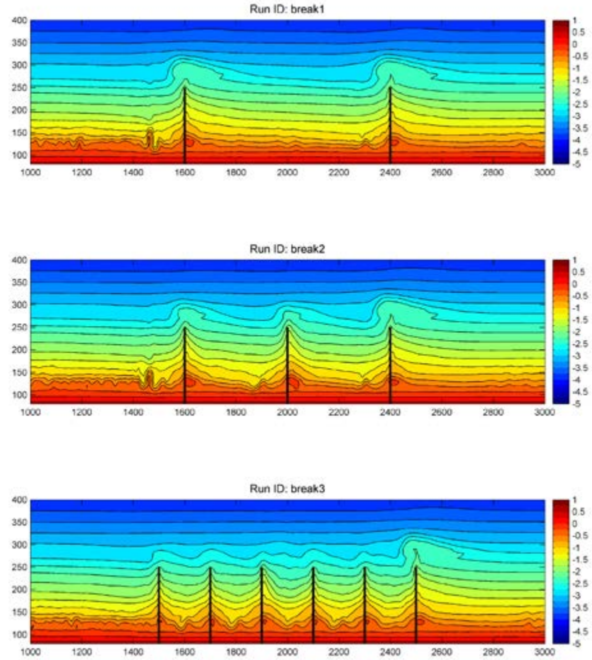


Figure 35B *Computed bathymetry after 45 days of Run B1, B2 and B3 (see Table 3)*
Top: Run B1: Angle= 15^o. Length L_g= 160 m, Spacing S = 800 m, (S/L_g=5, L_g/L_b=1)
Middle: Run B2: Angle= 15^o. Length L_g= 160 m, Spacing S = 400 m, (S/L_g=2.5, L_g/L_b=1)
Bottom: Run B3: Angle= 15^o. Length L_g= 160 m, Spacing S = 200 m, (S/L_g=1.25, L_g/L_b=1)

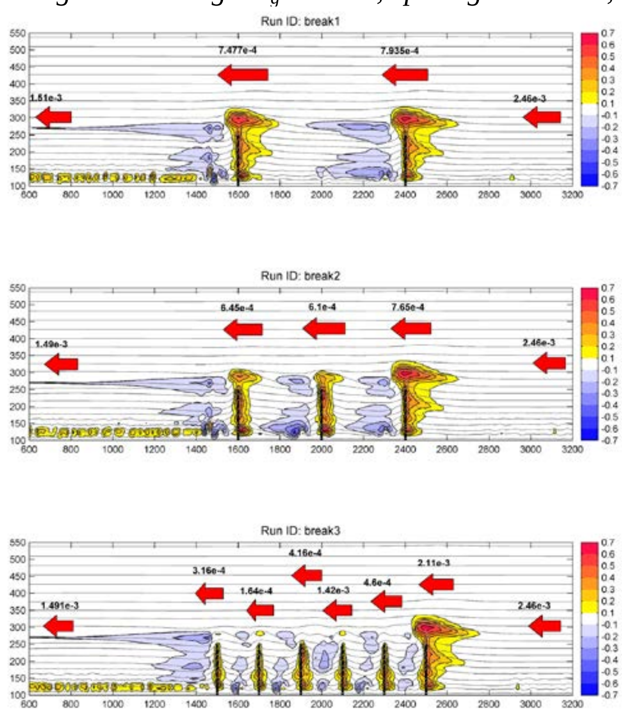


Figure 35C *Computed bed level changes after 45 days of Run B1, B2 and B3 (see Table 3)*
Top: Run B1: Angle= 15^o. Length L_g= 160 m, Spacing S = 800 m, (S/L_g=5, L_g/L_b=1)
Middle: Run B2: Angle= 15^o. Length L_g= 160 m, Spacing S = 400 m, (S/L_g=2.5, L_g/L_b=1)
Bottom: Run B3: Angle= 15^o. Length L_g= 160 m, Spacing S = 200 m, (S/L_g=1.25, L_g/L_b=1)

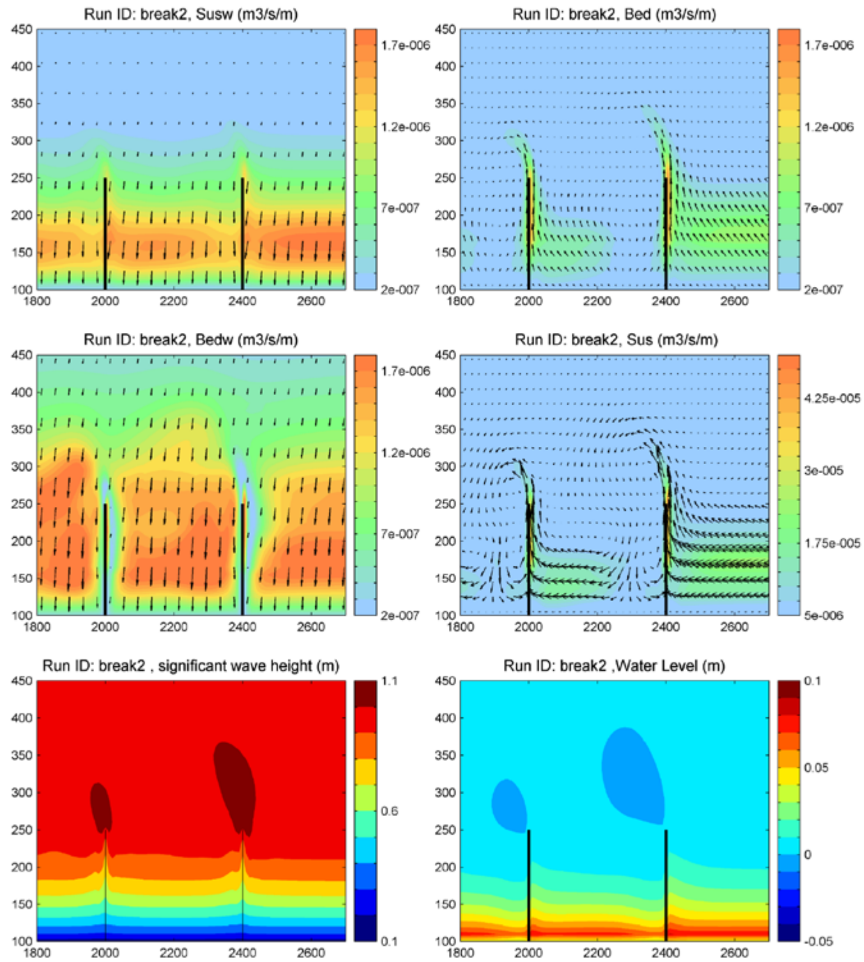


Figure 35D *Computed parameters of Run B2 (see Table 3); longshore current from right to left ←*
Top Left: wave-related bed load transport *Top right: current-related bed load transport*
Middle Left: wave-related suspended transport *Middle right: current-related susp. transport*
Bottom Left: significant wave height *Bottom Right: water level changes (set-up/down)*

The numerical modelling study of **Eslami Arab (2009)** also included the performance of T-head groynes focussing on an existing case along the coast of Turkey (**Özölçer et al., 2004**). The characteristics of the two T-head groynes are: length of about 50 m beyond the still water line, spacing of 100 m, length of head of about 40 m. The offshore wave height is set to 1 m (period of 7 s; duration of 15 days; no tide). The offshore wave incidence angle is 12^o. The sediment size is about 0.33 mm. Sensitivity runs show that the T-head groynes can be best modelled using the real dimensions of the groynes (not as thin walls) using vertical boundaries or sloping boundaries on both sides. The grid resolution should be rather high (2 m) to obtain accurate results. The roughness of the walls or slopes (often rock) should be represented by realistic values. **Figure 36** shows the computed results after 15 days with a constant wave height of 1 m. The computed bathymetry is in close qualitative agreement with the observed bathymetry after 6 months (including calm periods with no waves). The cell between the groynes is large filled with sand due to trapping of bed load and suspended load from outside.

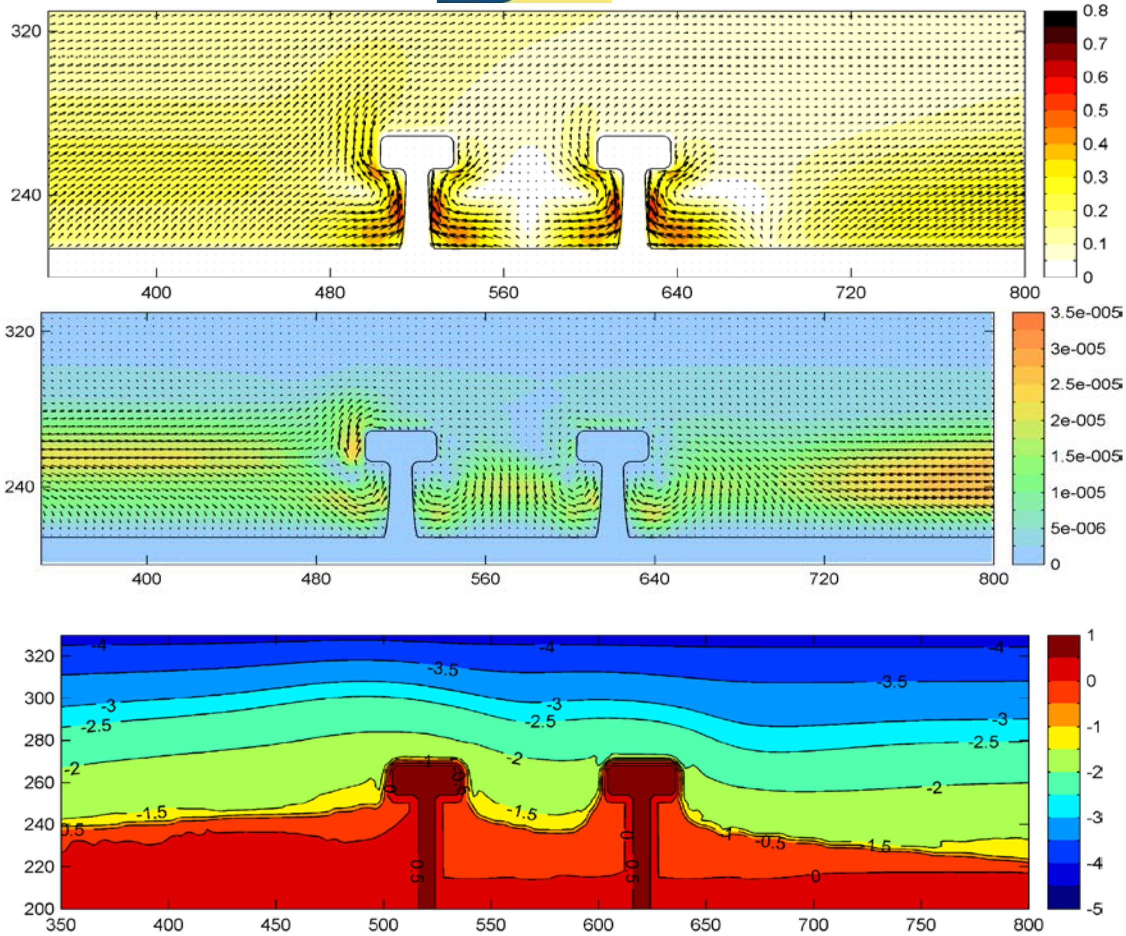


Figure 36 *Computed results for T-head groynes along coast of Turkey (longshore current and transport from left to right →)*
Top: depth-averaged velocity vectors
Middle: transport vectors (in m^2/s)
Bottom: bathymetry after 15 days (in m)

5.2.3 Design rules

Nowadays, the design of groyne fields along exposed, eroding coasts with recession rates exceeding 2 m per year is nearly always combined with the (regular) placement of beach fills inside the cells to widen the beaches for recreation and to reduce/stop downdrift impacts (**Kana et al. , 2004** and **Shabica et al., 2004**). Long curved groynes are used to protect a major beachfill at both ends creating a wide beach for recreational purposes (pocket beach) at locations where lee-side erosion is acceptable or manageable.

Basic groyne design rules are (see **Kana et al., 2004**; **Basco and Pope, 2004**):

1. groynes should only be constructed along coasts with recession rates exceeding 2 m/year and dominant longshore transport processes; groynes cannot stop erosion, but only reduce erosion; groynes are most effective at coarse-grained beaches (0.3 to 1 mm) along swell-dominated coasts;
2. groyne length (L) should only extend over the inner surf zone (up to the landward flank of the inner bar trough) and crest levels should be relatively low to allow sufficient sediment bypassing so that lee-side erosion is reduced as much as possible; groyne spacing should be in the range of S = 1.5 to 3L; groyne tapering can also be used (reduced lengths at downcoast end of groyne field);
3. groynes should be constructed from downcoast to upcoast;

4. groyne cells should be filled to capacity immediately after construction;
5. groynes made of rock should have a smooth cover layer of armour units (no rip rap or rubble mound) to minimize visual intrusion.

The numerical model study (**Eslami Arab, 2009**) shows that:

1. the trapping efficiency of the cells between straight groynes is very small;
2. the trapping of sand increases with decreasing spacing (narrow cells are more effective than wide cells);
3. the trapping of sand increases with increasing wave incidence angle (erosion prevails if waves are normal to coast);
4. the trapping of the cells between the groynes can be highly enhanced by using T-head groynes in stead of straight groynes.

Table 5 of **Section 6** summarizes the effectiveness of hard structures to protect the shoreline.

5.3 Detached breakwaters and reefs

5.3.1 Types and hydraulic behaviour

A detached breakwater (**Figures 37**and **38**) is herein defined as a hard shore-parallel structure (occasionally obliquely positioned) protecting a section of the shoreline by forming a shield to the waves (blocking of incident wave energy). The crest may be positioned above the still water level (emerged) or below the still water level (submerged) and has a width of the order of the local water depth. There are many variants in the design of detached breakwaters, including single or segmented breakwaters with gaps in between, emerged (crest roughly 1 m above high water line) or submerged (crest below water surface), narrow or broad-crested, etc. Submerged breakwaters are also known as reef-type breakwaters and are attractive as they are not visible from the beach. A reef (hard or soft) is a relatively wide, submerged structure in the shallow nearshore zone.
Three basic types of detached breakwaters have been used: (1) rubble mound with trapezoidal cross-section of rock or conctre units, (2) prefabricated concrete units of triangular shape and (3) flexible membrane (geotextile) units constructed of sand-filled containers.

Low-crested structures are often constructed to increase the lifetime of beach fills along straight or slightly curved beaches or along pocket beaches suffering from structural erosion in microtidal conditions (Meditarranean). Sometimes, low submerged breakwaters are constructed as sills between the tip of groynes to support the seaward toe of beach fills (perched beaches); Italian coast near Carrara.
Submerged structures cannot stop or substantially reduce shoreline erosion (dune-cliff erosion) during storm conditions, as most of the waves will pass over structure to attack the dune or cliff front. Supplementary beach nourishments are required to deal with local storm-induced shoreline erosion erosion (especially opposite to gaps). Downdrift erosion generally is manageable as longshore transport is not completely blocked by low-crested structures. A major problem of submerged breakwaters and low-crested emerged breakwaters is the piling up of water (wave-induced setup) in the lee of the breakwaters resulting in strong longshore currents when the breakwater is constructed as a long uninterrupted structure (no gaps) or in strong rip currents through the gaps when segmented structures are present. These processes are schematically shown in **Figure 37** (**Cáceras et al., 2005a,b**).

The wave filter effects depend on the mean water level conditions, the incident wave parameters and the structural geometry. The shoaling/breaking processes in front of a structure, which is frequently overtopped, increases the pumping of wave fluxes over the detached breakwater. Resulting sediment fluxes and morphodynamic evolution are, therefore, a function of the wave and the circulation fields associated to the structure. Any attempt to understand and model the morphodynamic impact requires the explicit consideration of terms driving the pumping and circulation effects. **Cáceras et al. (2005)** have studied various methods to deal with wave overtopping and enhanced mass fluxes and associated design difficulties for low-crested breakwaters. If a submerged or low-crested breakwater is not designed properly, additional negative morphological effects such as local scour and shoreline erosion may easily occur. For example, the submerged breakwater (consisting of precast interlocking units without gaps) built on the lower east coast of Florida (USA), approximately 7 km south of the entrance of the Port of Palm Beach was later (1995) removed because of excessive erosion problems in the lee of the breakwater (**Dean et al.,1997**; **Browder et al., 2000**). A review of submerged structures by **Ranasinghe and Turner (2006)** reveals that a majority of these structures have resulted in shoreline erosion in their lee. Their conclusion is that the use of these structures is likely to remain relatively limited.
Disadvantages of detached breakwaters are the relatively high construction and maintenance costs, inconvenience/danger to swimmers and small boats and aesthetic problems (visual blocking of horizon).

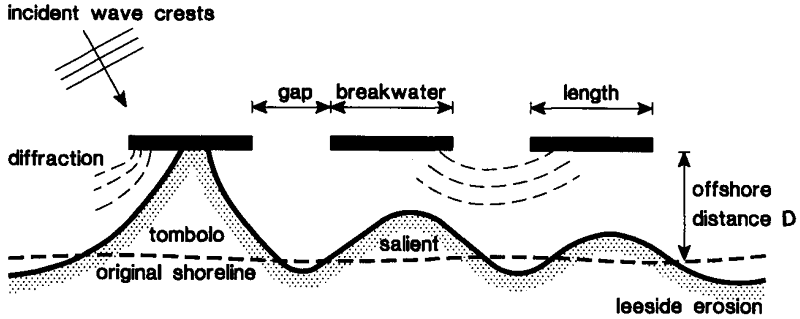


Figure 37 *Shore-parallel detached breakwaters*

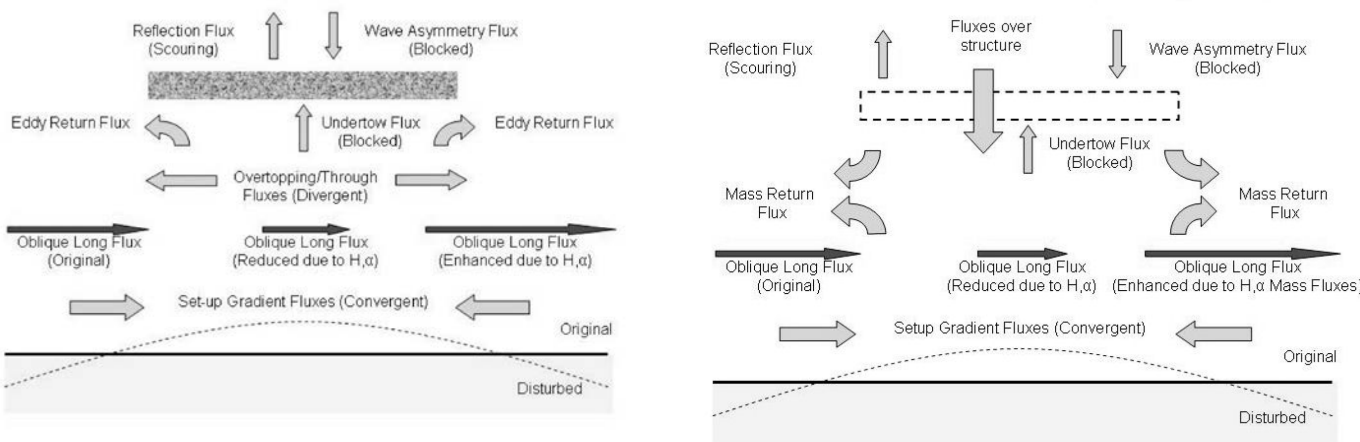


Figure 38 *Functioning of emerged detached (left) and submerged detached (right) breakwaters*

Figure 39 *Emerged breakwater (left=June 2005; right=June 2007) at Barceloneta beach, Barcelona, Spain (L=150m, D=175 m, crest at =+1 m above MSL, beach sediment=0.5 mm)*

Most ***emerged*** breakwaters have been built along micro-tidal beaches in Japan, in the USA and along the Mediterranean. Few have been built along open, exposed meso-tidal and macro-tidal beaches. The crest should be in the range of +1 m to +4 m above MSL depending on tidal range to be effective against storm-induced shoreline erosion. The type of beach planform in the lee of these structures strongly depends on dimensions and geometry (L= breakwater length, D=offshore distance to original shoreline, L_{gap}= length of gap between segments, see **Figure 37**). The beach can built out to the structure (permanent tombolo for L/D>1) or not (salient for L/D<1), if sufficient sediment is available; otherwise additional beach fills (nourishments) are required. Shoreline erosion generally occurs opposite to the gaps for $L_{gap}/L>1.3$, but is minor for $L_{gap}/L<0.8$. Emerged breakwaters cannot stop storm-induced erosion completely, as large storm waves will pass over the structure in conditions with high surge levels above the crest level. Emerged breakwaters can be built: (1) to increase the local beach width and to stop the beach rotation along recreational pocket beaches between two headlands and (2) to reduce chronic shoreline erosion and storm-induced erosion to acceptable limits in combination with regular nourishments to restore the original shoreline. The ideal emerged breakwaters in terms of coastal protection are made of rock and built close to the shore with a high crest level and small gap lengths, but such a structure will largely block the horizon and is not attractive in terms of beach recreation.

Figure 39 shows the new emerged breakwater at the beach of Barceloneta (north of Barcelona, Spain) built in the middle of a pocket beach with a length of about 1 km to increase the local beach width and to reduce beach rotation problems. The L/D ratio is smaller than 0.9 resulting a salient type of beach. The length of the salient beach is about 300 m or twice the breakwater length ($L_{salient} \cong 2L_{breakwater}$) with an amplitude of 20 m. Beach nourishment was applied to increase the overall beach width. The breakwater was built from the beach out by first creating a temporary dam to the offshore breakwater location, which was removed after construction of the breakwater. The breakwater should be placed on geotextile to prevent significant settlement of the structure.

Bricio et al. (2008) have analyzed 27 detached breakwater projects along the northeast Catalonian coastline (almost tideless) of Spain based on pre- and post-project aerial photographs. The offshore distance D is defned as the distance to the original shoreline (in the range of 80 to 234 m). The (emerged) breakwater lengths L are in the range of 57 to 236 m. Tombolos are present for L/D > 1.3 and salients for 0.5 < L/D < 1.3. No information was available on additional beach nourishments.

Based on the results observed along various micro-tidal USA-sites (**Stone et al. 1999**; **Mohr et al. 1999** and **Underwood et al. 1999**), Mediterranean coasts (**Cáceras et al., 2005a,b**) and meso-tidal sites in the UK (**Fleming and Hamer, 2000**), it is concluded that the design of an emerged breakwater scheme is not a straightforward process, but rather an iterative process consisting of an initial design phase based on mathematical and physical modelling, the testing of the design by means of a field pilot project including a detailed monitoring programme and the fine tuning of the design by modification of breakwater lengths based on the field experiences. A major problem is the mitigation of downdrift (leeside) erosion, which can be established by creating a transitional zone with gradually increasing gap lengths and/or decreasing crest levels (submerged breakwaters).

Figure 40 presents a showcase of nearly all available coastal structures along a Mediterranean coastal section of about 5 km in Sitges (south of Barcelona, Spain). Open groyne cells with a spacing of about 500 m can be observed at the northern part of the beach and partly closed cells are present along the southern side of the beach. The harnassed solution with T-head groynes and detached breakwaters on the southern side is necessary to retain the beach sand within the cells. Although this type of beach protection looks massive, it has been done nicely using natural rocks and the view from the boulevard is not unattractive. The beach offers opportunities to all types of beach recreation: swimming, surfing, fishing, etc for adults, youngsters and families with small children.
Overviews of experiences are given by **Rosati (1990)** and **Chasten et al. (1993)**. **Liberatore (1992)** and **Lamberti** and **Mancinelli (1996)** give information of the experiences with emerged and submerged breakwaters along the Italian coasts. **Table 5** in **Section 6** summarizes the effectiveness of hard structures to protect the shoreline.

Figure 40 *Coastal protection by various hard structures at beach of Sitges, south of Barcelona, Spain*

5.3.2 Numerical modelling results

The basic effect of a detached breakwater on the hydrodynamics and the morphology can be very well computed by mathematical models, as shown by **Figures 41** and **42** (**Deltares/Delft Hydraulics, 1997**; see also **Bos et al., 1996** and **Cáceras et al, 2005a,b**). The breakwater is situated on a plane sloping beach with a slope of 1 to 50. The length of the detached breakwater is L = 300 m. Irregular waves normal to the shore (including directional wave spreading) with an offshore wave height of H_{rms} = 2 m and a peak wave period of T_p = 8 s have been used. The sediment diameter is d_{50} = 0.25 mm (d_{90} = 0.35 mm); the sediment fall velocity is w_s = 0.031 m/s. The bottom roughnes is k_s = 0.05 m. The breaker line outside the breakwater region is about 200 m from the shore, where the water depth to the still water level is 4 m (no tide).

Offshore distance D	**Dimesionless distance L/D**	**Type morphology**
120	2.5	double tombolo
150	2.0	single tombolo
200	1.5	single tombolo
300	1.0	single tombolo
500	0.6	salient

Table 4 *Morphology of detached breakwater based on mathematical computations (DELFT3D)*

The computed wave height patterns show a significant decrease of the wave height in the lee of the breakwater. Pronounced circulation zones are generated in the lee of the breakwater due to variations of the set-up along the shore (relatively low set-up values in lee and relatively high set-up values on both sides of the breakwater). Maximum velocities are in the range of 0.5 m/s for a relatively large distance from the shore (D = 500 m; L/D = 0.6) to 0.8 m/s for a relartively small distance to the shore (D = 120 m; L/D = 2.5). The computed morhology (see **Table 4**) shows the development of a double tombolo for an offshore breakwater distance of 120 m, a single tombolo for offshore distances in the range of 150 to 300 m and a salient for an offshore distance of 500 m. In the latter case large scour holes can be observed at the tips of the breakwater. These scour holes do not develop when tombolos are generated. The generation of a double tombolo with a dead water zone in-between is not very realistic. In practice, this zone will be rapidly filled with sediment by longshore transport in the swash zone, which is not included in the mathematical model.

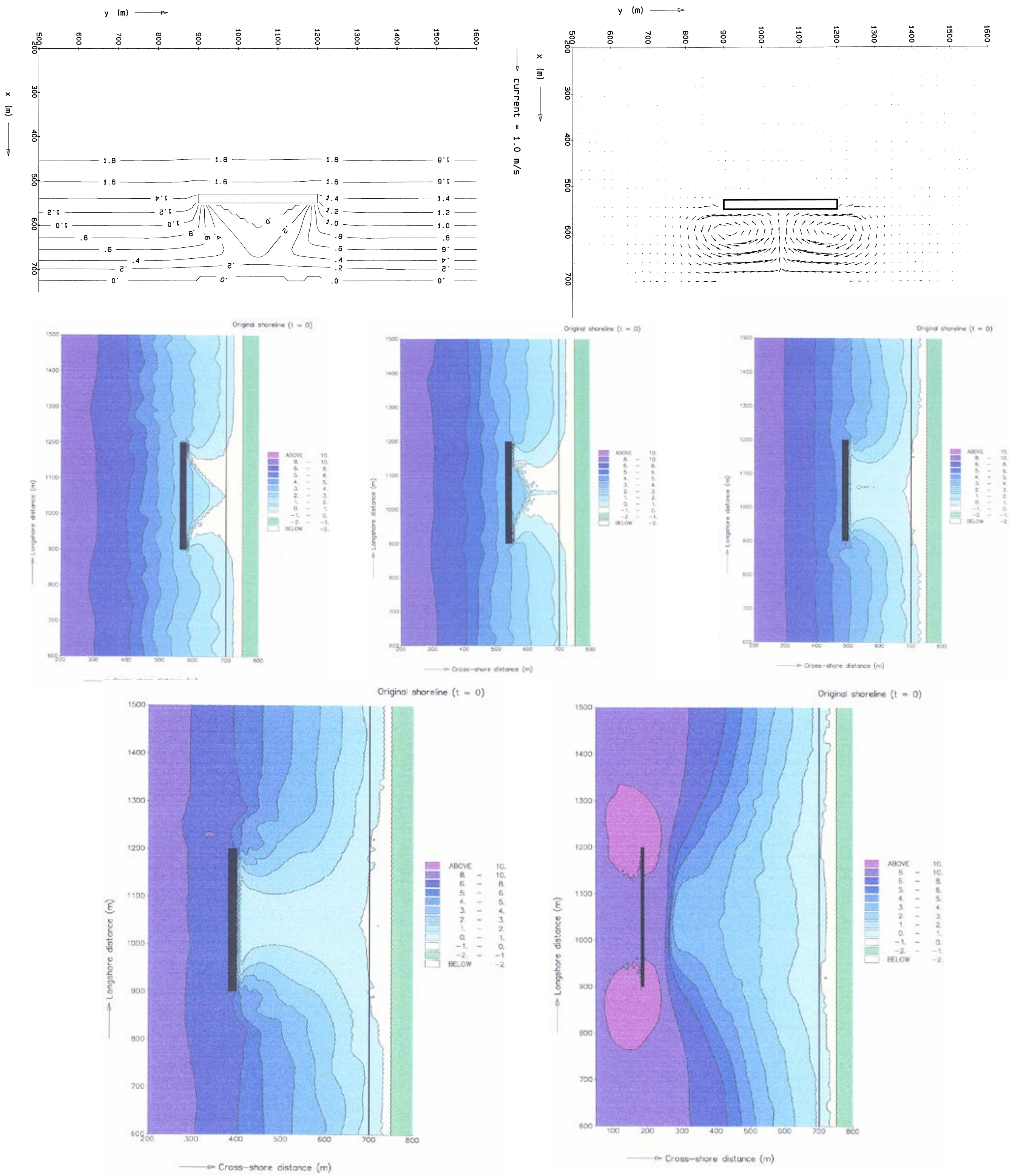


Figure 41 *Computed wave height, flow field and morphology of detached breakwaters*
Upper left, right: wave height and flow field (breakwater at 150 m from shore)
Middle: morphology after 50 days (breakwater at 120, 150 and 200 m from shore)
Lower: morphology after 75 days (breakwater at 300 and 500 m from shore)

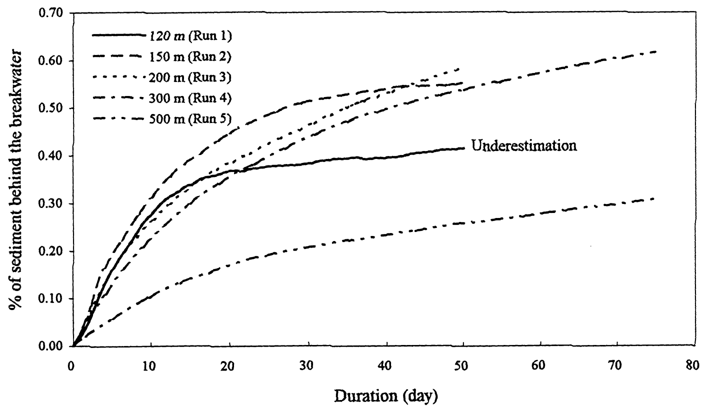


Figure 42 *Sediment trapping in lee of break water as percentage ot total volume*

Overall, the model predicts tombolo-morphology for L/D>1 and salients for L/D<0.6. The model results are in excellent agreement with the data of **Rosen and Vajda (1982)**, **Harris and Herbich (1986)** and others, which all are based on the development of tombolos for L/D >1.

Figure 42 shows the trapping percentage of sediment in the lee zone of the breakwater. The trapping percentage increases with decreasing distance to the shore except for the breakwater with the smallest distance to the shore (D = 120 m). The maximum trapping percentage is about 60% for D = 200 and 300 m. The trapping of the breakwater with the smallest D-value of 120 m is largely underestimated due to the presence of a dead water zone between the two tombolos (see **Figure 41**) which will, in practice, be filled with sediments by the longshore current in the swash zone (not included by the model). The time scale to obtain a quasi-equilibrium state is of the order of 50 to 75 days based on a constant wave height of H_{rms} = 2 m (minor storm event). Assuming a storm duration of 12 hours, this is equivalent to 100 to 150 minor storm events. In practice with a varying wave height the time scale to approach quasi-equilibrium will be 2 to 3 years.

5.4 Longshore coastal variability in case of hard structures

Both groynes and detached breakwaters are structures that are based on the compartimentalization of the coast into a series of small-scale coastal cells, each with its own sediment budget. The idea is that as long as the sediment budget within each cell remains approximately constant, the erosion of the shoreline is minimum. These ideas will hereafter be explored by example computations for a groyne field along an eroding coastal section with a length of 15 km. Shoreline changes can be simply understood by considering the sediment continuity equation for the littoral zone (roughly the surf zone) with alongshore length Δx, cross-shore length Δy_s and vertical layer thickness (h). The sand volume balance reads:

$$h\,(\Delta y_s/\Delta t) + \Delta Q_{LS}/\Delta x = 0 \qquad (1)$$

with: y= cross-shore coordinate, x= longshore coordinate, y_s= shoreline position, h= thickness of active littoral zone layer, Q_{LS}= longshore transport rate or littoral drift (bed-load plus suspended load transport in volume including pores per unit time, in m^3/s). Basically, Equation (1) which is solved by the LONGMOR-model (**Van Rijn, 1998, 2002, 2005**) states that a coastal section erodes if more sand is carried away than supplied; vice versa coastal accretion occurs if there is a net supply. Eqaution (1) shows that the shoreline changes are linearly related to the assumed depth (h) of the active zone.
The example computation refers to chronic erosion along a schematized sandy coast. The local wave climate (North Sea wave climate) is assumed to generate a net longshore transport of about 375,000 m^3/year at x= 0 and about

500,000 m^3/year at x= 15 km. Hence, a significant longshore transport gradient is imposed resulting in a chronic coastal recession of about 7 m in 5 years along this coastal section (see **Figure 43**). This value is equivalent with an overall erosion of 630,000 m^3 (recession x profile height x length = 7x6x15000) over 5 years along this section of 15 km.

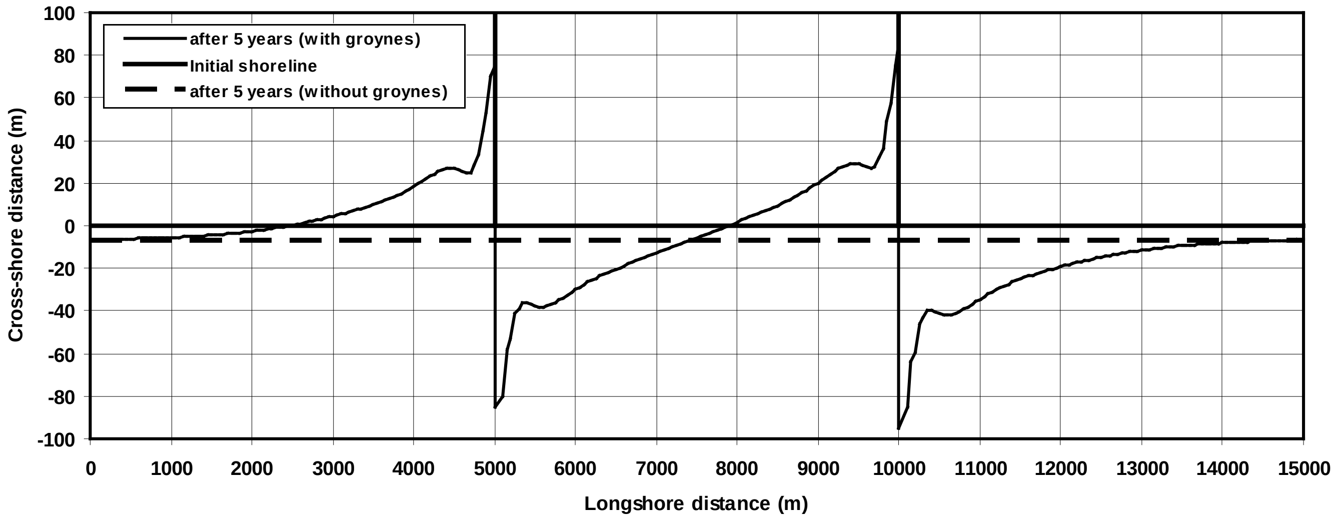


Figure 43 *Shoreline behaviour after 5 years based on imposed longshore transport gradient with and without groynes (net longshore transport from left to right); 2 groynes with spacing of 5000 m.*

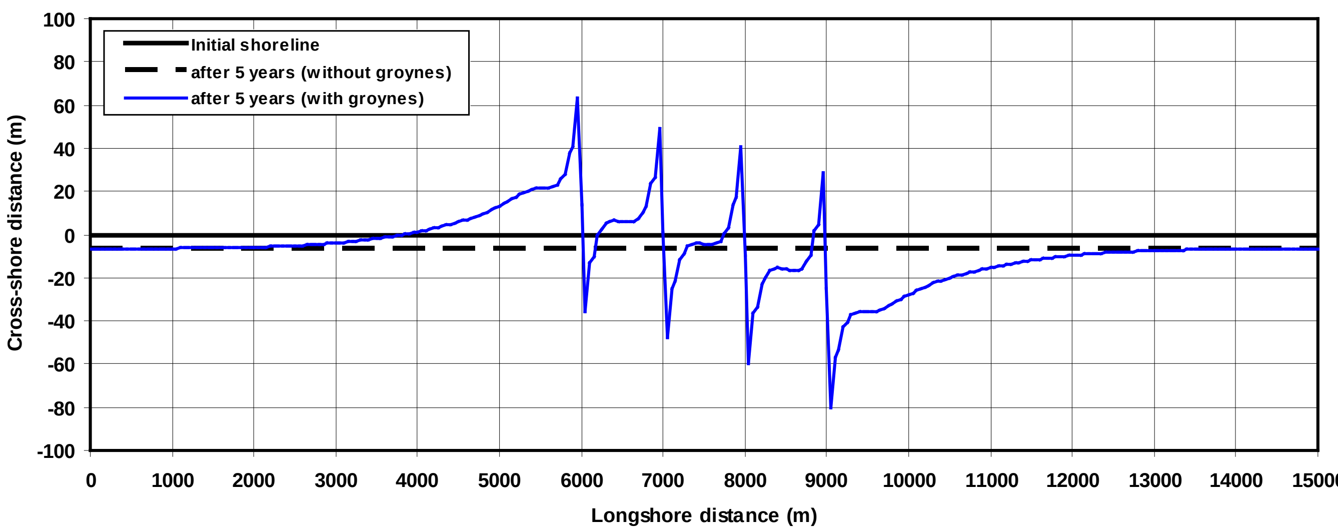
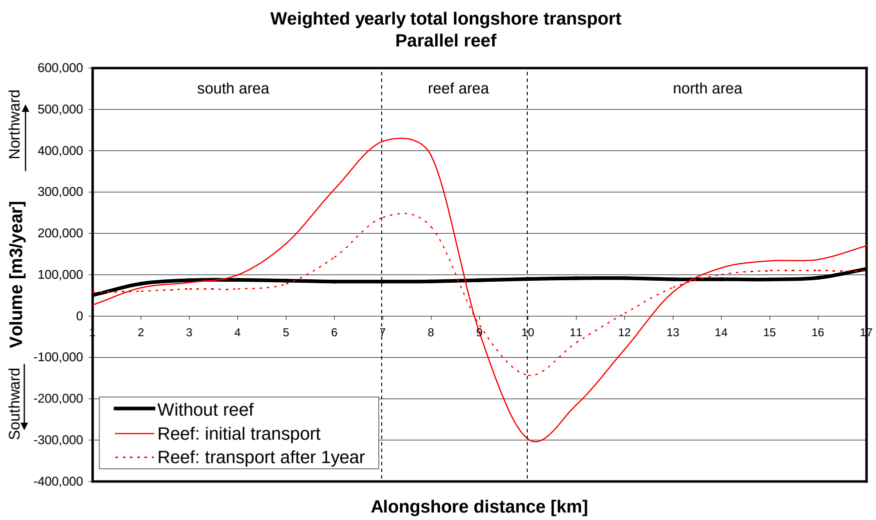


Figure 44 *Shoreline behaviour after 5 years based on imposed longshore transport gradient with and without groynes (net longshore transport from left to right); 4 groynes with spacing of 1000 m.*

The LONGMOR-model has been used to determine the consequences of creating coastal cells by means of long groynes (headland type of groynes). Relatively large groyne spacings of 5000 and 1000 m are explored to demonstrate the effects. The cross-shore length of the groynes is about 100 to 150 m beyond the mean water line (MSL) down to the –5 m depth contour. The layer thickness or profile height of the dynamic littoral zone is assumed to be 6 m. The beach sediment is sand with d_{50}= 0.2 mm and d_{90}= 0.3 mm. The local beach slope is assumed to be tanβ= 0.05 (slope of 1 to 20 from waterline to -6 m depth contour). The blocking coefficient of the groynes is assumed to be 50% (and thus 50% bypassing of sediment). The local wave breaking coefficient is assumed to be γ_{br}=

0.6. The longshore grid size is 50 m and the time step is 0.01 days. The shoreline changes over a period of 5 years have been determined using a wave climate with offshore waves in the range of 0.5 to 4 m and offshore wave incidence angles of 30^o and -15^o with respect to the coast normal yielding a net longshore transport rate of 375, 000 m^3/year at x=0 m based on the method of **Van Rijn (2006)**. The CERC-method produces values which are twice as large; the Kamphuis-method produces values which are about 30% smaller (**Van Rijn, 2005, 2006**).

Figure 43 shows the typical saw-tooth shoreline behaviour (spacing of 5000 m; S/L=25 to 30) with accretion on the updrift side and erosion on the downdrift side of the groynes for a wave climate with one dominant direction. The maximum local erosion is of the order of 60 m after 5 years, which is much larger than the original chronic erosion of about 7 m after 5 years. Smaller shoreline recession values can be observed inside a groyne field with a spacing of 1000 m (S/L=5 to 6), see **Figure 44**. The maximum shoreline recession on the downdrift side of the last (terminal) groyne is not affected by the groyne spacing and is of the order of 80 m after 5 years. Smaller spacings are required to reduce the erosion within the compartments to acceptable limits, but smaller spacings are not very cost-effective (higher construction costs). In both cases (**Figures 43 and 44**) the blocking coefficient of the groynes is assumed to be 50%. Larger blocking coefficients (up to the maximum value of 1; complete blocking) will result in larger shoreline recession values at the downdrift groynes. The results also linearly depend on the assumed depth (here h = 6 m) of the active zone. Shoreline erosion will be much less in a milder wave climate (Mediterranean). Shoreline erosion will be more symmetric in a multi-directional wave climate.



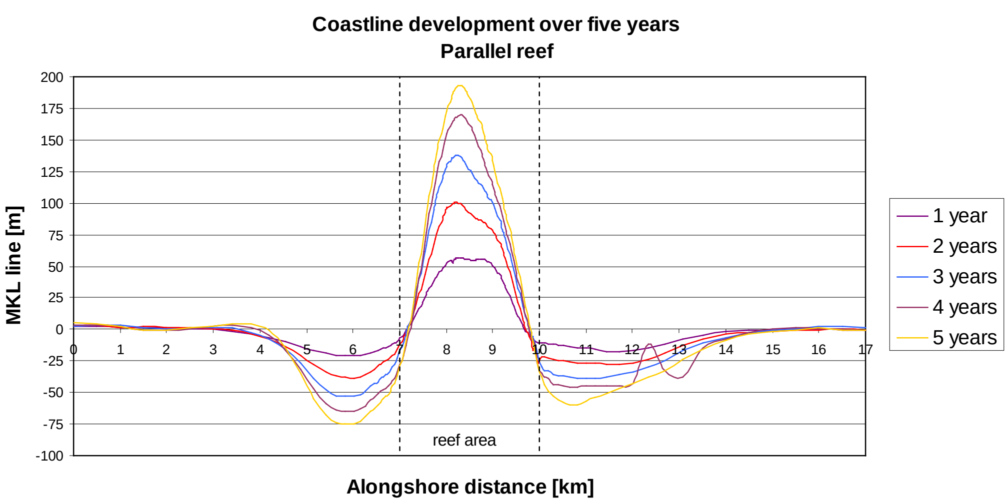


Figure 45 *Net longshore transport (upper) and shoreline variation (lower) in lee of offshore reef (Van der Hout, 2008)*

It is concluded that the implementation of a groyne scheme with relatively wide compartments leads to an increase of the variability of the local shoreline with maximum recession values much larger than the initial shoreline recession in the case of a wave climate with one dominant direction. Regular artificial beach restoration within each cell by nourishment (in the range of 100,000 to 500,000 m^3 after 5 years) will be required to keep the lee-side erosion within acceptable limits, which is not very attractive from a management perspective. Furthermore, straight groynes are not very efficient in cross-shore direction, as the erosion of the shoreline by cross-shore transport processes (wave-induced undertow) can carry on freely.

Another example is the shoreline erosion on both sides of an offshore reef. To protect the boulevard and beaches of a major city at the Holland coast (beaches of 0.2 mm sand), the effectiveness of an offshore reef with a crest level at 1 m below mean sea level and a length of 3 km at a depth of 10 m (1.5 km from the coast) was explored by using the DELFT3D modelling system. The local wave climate has two dominant directions: south-west and north-west. The net longshore transport being the sum of two large, but opposite values is quite small (order of 100,000 m^3/year to the north; from left to right), see **Figure 45upper**. However, when an offshore reef is present, the net transport at the southern beach side (x = 7 km) of the reef increases enormously because the longshore transport from the opposite direction is largely blocked resulting in a net longshore transport of about 400,000 m^3/year at x = 7 km. At the northern beach side (x = 10 km) of the reef the net transport of 100,000 m^3/year to the north in the old situation is turned into a net transport of 300,000 m^3/year to the south in the new situation. These significant transport variations over a length of about 3 km lead to relatively large shoreline variations after 5 years (see **Figure 45lower**): accretion of about 150 m in the middle of the reef zone and erosion of about 75 m on both sides of the reef zone. Basically, sand from both sides is carried into the middle lee zone of the reef. The reef functions well in terms of protection of the beach and boulevards against wave attack in the lee of the reef but serious side effects (erosion) are introduced which have to be mitigated by nourishment.
These types of shoreline structures seem to make things worse by introducing excessive longshore variability and local erosion and may therefore be unattractive to control beach erosion if alternative solutions are available (nourishment). An exception is the erosion near a tidal inlet. In that case the most downdrift groyne can function as a long jetty preventing that the longshore drift moves into the inlet. Another exception is the erosion along a beach where nearby sand sources are very scarce. In that case a very harnassed solution consisting of relatively small cells with T-head groynes and detached breakwaters (see **Figure 46)** can be used to maintain a minimum beach for recreation and to reduce coastal erosion. The compartments should be small to contain the sediments within the compartments. When a boulevard is present, the back-beach needs to be protected by revetments and seawalls. Such a solution is expensive and requires relatively large maintenance budgets in a severe wave climate, but may be necessary when regular beach nourishment by (scarce) sandy material is not economically feasible.

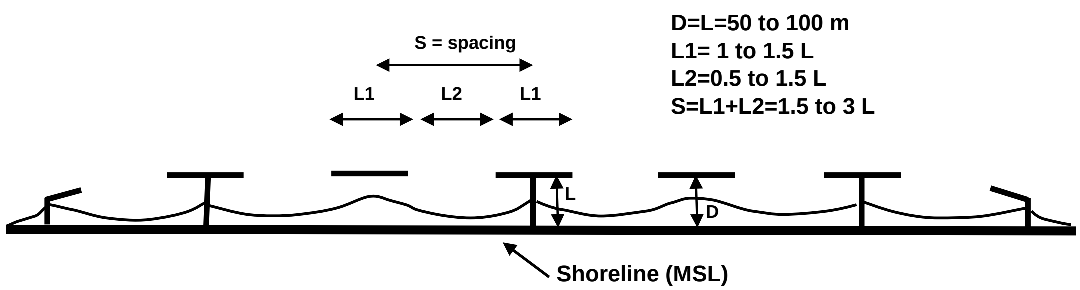


Figure 46 *Coastal protection by T-head groynes and detached breakwaters*

The cross-shore length of the groynes should be as small as possible (of the order of 50 to 100 m, see **Figure 46**) to reduce on the construction coasts and to minimize the effect on the longshore transport and thereby to minimize the lee-side erosion effects. Generally, the crest level near the groyne tip should be slightly higher (0.5 to 1 m) than the mean sea level (MSL) and the crest level near the dune toe should be slightly lower than the local beach.
Figure 47 shows the longshore transport distribution for a typical sandy coastal profile (0.2 mm sand) and offshore wave heights in the range of 1 to 3 m (offshore wave incidence angle of 30^o). In that case the cell system of relatively short groynes and breakwaters will only block a minor part of the total littoral drift.

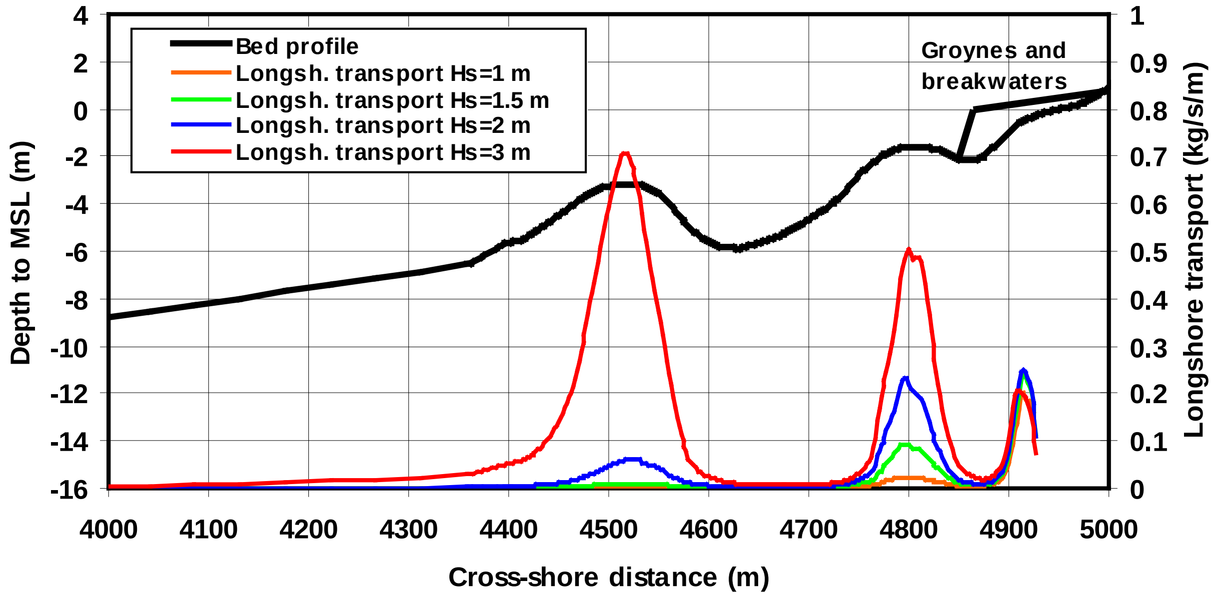


Figure 47 *Cross-shore distribution of longshore transport for offshore wave heights of 1 to 3 m; offshore wave incidence angle of 30^o and d_{50}=0.2 mm (sand)*

5.5 Conclusions coastal structures

- coastal structures such as groynes, detached breakwaters and artificial reefs are built to significantly reduce coastal beach erosion and to maintain a minimum beach width for recreation or to protect beach fills; they are, however, no remedy for dune and soft cliff erosion during storm conditions with relatively high surge levels; seawalls and revetments have to be built to stop dune and cliff erosion completely;
- high-crested, impermeable groynes should only be considered along exposed, swell-dominated coasts of sand, if the shoreline recession rates are exceeding 2 m per year; regular beach fills are required to reduce the beach erosion and lee-side effects to manageable quantities;
- the effectiveness of straight high-crested groynes can be substantially increased by using T- or L- head groynes, which may be designed along very exposed, eroding coasts to reduce the wave energy into the compartments and to prevent/diminish the generation of rip currents near the groyne heads;
- low-crested, permeable groynes are only effective at sheltered beaches with mild wave climates;
- the type of beach planform (tombolo or salient) in the lee of detached (shore-parallel) breakwater structures strongly depends on the breakwater dimensions (breakwater length L), distance to the original shoreline (D) and the length of the gaps (L_{gap}) between the breakwaters; the beach may be attached to the structure (permanent tombolo for L/D>1.3) or not (salient for L/D<1.3); beach erosion generally occurs opposite to the gaps for L_{gap}/L>1.3 and is only minor for L_{gap}/L<0.8;
- modelling results show that the implementation of structures often leads to an increase of the variability of the local shoreline with maximum recession values much larger than the initial shoreline recession; regular artificial beach fills within the cells are required to keep the lee-side erosion (sie effects) within acceptable limits;
- the design of coastal structures is not a straightforward process, but rather an iterative process consisting of an initial design phase based on mathematical and physical modelling, the testing of the design by means of a field pilot project including a detailed monitoring programme and the fine tuning of the design by modification of breakwater lengths based on the field experiences.

6. Summary, evaluation and conclusions

Nearly all coastal states have to deal with the problem of coastal erosion. Coastal erosion and accretion has always existed and these processes have contributed to the shaping of the present coastlines. Often, coastal erosion is intensified due to human activities.
A straight coast consisting of various coastal arcs can be considered as a geomorphic system consisting of various coastal cells, each with its own spatial and temporal scale. Cells are self-contained units within which sediment circulates with cycles of erosion and deposition including sources, transport paths and sinks. In each cell the morphology is driven by water and sediment motions, based on energy input from the incoming wind, waves and currents. Gradients in sediment transport result in morphological changes, which in turn influence the water motion in a continuous cycle.
Coastal erosion strongly depends on the type of coast (exposure, wave climate, surge levels, sediment composition, beach slope). Coastal erosion has both cross-shore and longshore components. Dune erosion during extreme events with high surge levels up to 5 m mainly is a cross-shore process bringing the sediments from the immobile dune front into the mobile littoral system. Computed dune erosion values are of the order of 20 m^3/m for a surge level of 1 m and up to 300 m^3/m for a large surge level of 5 m. Beach erosion also is an alongshore process due to the presence of eroding longshore currents including tidal currents. Beach erosion during minor storm events with surge levels below 1 m and offshore waves up to 4 m is of the order of 10 to 20 m^3/m per event.
Coastal erosion is enhanced by relative sea level rise according to the Bruun rule, which is based on the idea that the (dynamic) equilibrium profile of the beach and surf zone moves upward and landward in response to sea level rise. Using this concept, the annual input of sediment from the coast to the nearshore zone is equal to the area (m^2) of the nearshore zone times the annual rate (m/year) of relative sea level rise. Assuming that relative sea level rise is 2 mm/year and that the width of the nearshore zone is in the range of 1 to 10 km, the sediment supply to the nearshore zone per unit length of shoreline is about 2 to 20 m^3/m/year. This volume of sediment is eroded from the coast.
Coastal variability (shoreline variations) is not the same as coastal erosion, which is herein defined as the permanent loss of sand from the system. Shoreline variations generally are variations around a systematic trendline (chronic erosion or deposition); the trendline may be caused by natural (autonomous) processes or related to man-made structures.

The available options of shoreline management to deal with erosion problems, are:
- to accept retreat in areas where beaches and dunes are wide and high;
- to maintain the coastline at a fixed position (to hold the line) by hard structures and/or by soft nourishments;
- to bring the coastline at a more seaward position by reclaiming land from the sea.

If there is a substantial loss of sediment over a period of 5 years or so , it may considered to nourish the area with a sediment volume equal to the observed volume loss. Sand nourishment is the mechanical placement of sand in the nearshore zone to advance the shoreline or to maintain the volume of sand in the littoral system. It is a soft protective and remedial measure that leaves the coast in a more natural state than hard structures and preserves its recreational value. The method is relatively cheap if the borrow area is not too far away (<10 km) and the sediment is placed at the seaward flank of the outer bar (shoreface nourishment) where the navigational depth is sufficient for hopper dredgers. Beach nourishment is about twice as expensive as shoreface nourishment amd even more if lifetimes are very short (1 to 2 years).
Beachfills are mainly used to compensate, local short-term erosion in regions with relatively narrow and low dunes (in regions of critical coastal safety) or when the local beach is too small for recreational purposes. Shoreface nourishments (also known as feeder berms) are used in regions of relatively wide and high dunes (relatively safe coastal regions) to maintain or increase the sand volume in the nearshore zone with the aim to nourish the nearshore zone on the long term by natural processes (net onshore transport).
Practical experience of individual shoreface nourishments shows an efficiency (defined as the ratio of local volume increase and initial nourishment volume) of 20% to 30% after 4 to 5 years with respect to the nearshore zone between +3 and −4.5 m (to MSL). The efficiency with respect to the beach zone between +3 m and −1 m is

extremely low (about 2% to 5%). Given a typical shoreface nourishment volume of 400 m^3/m, the potential increase of the beach volume between -1 m and +3 m after 4 to 5 years is not more than about 10 to 15 m^3/m or a layer of sand with a thickness of about 0.1 m to 0.15 m over a beach width of 100 m. Beach nourishments have extremely low life times of 1 to 2 years along the Holland coast.

Practical experience of the Holland coast also shows that large-scale erosion can be stopped by massive beach and shoreface nourishment over long periods of time (20 years). This approach is only feasible if sufficient quantities of sand are available and the dredging and dumping costs are acceptable (about 10 to 15 million Euro per year or 100 to 150 Euro per m coastline per year for the Holland coast with a total length of about 100 km). Although sand nourishment offers an attactive solution in terms of coastal safety and natural values, it may not be the cheapest solution because of the short nourishment lifetimes involved (regular renourishments every 2 to 5 years). In regions where sand is not easily available, it should be assessed whether hard structures may offer a more cost-effective solution to deal with chronic erosion, particularly if rock is available at nearby locations.

Type of structure	**Dimensions**	**Effectiveness**		
		Reduce shoreline erosion	**Stop shoreline erosion**	**Beach width**
Seawall Revetment	Slope not larger than 1 to 3; crest at +5 m to +7 m above MSL	yes	yes	none or very small
Groynes	Length = 50 to 100 m; Spacing/Length= 1 for wave incidence angle >30^o and maximum 3 for angle=10^o to 30^o; Crest at tip= +1 m; crest at root= +3 m to MSL	yes, especially at beaches of relatively coarse sediment (0.3 to 1 mm)	no, dune and cliff erosion will continue during major storms with high water levels	wider for narrower cells; smaller and saw-tooth effect for wider cells
T-head Groynes	Length = 50 to 100 m; Spacing/Groyne length=1.5 to 3 Head length/Groyne length=1 to 1.5 Crest at tip= +1 m; crest at root= +3 m to MSL	yes, especially at very exposed, eroding beaches of fine sand	no, dune and cliff erosion will continue during major storms with high water levels	medium wide
Submerged detached breakwater/reef	Located 50 to 150 m from shoreline; Crest at -1 m to -0.5 m below MSL; (only in combination with regular beach fills)	yes, but minor	no, dune and cliff erosion will continue during major storms with high water levels	small
Emerged breakwater (low crested)	Located 50 to 150 m from shoreline; Crest at +1 to +2 m to MSL (micro-tidal conditions)	yes at lee side; extra shoreline erosion opposite to gap if $L_{gap}/L>1.3$	no , dune and cliff erosion will continue during major storms with high water levels	medium to wide at lee side; salient for L/D<1, tombolo for L/D>1 L=length of structure D=distance between shoreline and structure
Emerged breakwater (high crested)	Located 50 to 150 m from shoreline; Crest at +2 to +3 m to MSL (meso-tidal conditions)	yes at lee side; extra shoreline erosion opposite to gap if $L_{gap}/L>1.3$	no, dune and cliff erosion will continue during major storms with high water levels	medium to wide at lee side; salient for L/D<1, tombolo for L/D>1 L=length of structure D=distance between shoreline and structure

Table 5 *Effectiveness of hard structures*

Generally, hard coastal structures such as groynes, detached breakwaters and artificial reefs are built in urban areas to significantly reduce coastal beach erosion and to maintain a minimum beach for recreation. Preferably, these types of hard structures should be built at locations (downdrift of protruding coastal section) where the transport gradient is almost zero at the transition from increasing to decreasing longshore transport to prevent lee-side erosion. Hard structures such as groynes and breakwaters are, however, no remedy for dune erosion during conditions with relatively high surge levels (above the dune toe level). Seawalls and revetments have to be built to stop dune erosion completely for reasons of coastal defence in urban areas. The functioning and effectiveness of hard structures is summarized in **Table 5**.

Both groynes and detached breakwaters are structures that are based on the compartimentalization of the coast into a series of small-scale coastal cells, each with its own sediment budget. The idea is that as long as the sediment budget within each cell remains approximately constant, the erosion of the shoreline is minimum.
Computational results show that the implementation of a groyne scheme leads to an increase of the variability of the local shoreline with maximum recession values much larger than the initial shoreline recession in the case of a wave climate with one dominant direction. Artificial beach restoration within each cell by dredging will be required regularly to keep the lee-side erosion within acceptable limits, which is not very attractive from a management perspective. Furthermore, straight groynes are not very efficient in cross-shore direction, as the erosion of the shoreline by cross-shore transport processes (wave-induced undertow) can carry on freely.
These types of hard open groyne structures seem to make things worse by introducing excessive longshore variability and local downdrift erosion and are therefore not attractive to control erosion if alternative solutions are available (nourishment). An exception is the erosion near a tidal inlet. In that case the most downdrift groyne can function as a long jetty preventing that the longshore drift exits into the inlet.
Another exception is the erosion along a beach where nearby sand sources are very scarce. In that case a very harnassed solution consisting of relatively small cells with T-head groynes and detached breakwaters can be used to maintain a minimum beach for recreation and to reduce coastal erosion in urban areas. When a boulevard is present the back-beach needs to be protected by revetments and seawalls. Such a solution is expensive and requires relatively large maintenance budgets in a severe wave climate, but may be necessary when regular beach nourishment by (scarce) sandy material is not economically feasible.

The use of sand nourishment is problematic if sand is not available in sufficient quantities in the surrounding of the project site and if dredging equipment is not easily available. For example, sand material suitable for beach nourishment cannot easily be found at most Italian and Spanish sites along the Mediterranean. Furthermore, beach fills may a have a very short lifetime (only 1 year) depending on local wave conditions. A very stormy winter season will remove most of the beach fills from previous summer-autumn season. Hence, hard structures have often to be used to deal with erosion along these latter sites.
Hard structures (groynes, detached breakwaters) require relatively high capital investments plus the continuous costs of maintenance works (storm damage, subsidence, scour problems, redesign, etc.) and costs of supplementary beach nourishments to deal with local erosion problems (opposite to gaps and along the downdrift side). Indicative figures are given in **Table 6**. The construction costs of rubble-mound groynes with a length of 200 m (spacing of 600 m) are about 1 million Euro. Adding interest and mainteneance costs, this will be about 3 to 5 million Euro over a lifetime of 50 years or about 100 to 150 Euro per m coastline per year. The construction of detached breakwaters is considerably larger in the range of 200 to 300 Euro per m coastline per year. The use of soft shoreface nourishments requires less initial investments, but the costs of regular maintainance of the feeder berm (every 3 to 5 years) have to be added resulting in annual costs of about 100 to 200 Euro per m coastline per year. Beach nourishments are more expensive (200 to 300 Euro per m coastline per year) and even more if the lifetime is only 1 to 2 years. **Pluijm et al. (1994)** have shown that the mitigation of shoreline erosion by full-scale nourishment is somewhat cheaper than that based on the construction of detached breakwaters for a meso-tidal, open coast. Given all uncertainties involved, it may be concluded that goynes are relatively cheap and emerged breakwaters are relatively expensive structures. Since groynes are not very effective at most sites, the real choice generally is between nourishment and detached breakwaters. As the costs of these alternatives are of the same order of magnitude, other decisive factors (impact, aesthetics, available building materials) should be taken into account based on detailed studies. An important trend that can be seen recently at touristic beaches is the gradual change from small-scale cells (groyne fields; 100 m scale)

to larger scale cells (headland type groynes with beach fills in between; 1 km scale) to accomodate high-quality beach recreation requirements, see **Gómez-Pina (2004**).

Type of structure	**Construction + maintenance costs over 50 years (in Euro per m coastline per year)**
Straight rock groynes	50 to 150
Rock revetments	100 to 200
Shoreface nourishments (every 5 years)	100 to 200 (if sand is easily available)
Sea walls	150 to 300
Beach fills (every 3 years)	200 to 300 (if sand is easily available)
Submerged breakwaters	200 to 400
Emerged breakwaters	250 to 500

Table 6 *Investment cost of shoreline protection measures*

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