

# Sediment transport and budget of the central coastal zone of Holland

Leo C. van Rijn \*

*Delft Hydraulics, Marine Coastal Management, P.O. Box 177, 2600 MH Delft, The Netherlands*

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## Abstract

Based on the available short-term morphological data (1964–1992), the net yearly-averaged sand volume change in the surfzone (3/–8 m NAP; to local datum approximately mean sea level) along the coast of Holland was found to be 125,000 m<sup>3</sup>/year (sedimentation), including beach nourishments. A sand budget model has been developed, which describes the sand volume change (in m<sup>3</sup>/year) in each compartment of the coastal area given known gradients of the computed longshore and cross-shore transport rates and known source/sink terms (nourishment, dumping and dredging). The model area extends in cross-shore direction from the +3 m NAP contour to the –20 m NAP contour. The sand budget model has been calibrated (hindcast study) using the yearly-averaged sand volume changes derived from bathymetry data (Jarkus-data base) collected during the period 1964–1992. Input data are the gradients of the yearly-averaged longshore and cross-shore transport rates at the boundaries of the compartments and the available data of beach nourishment, dumping and dredging in the same period. A 2DV-mathematical model representing the hydrodynamic (waves and currents) and sand transport processes in a cross-shore profile was applied to compute the yearly-averaged transport rates in various profiles along the coast at depths of 20 and 8 m and in the surf zone. A detailed sensitivity study was performed to determine the variation ranges of the transport rates. © 1997 Elsevier Science B.V.

**Keywords:** Sediment budget; Shoreline migration; Coastal erosion; Deposition; Longshore and cross-shore transport

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\* Fax: +31-15 285 85 82; E-mail: leo.vanRijn@wDelft.nl.

## **1. Introduction**

### *1.1. Background*

The defence of sandy coastal zones in erosive hydrodynamic conditions requires detailed information of the sediment budgets involved. Especially, the large-scale and long-term coastal behaviour is of importance in relation to changes in exogeneous conditions such as sea level rise, changes in wave climate and in tidal ranges. These effects may result in the necessity of large-scale and long-term dumping of sand in the beach zone (nourishment) and associated mining of sand in offshore areas. The long-term consequences of these measures are of vital importance for coastal management and coastal defence and can be studied by means of sediment budget calculations, as presented in this paper.

The coastal defence policy in The Netherlands is primarily aimed at protection against flooding of the lowland areas situated behind the coastline, which prior to 1960 has been achieved by building groynes, dikes and seawalls. Since then, beach nourishment has become a keystone of coastal defence to further reduce the retreat of the coastline in the eroding sections.

In 1990 a historic decision was made to maintain the coastline at the position of that date by all means. Since then a program of massive and continuous beach nourishment has been initiated to compensate the loss of beach and dune sediments as caused by natural erosion processes.

A basic element of an effective coastal defence policy is a good understanding of the physical processes involved. Therefore, a multi-disciplinary research program was initiated, titled 'Coastal Genesis' in cooperation with the National Centre of Coastal Research (NCK) and the European MAST-program.

A sand budget model based on a schematization of the cross-shore profile in three subzones (surf, middle shoreface and lower shoreface zone) has been developed. Along the coastline sixteen compartments have been distinguished. The net yearly-averaged cross-shore and longshore sand transport rates at the boundaries of the various compartments have been computed by using a detailed process-related coastal profile model. The accuracy of the computed transport rates has been estimated on the basis of extensive sensitivity computations. Source/sink terms (nourishment, dumping and dredging) have been taken into account.

The model has been calibrated by matching measured long-term erosion/deposition volumes and computed sand transport rates. This example shows the capabilities of sand transport and budget models and the accuracies involved. The application of transport models is considered to be essential for the understanding of the various transport components of the sediment budget and the associated erosion and deposition volumes. Finally, recommendations for future research are given to improve the accuracy of sand budget computations.

## 2. Coastal system between Den Helder and Hoek van Holland, The Netherlands

### 2.1. Historical developments

Since 1600 the central coast of The Netherlands between Den Helder and Hoek van Holland (see Fig. 1) 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 northern (north of Egmond) and the southern (south of Scheveningen) sections of the central coastal system have suffered from structural erosion because of the sediment-importing capacity of the neighbouring tidal inlets.

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 and intensified by the stirring action of shoaling and breaking waves.

From 1800 onwards the coastline was more actively defended by building groynes and seawalls. 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 larger vessels to the harbour of Rotterdam and Amsterdam. At present the maximum length of the barriers is about 4.2 km near Hoek van Holland and about 2.3 km near IJmuiden. 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. Around 1910 some negative effects related to the construction of relatively long groynes and barriers were first realized, being the erosion and associated profile steepening in the deeper surf zone and shoreface zone because of the wave- and tide-induced longshore currents forced to flow around the harbour barriers at higher velocities.

### 2.2. Hydrodynamic and sediment characteristics

The coastline between Den Helder and Hoek van Holland has a length of about 118 km and consists of sandy beaches with sediment sizes in the range of 150 to 500  $\mu\text{m}$  (Eisma, 1968). The coastline is shown in Fig. 1.

Man-made structures have a significant influence in this part of the Dutch coast. The most dominant are the relatively long barriers of Hoek van Holland and IJmuiden. The seawall south of Callantsoog protects the coastal section between 20–26 km (from Den Helder) against wave attack. Due to local erosion the seawall protrudes into the surf zone over a cross-shore distance of about 200 m. Groynes with a length of 200 to 300 m and spacings of 200 to 500 m are present in the 0–30 km and 100–118 km.

Tidal surface waves, tidal currents, wind-induced currents, storm surges and wind waves occur and contribute to the local coastal processes. The tidal ranges along the coast are 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.

The wind climate of the North Sea generates most of the waves arriving at the Dutch coast. Most important for the coastal morphology is the highly variable wave climate



near the coast. The highest waves in the Dutch sector of the North Sea are recorded at the K13 station located 110 km off Den Helder. The lowest waves are recorded at the MPN station located 10 km off Noordwijk in 18 m water depth. At the outer edge of the surf zone the waves will be somewhat lower due to energy dissipation by bottom friction.

The wave climate at the breaker zone is dominated by waves of a moderate height (about 1.5 m) and a relatively short period (about 5 s). Waves offshore exceed 2 m approximately 10% of the time and 3 m approximately 2% of the time. Most waves arrive from the southwest to the northwest directions. The highest waves are from the northwest direction because of the longer fetches in this sector. Swell is also dominant from the northwest direction.

### *2.3. Transport processes*

Wave motion over an erodible sand bed can generate a suspension with large near-bed concentrations, as shown by laboratory and field measurements. Mean currents such as tide-, wind- and density-driven currents carry the sediments in the direction of the main flow; this type of transport usually is termed the current-related transport.

Wave-induced transport processes are related to the oscillating and mean currents generated in the wave boundary layer by high-frequency waves. Net onshore transport due to wave asymmetry generally is dominant in non-breaking wave conditions outside the surf zone, whereas net offshore transport generally is dominant during conditions with breaking waves.

The major transport components contributing to the wave-induced transport processes are:

- Net onshore-directed transport (bed load and intermittent suspended load) due to asymmetry of the near-bed orbital velocities with relatively large onshore peak velocities under the wave crests and relatively small offshore peak velocities under the wave troughs.
- Longshore-directed transport due to the generation of longshore wave-driven currents due to breaking waves.
- Net offshore-directed transport due to the generation of a net return current (undertow) in the near-bed layers balancing the onshore mass flux between the crest and trough of breaking waves.
- Net onshore-directed transport due to the generation of a quasi-steady weak current (Longuet-Higgins streaming, 1953) in the wave boundary layer.
- Net offshore-directed transport due to the generation of bound long waves associated with variations of the radiation stresses under irregular wave groups (peak velocities and sand concentrations are out of phase).

Gravity-induced transport components related to bed slopes.

### *2.4. Morphological characteristics*

The nearshore bed profiles show a system of bars and troughs. Generally, a swash bar attached to the beach and two or more breaker bars are present in the central sections

north and south of IJmuiden. Near Den Helder and Hoek van Holland only one breaker bar is present.

Large sand ridges are present in the lower and middle shoreface; the latter are almost connected to the shore (see Fig. 1)

Detailed analysis of short-term and long-term morphological data (bed-profile soundings; Jarkus data base, Rijkswaterstaat, 1994) of the central zone between Den Helder and Hoek van Holland over the period 1964–1992 shows the following basic features:

- Systematic retreat of the coastline north of Egmond and south of Scheveningen.
- Erosion of the middle and lower shoreface zone ( $-8/-12$  m NAP; to local datum approximately equal to mean sea level); minor erosion in the central sections; increasing erosion towards the harbour barriers and the Marsdiep channel (tidal inlets).

To obtain a better understanding of the sedimentation and erosion patterns along the coast, Fig. 2 presents the volume changes per unit length for 16 sections between Den Helder and Hoek van Holland. Beach and dune nourishments were carried out regularly during the period 1964–1992. The total yearly-averaged nourishment volume seaward of the dune crests during the considered period is about  $440,000 \text{ m}^3/\text{year}$ .

Most of the sections north of IJmuiden (0–50 km) show erosion in the zones between the  $-12$  and the  $3$  m NAP depth contours. In most sections near Den Helder the beach nourishment is not sufficient to compensate for the erosion processes in the dune and beach zone. An exception is section 8–16 km near Den Helder where the beach nourishment volume is relatively large.

The typical erosion pattern in the zone  $-8/-12$  m NAP (Fig. 2) with increasing erosion towards the harbour barriers of IJmuiden and the Marsdiep inlet channel (near Den Helder) may be an indication of erosion by gradually converging tidal flood and ebb currents upstream of the barriers. Another cause for the erosion near the barriers may be wave-induced cross-shore transport processes.

Direct north and south of the barriers of IJmuiden sedimentation can be observed in the zone  $-8/-12$  m NAP, which may be caused by: (1) blocking of longshore transport by the barriers, (2) sedimentation of particles eroded upstream by the converging tidal current entering deeper water (reduced wave stirring effect) and (3) by diffusive sedimentation in the circulation zone generated downstream of the barriers by the diverging current.

The zone  $3/-8$  m NAP between Den Helder and Hoek van Holland shows an overall net sedimentation of  $125,000 \text{ m}^3/\text{year}$ . Erosion can be observed north of profile 40 km (Egmond); near the harbour barriers of IJmuiden in sections 47–50, 60–77 km and in section 92–97 km, which is the first section without groynes north of Scheveningen. The total amount of erosion in the zone  $3/-8$  m NAP is about  $730,000 \text{ m}^3/\text{year}$ ; most of the erosion (50%) occurs in section 0–39 km north of Egmond, in section 60–79 km near Bloemendaal (30%) and in section 92–97 km north of Scheveningen (10%).

Short-term and long-term migration rates of the  $-1$  and  $-8$  m depth contours are shown in Fig. 3. The  $-1$  m depth contour in section 0–8 km near Den Helder and in 16.3–28 km near the seawall south of Callantsoog shows relatively large landward

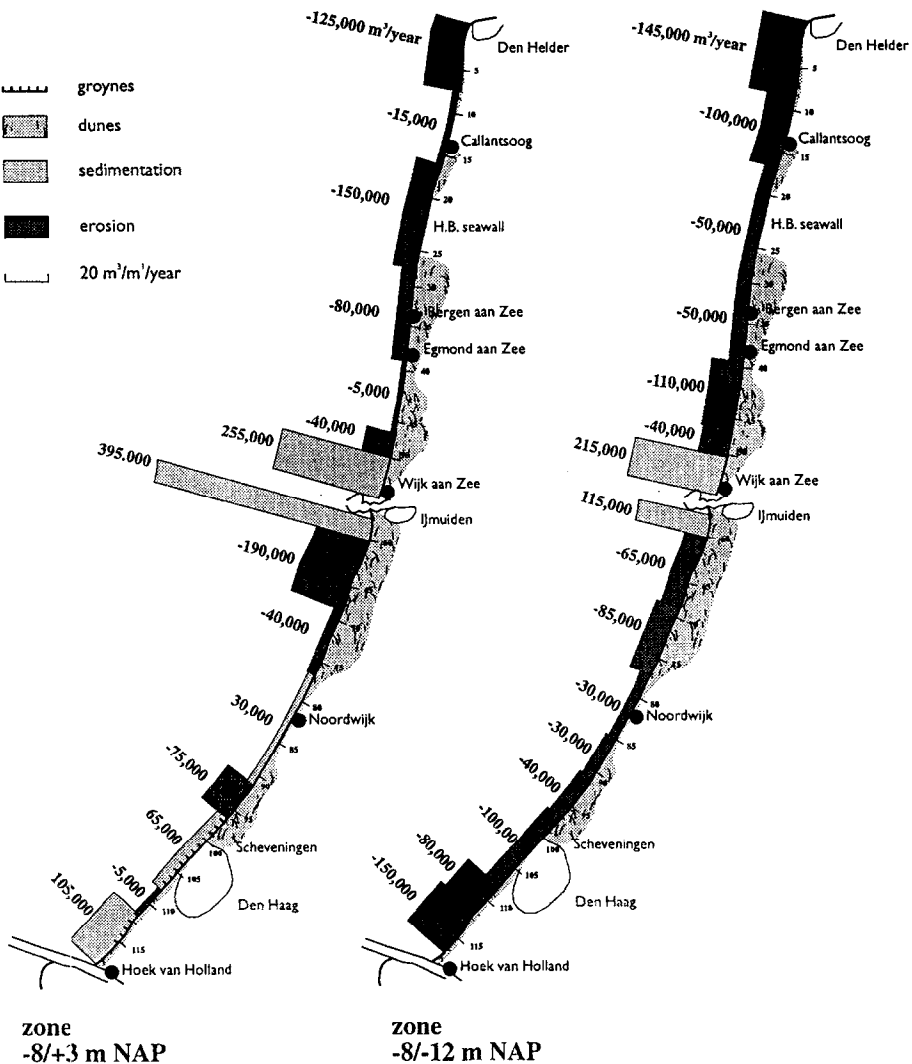


Fig. 2. Yearly-averaged sedimentation and erosion volumes in cross-shore zones 3/-8 m and -8/-12 m NAP along the Dutch coast.

migration (erosion) of about 1 to 2 m/year, resulting in significant steepening of the profile in front of the seawall. The -1 m depth contour in sections 47–50 and 60–68 km further away northward and southward of IJmuiden shows landward migration of 0.5 to 1 m/year; the erosion effects are most likely related to the extension of the harbour barriers in 1962–1967. In all other sections the -1 m depth contour shows seaward migration up to 10 m/year near the harbour barriers of IJmuiden.

The -8 m depth contour in section 50–60 km near the harbour barriers of IJmuiden

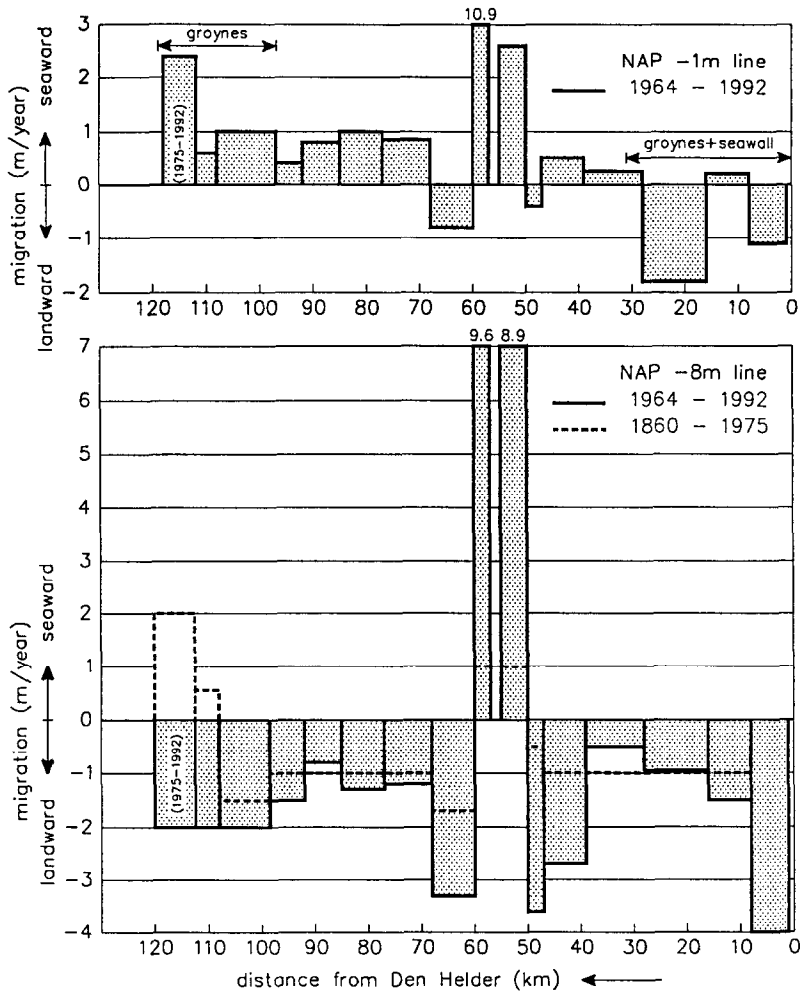


Fig. 3. Migration rates of  $-1$  and  $-8$  m depth contours along the Dutch coast.

shows seaward migration of about 10 m/year; the short-term values are considerably larger than the long-term values showing the effect of the extension of the harbour barriers in 1962–1967.

The  $-8$  m depth contour in the central sections (18–39 km, 68–97 km) north and south of IJmuiden shows landward migration of about 0.1 to 1 m/year increasing to about 3 to 4 m/year towards the harbour barriers and the Marsdiep channel (near Den Helder); the spatial pattern is similar to that of the sedimentation and erosion volumes in the  $-8/-12$  m zone (see Fig. 3). The effect of the extension of the harbour barriers in 1962–1967 can be clearly observed from the increased short-term erosion (landward migration) in the sections closer to the harbour barriers.



### 3. Sand budget model

#### 3.1. Introduction

The sand budget model describes the sand volume changes and corresponding changes of characteristic depth contours, given known transport gradients (both cross-shore and longshore) and source/sink terms (dredging, nourishment). The model compartments extend in the cross-shore direction from the +3 m NAP contour to the –20 m NAP contour and in the longshore direction from Den Helder to Hoek van Holland (0–118.5 km). The seabed in this area is represented as the space-averaged (eliminating the bars) and time-averaged bed, over which longterm-averaged bed level changes will be evaluated. Evidently, the short term (almost instantaneous) response of the bed profile in the surf zone to hydrodynamic events such as storms cannot be modelled.

The morphological behaviour of the compartments is assumed to be uniform or quasi-uniform in longshore direction, which implies that the hydrodynamic and morphologic parameters are constant or have a constant gradient in space. Furthermore, the compartments are assumed to show a quasi-stationary behaviour in time, which implies a slow and gradual variation of the morphological processes on larger scales (yearly-averaged and section-averaged quantities). This approach may be realistic for the compartments further away from man-made structures such as harbour barriers. The morphological behaviour of the compartments adjacent to structures cannot be represented accurately by the proposed model, if the behaviour of the transport gradients in time is unknown. These compartments typically show a transition to a (new) state of equilibrium.

The sand budget model has been calibrated using the yearly-averaged erosion, sedimentation, nourishment and dredging volumes over the period 1964–1992 (Jarkus-data, Rijkswaterstaat, 1994).

#### 3.2. Model description

The sand budget model is based on a subdivision of the coastal area in rectangular compartments (see also Stive et al., 1990 and De Vriend et al., 1993), as shown in Fig. 4. Three compartments with boundaries at the 3, –3, –8 and the –20 m NAP contours are present in cross-shore direction. The –3 m NAP contour is herein taken as the boundary between the inner and outer surf zone because it divides the total net longshore transport including the tide-related longshore transport rate roughly in two equal parts (50% in inner zone and 50% in outer surf zone). Furthermore, the computed longshore and cross-shore transport rates show a strong increase landward of the –3 m NAP contour indicating that this zone is the most dynamic subzone of the surf zone.

Based on the principle of mass conservation, the yearly-averaged sand volume changes (assuming constant sediment density) for each cross-shore compartment can be expressed, as:

$$V_U = C_U - C_D + \Delta L_U + \Delta X_{u,s}(\alpha h_D + h_U)B + S_U \quad (1)$$

$$V_M = C_M - C_U + \Delta L_M - \Delta X_{u,s}(\alpha h_D + h_U)B + S_M \quad (2)$$

$$V_L = C_L - C_M + \Delta L_L + S_L \quad (3)$$

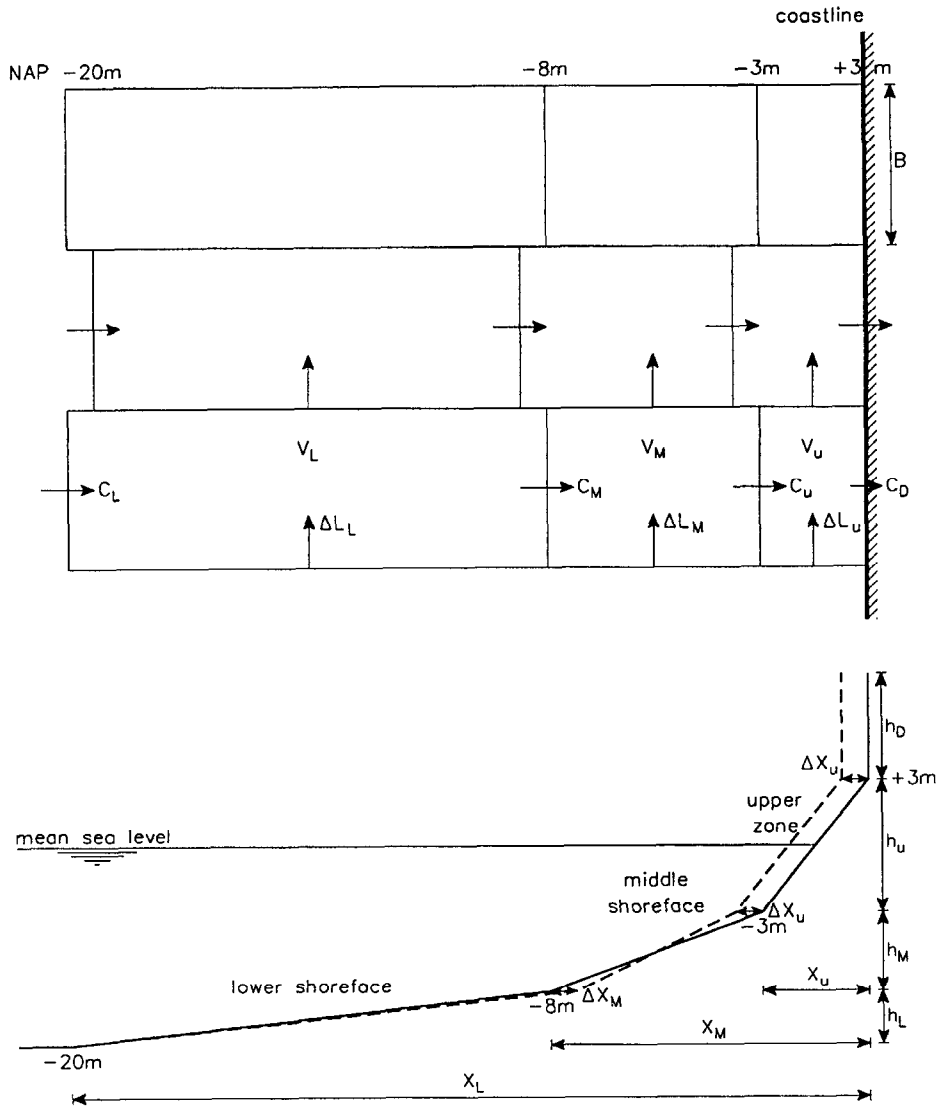


Fig. 4. Compartments and schematized bed profile.

Simple linear geometrical expressions relating volumes to cross-shore, longshore and vertical scales, are:

$$V_U = \alpha_1 (h_D + h_U) (\Delta X_U) B \quad (4)$$

$$V_M = \alpha_2 (h_M) \left( \frac{1}{2} \Delta X_U + \frac{1}{2} \Delta X_M \right) B \quad (5)$$

$$V_L = \alpha_3 (h_L) \left( \frac{1}{2} \Delta X_M + \frac{1}{2} \Delta X_L \right) B \quad (6)$$

According to these expressions, the cross-shore changes of the depth contours can be derived, as follows:

$$\Delta X_U = \frac{V_U}{\alpha_1(h_D + h_U)B} \quad (7)$$

$$\Delta X_M = \frac{2V_M}{\alpha_2 h_M B} - \Delta X_U \quad (8)$$

$$\Delta X_L = \frac{2V_L}{\alpha_3 h_L B} - \Delta X_M \quad (9)$$

in which:  $V_U$ ,  $V_M$ ,  $V_L$  = yearly-averaged sand volume changes (in  $\text{m}^3/\text{year}$ , including pores); deposition is positive,  $C_U$ ,  $C_D$ ,  $C_L$  = yearly-averaged cross-shore transport rates (in  $\text{m}^3/\text{year}$ , including pores); landward is positive,  $\Delta L_U$ ,  $\Delta L_M$ ,  $\Delta L_L$  = yearly-averaged longshore transport differences along compartments (in  $\text{m}^3/\text{year}$ , including pores),  $S_U$ ,  $S_M$ ,  $S_L$  = source/sink terms (in  $\text{m}^3/\text{year}$ , including pores),  $h_D$ ,  $h_U$ ,  $h_M$ ,  $h_L$  = height (m),  $\Delta X_U$ ,  $\Delta X_M$ ,  $\Delta X_L$  = horizontal change of depth contours (m/year); landward is negative,  $\Delta X_{u,s}$  = horizontal coastline change due to sea level rise based on Bruun-rule (m/year),  $B$  = longshore length of section (m) and  $\alpha_1$ ,  $\alpha_2$ ,  $\alpha_3$  = calibration coefficients (matching computed and measured results).

The basic input data are: yearly-averaged cross-shore transport rates and longshore transport differences, source and sink terms, geometrical information and calibration coefficients.

The output data are: yearly-averaged volume changes and yearly-averaged coastline changes.

### 3.3. Sea level rise effect

The sea level rise effect on the coastline development is represented by the modified Bruun-rule (Bruun, 1962; Bruun, 1988). The precise location of the seaward boundary (closure depth separating the active and inactive zone) is not well-defined. Herein, the following two values of the closure depth have been used:  $-5.5$  and  $-8$  m NAP. The closure depth at  $-5.5$  m NAP should be interpreted as a boundary halfway between the  $-3$  and  $-8$  m NAP contours. This latter value ( $-8$  m NAP) roughly represents the edge of the surf zone. Fig. 5 shows a schematic representation of the sea level rise effect according to the modified Bruun-rule. According to this rule, it follows that (closure depth at  $-5.5$  m):

$$r(X_U + \frac{1}{2}\Delta X_M - \frac{1}{2}X_U) = \Delta X_{u,s}(\alpha_4 h_D + h_U + \frac{1}{2}h_M) \quad (10)$$

and

$$\Delta X_{u,s} = \frac{1/2r(X_M + X_U)}{\alpha_4 h_D + h_U + 1/2h_M} \quad (11)$$

in which  $r$  = sea level rise (m/year), positive upward;  $\alpha_4$  = coefficient representing effective dune erosion height (0–1) and  $\Delta X_{u,s}$  = horizontal coastline change (m/year), landward is negative.

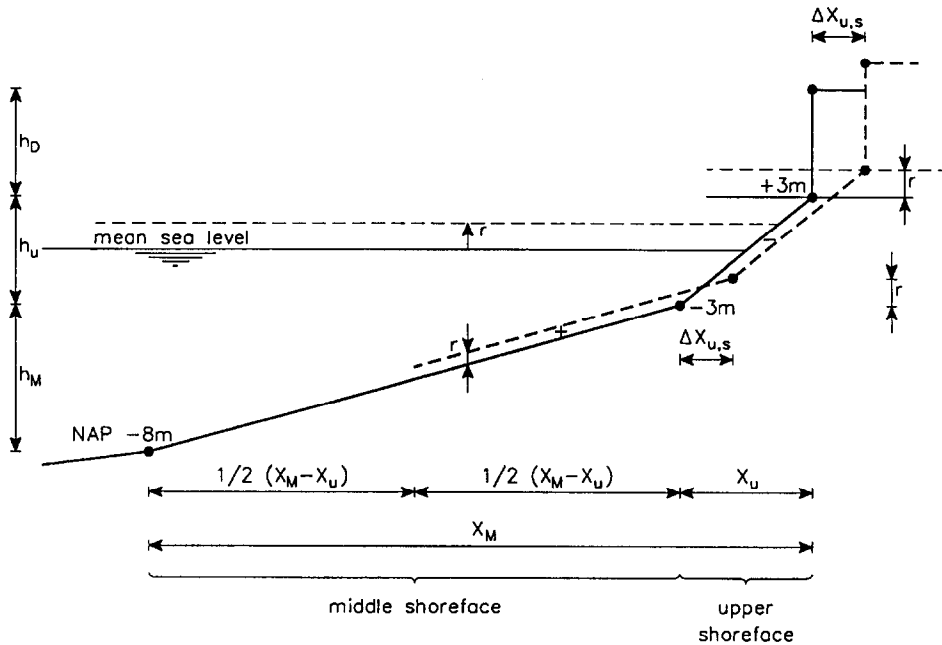


Fig. 5. Coastline change related to sea level rise (Bruun-rule), closure depth at  $-5.5$  m NAP.

Taking a closure depth at  $-8$  m NAP, Eq. (11) is slightly different.

Sensitivity computations have shown that the computed erosion volume in the zone  $3/-3$  m NAP due to the sea level rise effect will be increased by about 35% by taking the closure depth at  $-8$  m NAP instead of  $-5.5$  m NAP.

#### 4. Input data: Yearly-averaged sand transport rates along the Dutch coast

##### 4.1. Approach

To determine the yearly-averaged sand transport rates at the boundaries of the budget compartments, a physical-mathematical model representing the hydrodynamic and sand transport processes was applied, based on a one-dimensional approach in a direction normal to the shore. Details are given by Van Rijn et al., 1994.

The integrated model (Unibest model of Delft Hydraulics) consists of 3 sub-models: a wave propagation model, a vertical flow structure model and a sand transport model (Roelvink and Stive, 1990; Roelvink, 1993; Roelvink and Broker, 1993). The model was updated by improving the physics of the processes involved (see below and Roelvink and Reniers, 1994). The model was not calibrated for this particular application.

The wave propagation model computes the wave energy decay along a wave ray based on shoaling, refraction and energy dissipation by bottom friction and wave breaking. The near-bed instantaneous velocities are computed as time series representing irregular wave groups (including wave asymmetry and bound long wave effects).

The vertical flow structure model computes the vertical distribution of the horizontal flow velocities for a given depth-averaged velocity vector (input), wave height and period, fluid density gradient and wind shear stresses (surface). The streaming (Longuet-Higgins, 1953) in the wave boundary layer due to transfer of momentum by viscous and turbulent diffusion is taken into account. The expressions given by Longuet-Higgins (1953), which are valid for laminar flow in the boundary layer, have been applied. These expressions appear to give quite reasonable results for the turbulent case as well, based on comparison of measured and computed near-bed velocities (Van Rijn et al., 1994). The effect of wave breaking resulting in a longshore current and a cross-shore return current (undertow) and the Coriolis effect are taken into account. The model was improved by including the roller effect and a better vertical eddy viscosity coefficient (constant) with respect to the modelling of the longshore current in the surf zone.

The sand transport model which computes the magnitude and direction of the bed load and suspended load transport, has also been updated. The new bed-load transport function of Ribberink (1997) has been used to compute the net bed-load transport rates. Input parameters are the time series velocity data and the time-averaged velocity data computed by the wave model and the vertical structure model; the various velocity components are composed to an instantaneous velocity vector, which is converted to an instantaneous bed-shear stress applying a friction factor. The suspended load transport is computed from the time-averaged velocity and sand concentration profiles (Van Rijn, 1993). The transport model of Bailard–Bagnold (see Roelvink and Stive, 1990) has also been used in the sensitivity computations.

The sediment transport rates are computed for the schematised wave and corresponding current conditions. Tidal averaging is applied to obtain the tide-averaged transport rate for each wave direction and wave height class. The tide-averaged transport rate is multiplied by the percentage of occurrence of each specific wave condition, resulting in the weighted transport rate. Adding all individual weighted values, yields the yearly-averaged sediment transport rate.

The output results of the mathematical model are net cross-shore and longshore transport rates at various locations along the shore. A basic question is whether these results are reasonable in terms of the overall continuity equation and observed erosion/deposition volumes. This will be addressed in Section 5 of this paper. It will be shown that the transport gradients and the other components of the sediment balance can explain the observed volume changes in the coastal zone.

#### *4.2. Boundary conditions and input data*

The boundary conditions required to compute the yearly-averaged sand transport rates, are: cross-shore bottom profiles, yearly-averaged wave climate, tide- and wind-induced water levels and velocities, fluid density-gradients, sediment composition and effective bed roughness.

The tidal water levels and depth-averaged flow velocities (including wind effects) in the stations of interest were derived from computations made by the Department RIKZ of Rijkswaterstaat using a two-dimensional horizontal flow model.

The neap-spring tidal cycle (tidal range of about 1.3 m for neap, and about 1.9 m for

spring) was represented by one representative tide. The tidal range of this latter tide was selected to be 10% larger than the mean tidal range (about 1.6 m) near the Dutch coast to account for the non-linear relationship between sand transport and depth-averaged flow velocity. This representative tide is approximately equivalent to a low spring tide. Computations were made for 8 wind directions and 4 wind velocities (per direction) being: no wind and wind velocities corresponding to wave heights of 1.25, 2.75 and 4.25 m. In all, 25 ( $= 8 \times 3 + 1$ ) computations were made and analyzed.

The spatial distribution of the cross-shore density gradients along the coast are based on field measurements.

Information of the sediment size of the top layer of sea bed near the stations of interest was obtained from field data. The available data were analyzed to determine the characteristic particle diameters ( $d_{10}$ ,  $d_{50}$  and  $d_{90}$ ), yielding values in the range of  $d_{50} = 150$  to  $250 \mu\text{m}$  and  $d_{90} = 200$  to  $400 \mu\text{m}$ . Spatial variations in the  $d_{50}$ -values were found to be of the order of 25 to  $50 \mu\text{m}$ . A particle size of  $250 \mu\text{m}$  was used in most computations. Values of 200 and  $300 \mu\text{m}$  were used in the sensitivity computations.

The effective bed roughness is related to the shape and dimensions of the bed forms generated by the tidal currents in combination with the short wave motion. Information of the shape and dimensions of the bed forms was obtained from the literature (Van Rijn, 1993). Generally, small scale ripples (height of 0.01 to 0.05 m; length of 0.1 to 0.5 m) are generated by relatively low waves, which are washed out by the higher waves yielding the sheet flow regime. The bed forms most commonly observed in tidal sea currents are megaripples (height of 0.1 to 0.5 m, length of 10 to 50 m). In conditions with waves superimposed on a tidal current, the wave-related bed forms are generated on the back of the megaripples. Based on this information, the current-related ( $k_c$ ) and wave-related ( $k_w$ ) bed roughness values were estimated to be in the range of 0.01 to 0.1 m.

#### 4.3. Yearly-averaged cross-shore and longshore sand transport rates at the $-20$ m depth contour

The yearly-averaged cross-shore and longshore transport rates at the  $-20$  m depth contour have been computed in four cross-shore profiles 14, 40, 76, 103 km from Den Helder (see Fig. 1).

It is known that the net cross-shore transport rates in the nearshore zone are the result of a delicate balance of various onshore and offshore-directed transport components. Most of these transport components cannot yet be represented with sufficient accuracy. Therefore, a detailed sensitivity study (based on 18 model computations, see Table 1) was performed varying the most important input and model parameters to come up with variation ranges of the net transport rates rather than absolute values.

The sensitivity computations have been made for profile 76 (Noordwijk) and will be presented first. The transport rates are given in values including pores (40%) to be consistent with the observed volume changes.

The yearly-averaged *cross-shore* transport component based on the Delft Hydraulics model (Unibest) at the  $-20$  m contour of profile 76 is onshore-directed and varies predominantly in the range of 0 to  $15 \text{ m}^3/\text{m}/\text{year}$ . The cross-shore transport component

Table 1  
Description of sensitivity computations for profile 76 (Noordwijk)

Description of transport computations	
CN01	base computation, all hydrodynamic effects included, particle diameter = 0.00025 m ( $d_{90} = 2d_{50}$ )
CN02	particle diameter = 0.0002 m ( $d_{90} = 2d_{50}$ ) (decrease of diameter will result in increase of transport rate)
CN03	particle diameter = 0.0003 m ( $d_{90} = 2d_{50}$ ) (increase of diameter will result in decrease of transport rate)
CN04	near-bed mean current velocities are reduced by 50% (only bed-load transport is affected)
CN05	near-bed mean current velocities are increased by 50% (only bed-load transport is affected)
CN06	the depth-averaged velocity of the ebb tidal phase is increased by 10% (net longshore transport rate will be reduced)
CN07	the wind-induced current velocities are neglected (only astronomical tidal velocities are taken into account)
CN08	depth-averaged tide-induced and wind-induced current velocity is reduced by 25% (transport rates will be reduced)
CN09	onshore density gradient is neglected (onshore transport will be reduced, because the onshore near-bed mean current generated by the density gradient is neglected)
CN10	near-bed return current (undertow) is reduced by 50% (offshore transport will be reduced)
CN11	Longuet-Higgins streaming is neglected (onshore transport will be reduced, because LH-streaming yields onshore velocities)
CN12	asymmetry of orbital velocity is neglected (onshore transport will be reduced)
CN13	long waves are neglected (offshore transport will be reduced)
CN14	current-related bed roughness is reduced and taken equal to the wave-related bed roughness (bed-load transport and suspended load transport will be reduced)
CN15	bed is assumed to be plane with a roughness height equal to 0.01 m (increase of near-bed velocities, decrease of stirring effect)
CN16	different method for computation of bed-shear stress in combined currents and waves (quadratic summation of friction factors)
CN17	(Smaller bed-shear stress and hence smaller bed-load transport)
CN18	base computation including all hydrodynamic effects using Bailard–Bagnold transport model
	base computation neglecting wind-induced velocities and density-gradient using Bailard–Bagnold transport model

Table 2

Contribution of various hydrodynamic processes to cross-shore transport rate (all values incl. pores)

Process	Contribution to cross-shore transport rate (in $\text{m}^3/\text{m}/\text{year}$ )	
	depth = 20 m	depth = 8 m
Wave velocity asymmetry effect	0	15
Bound long wave effect	0	– 15
Longuet-Higgins streaming effect	0	15
Reduced (50%) return current effect (related to breaking waves)	0	25
Fluid density-gradient effect	10–25	10

+ onshore; – offshore.

is dominated by tide-induced, wind-induced (dominant southwesterly winds) and density-induced currents in combination with the wave motion acting as a stirring mechanism. The upper limit is mainly related to the influence of the density gradient favouring onshore-directed near-bed velocities and hence transport rates. The fluid density decreases in landward direction due to the presence of less saline water in the nearshore zone caused by the fresh water discharge of the Rhine river at the southern boundary of the coast of Holland.

The yearly-averaged *longshore* transport component based on the Delft Hydraulics model is northward directed and varies predominantly in the range of 15 to 60  $\text{m}^3/\text{m}/\text{year}$ . The lower limit is related to reduced tidal current velocities. The upper limit is related to a relatively small particle diameter.

Based on the results of the sensitivity analysis, the contributions of various hydrodynamic processes to the cross-shore transport rates can be estimated (Table 2). The wave velocity asymmetry effect, the bound long wave effect, the LH (Longuet-Higgins) streaming effect and the reduced return current effect do not contribute to the cross-shore transport rate at a depth of 20 m. The contribution of the fluid density gradient effect to the cross-shore transport rate at 20 m is about 10 to 25  $\text{m}^3/\text{m}/\text{year}$ , dependent on the location along the coast.

The net bed-load transport component of the cross-shore transport at a depth of 20 m is generally onshore-directed, whereas the net suspended load transport is offshore-directed; generally the bed-load transport is dominant. The net bed-load and the net

Table 3

Best estimates of yearly-averaged total transport rates at a depth of 20 m and 8 m in profiles 14, 40, 76 and 103 (all values incl. pores)

Cross-shore profile	Yearly-averaged total load transport ( $\text{m}^3/\text{m}/\text{year}$ )			
	cross-shore		longshore	
	depth = 20 m	depth = 8 m	depth = 20 m	depth = 8 m
14 Callantsoog	$5 \pm 10$	$0 \pm 10$	$75 \pm 30$	$150 \pm 60$
40 Egmond	$15 \pm 10$	$0 \pm 10$	$60 \pm 25$	$135 \pm 50$
76 Noordwijk	$10 \pm 10$	$0 \pm 10$	$35 \pm 15$	$85 \pm 45$
103 Scheveningen	$0 \pm 10$	$0 \pm 10$	$25 \pm 15$	$65 \pm 40$

+ north/onshore; – south/offshore.



suspended load components of the longshore transport at a depth of 20 m are both northward-directed and equally important in magnitude.

Based on the results of all available computations, a best estimate (including variation ranges) of the yearly-averaged transport rates at a depth of 20 m in the profiles 14, 40, 76 and 103 km from Den Helder is given in Table 3 and Fig. 6. It is noted again that the values of Table 3 are small values remaining from relatively large bidirectional components.

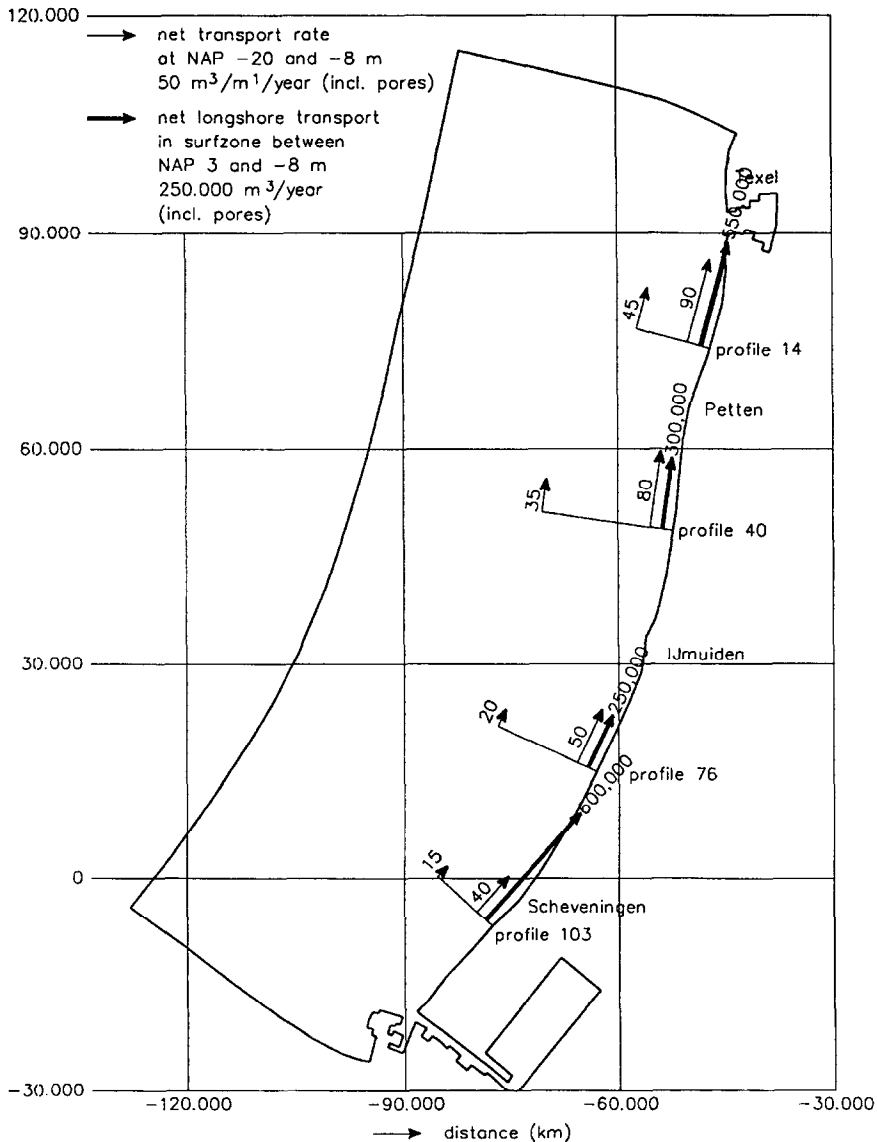


Fig. 6. Net sand transport vectors along the coast.

#### 4.4. Yearly-averaged cross-shore and longshore sand transport rates at the $-8$ m depth contour

Fig. 7 shows an overview of all computed *net cross-shore* transport rates for a depth of 8 m in profile 76. The yearly-averaged cross-shore transport component based on the

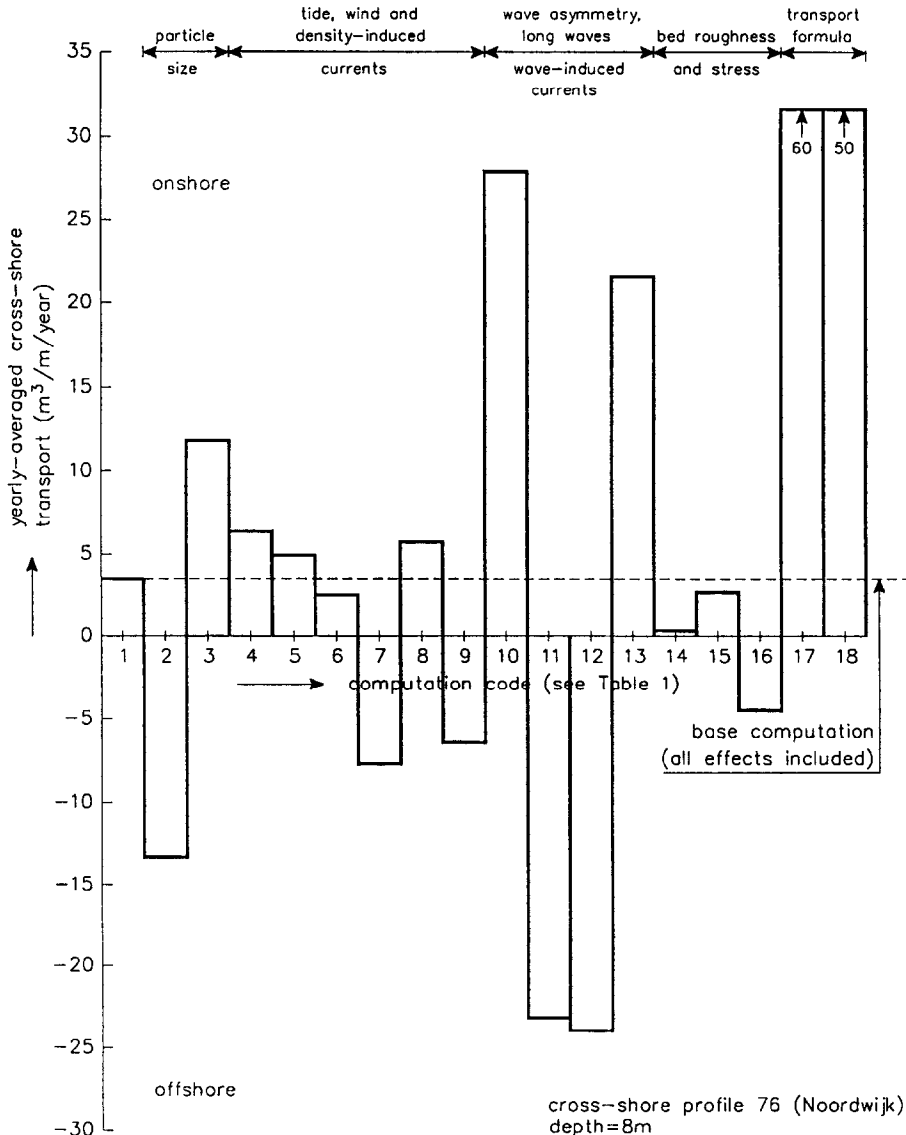


Fig. 7. Effect of model parameters on yearly-averaged total cross-shore transport rate at depth of 8 m in profile 76.

Delft Hydraulics model varies predominantly in the range of  $-15$  to  $+15 \text{ m}^3/\text{m}/\text{year}$ . Net onshore (LH-streaming, wave velocity asymmetry, density gradient) as well as offshore (long waves, undertow) transport rates can be observed. Relatively fine sediment material may result in relatively large offshore-directed transport, whereas relatively coarse sediment material may result in onshore-directed transport. Overall, there is a slight tendency for a net onshore transport (CN01). The application of the transport formula of Bailard–Bagnold yields an unrealistically large onshore transport rate of about  $60 \text{ m}^3/\text{m}/\text{year}$  (CN17), which is a factor 20 larger than that of the Delft Hydraulics model (CN01).

Fig. 8 shows an overview of all computed *net longshore* transport rates for a depth of 8 m. The yearly-averaged longshore transport component based on the Delft Hydraulics model is northward directed and varies predominantly in the range of 20 to  $80 \text{ m}^3/\text{m}/\text{year}$ . The lower limit is related to relatively small mean velocities and no wind effects. The upper limit is related to relatively fine sediment material.

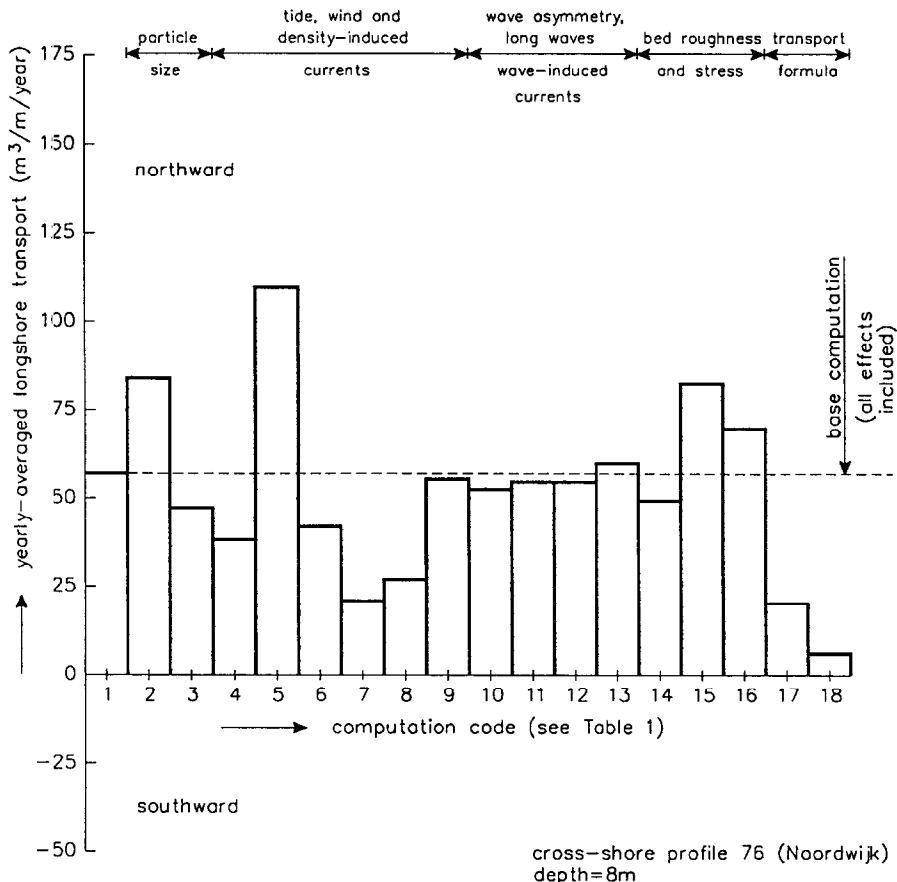


Fig. 8. Effect of model parameters on yearly-averaged total longshore transport rate at depth of 8 m in profile 76.

The estimated contributions of various hydrodynamic processes to the cross-shore transport rate are given in Table 2. The effect of wave velocity asymmetry, the bound long waves, the LH-streaming, the reduced return current and the fluid density gradient to the cross-shore transport rate is in the range of 10 to 25 m<sup>3</sup>/m/year.

The net bed-load component of the cross-shore transport at a depth of 8 m is always onshore-directed whereas the net suspended load transport which is dominated by the mean currents, is always offshore-directed; both modes of transport are equally important. The net bed-load and net suspended load components of the longshore transport at a depth of 8 m are both northward-directed; the suspended load transport generally is dominant.

Based on the results of all available computations, a best estimate (including variation ranges) of the yearly-averaged transport rates at a depth of 8 m in profiles 14, 40, 76 and 103 km from Den Helder is given in Table 3 and Fig. 6, showing a zero net onshore transport of sediment over the 8 m depth contour with variation ranges of about 10 m<sup>3</sup>/m/year and a net northward longshore transport rate in the range of 65 to 150 m<sup>3</sup>/m/year with variation ranges of about 50 m<sup>3</sup>/m/year.

#### 4.5. Yearly-averaged longshore transport rates in the surf zone

The yearly-averaged longshore transport rates in the surf zone (total transport landward of the –8 m depth contour) have been computed in the cross-shore profiles 14, 28, 40, 47, 68, 76, 92, 103 and 108 km from Den Helder, see Fig. 1.

First, the sensitivity computations for profile 76 (see Table 4) are discussed and after that the best estimates of the net yearly-averaged transport rates are given.

Table 4  
Description of sensitivity computations for Profile 76 (Noordwijk)

Description of transport computations	
CS01	base computation, all hydrodynamic effects included, particle diameter $d_{50} = 0.00025$ m ( $d_{90} = 2 d_{50}$ ), bed roughness $k_{s,c} = k_{s,w} = 0.01$ m Wave climate 1980–1993
CS02	particle diameter = 0.0002 m ( $d_{90} = 2 d_{50}$ )
CS03	particle diameter = 0.0003 m ( $d_{90} = 2 d_{50}$ )
CS04	near-bed mean current velocities are reduced by 50%
CS05	near-bed mean current velocities are increased by 50%
CS06	no wind effect on the current velocities
CS07	depth-averaged tide and wind-induced current velocities are reduced by 25%
CS08	tidal current velocities are neglected; only wave-induced currents
CS09	wave-induced current velocities (longshore and cross-shore) are reduced by 50%
CS10	Longuet-Higgins streaming is neglected
CS11	asymmetry of orbital velocity is neglected
CS12	long waves are neglected
CS13	bed roughness $k_{s,c} = k_{s,w} = 0.03$ m
CS14	two breaker bars (date 1985) superimposed on mean bed profile
CS15	two breaker bars (date 1975) superimposed on mean bed profile
CS16	bottom slope of 0.0075 (shoreline to 8 m contour)
CS17	bottom slope of 0.010 (shoreline to 8 m contour)
CS18	modified wave climate 1980–1993
CS19	wave climate 1980–1988

The effect of systematic variation of model and input parameters on the longshore transport rate (bed load and suspended load) integrated over the surf zone is shown in Fig. 9.

In all computations the net integrated longshore transport rate is in the northward longshore direction. Generally, the northward transport rates are about 2 to 3 times as large as the southward transport rates.

The base computation yields a net longshore transport of about 400,000 m<sup>3</sup>/year (including pores) for a smooth (time-averaged) bed profile. The cross-shore distribution of the longshore transport rate shows a large transport peak in the shallow surf zone near the shoreline. About 60 to 70% of the total integrated longshore transport does occur in the inner surf zone with a width of about 200 m.

The total load transport consists of two components: bed load and suspended load transport. In the longshore direction the suspended load transport is the dominant mode of transport at all locations.

The net longshore transport was found to be most strongly affected by the wave climate, the depth-averaged longshore current, the presence of breaker bars, the bottom slope and the particle diameter, as known qualitatively from the literature. The results of Fig. 9 present quantitative information of these effects.

The net longshore transport in all profiles was found to be strongly affected by the magnitude of the wave-induced longshore current. A 50%-reduction of the wave-induced longshore current results in a reduction of the net longshore transport rate by a factor of 5 to 10.

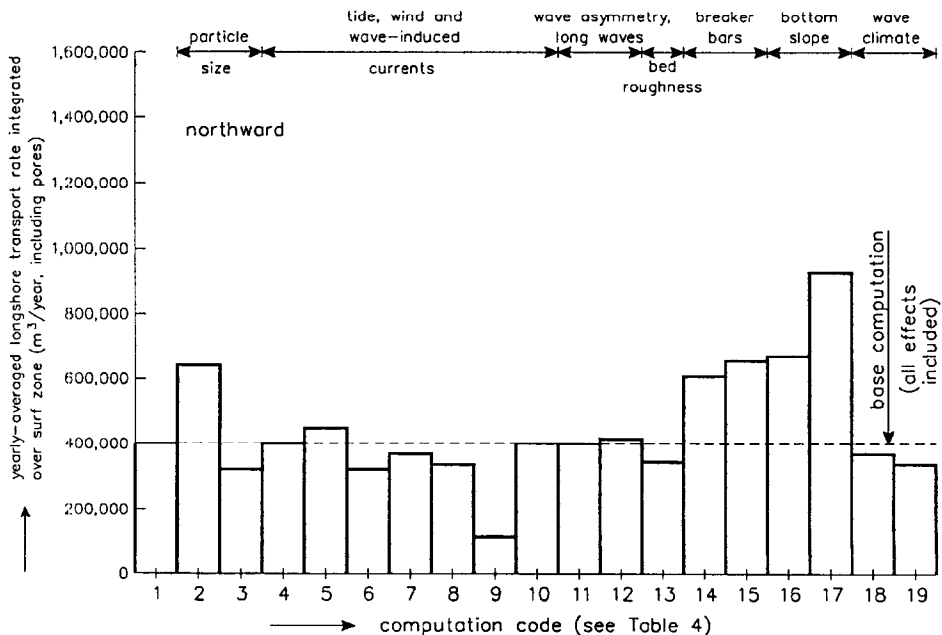


Fig. 9. Effect of model parameters on integrated net longshore transport rate in surf zone (landward of  $-8$  m depth contour) of profile 76.

The tidal currents also have a marked effect on the longshore transport rate. In profile 76 (Noordwijk) the contribution of the tidal current to the longshore transport rate is not more than 20%, but the effect increases in the northern direction to about 40% for profile 40 (Egmond) as a result of the larger tidal asymmetry in the northern part of the Dutch coast.

The presence of breaker bars has a significant effect on the net longshore transport in those sections of the coast where relatively large bars do occur (profiles 40 and 76). Representation of the bars in the cross-shore profile results in a 50%-increase of the net longshore transport rate due to the presence of large transport peaks at the bar crests (see

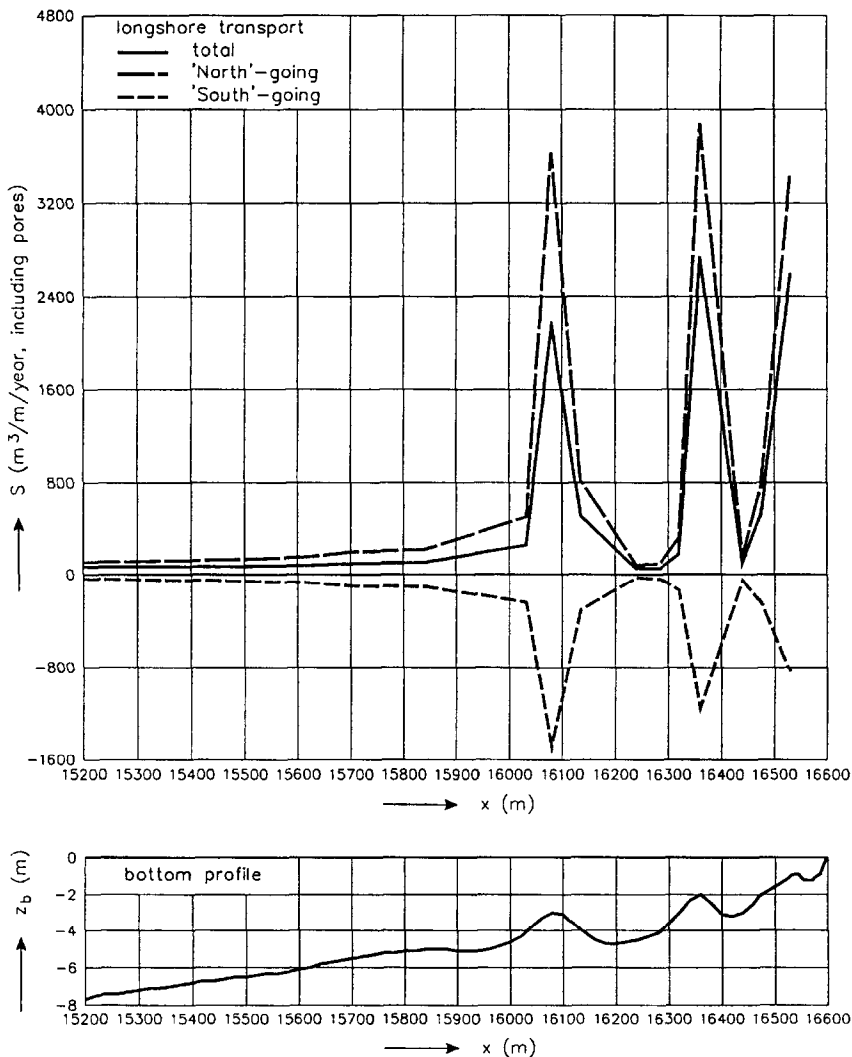


Fig. 10. Cross-shore distribution of longshore transport in profile 76 (bed profile with breaker bars).

Fig. 10). This effect is less pronounced (10 to 20%) in profile 14 and 103, where only one relatively small bar is present.

Finally, the influence of the wave climate on the longshore transport process is discussed. This effect, which has been simulated by assuming a change of  $5^\circ$  of the local coastline orientation, is relatively small (about 20%) for profiles 14, 76 and 103, because the coastline orientation is relatively large ( $> 15^\circ$ ) in those profiles. In profile 40 (Egmond) where the coastline orientation is not more than  $8^\circ$ , the effect of a modified wave climate (somewhat more waves from the north-west; and somewhat less from the south-west) which has been simulated by a shift of  $5^\circ$  of the local coastline orientation results in a 50%-decrease of the net longshore transport rate from 600,000 to 300,000  $\text{m}^3/\text{year}$ .

Using the wave climate of 1989 instead of that of 1994, results in a reduction of the longshore transport rate from 600,000 to 30,000  $\text{m}^3/\text{year}$  (factor 20!) in profile 40. The dominant effect of the wave climate on the transport process will be similar in all those sections, where the coastline orientation is relatively small (25 to 45 km from Den Helder).

The above-given results and those of the sensitivity study for profile 76 have been used to estimate the net longshore transport rates along the coast in the period 1964–1992. These best estimates (including variation ranges) are presented in Fig. 11.

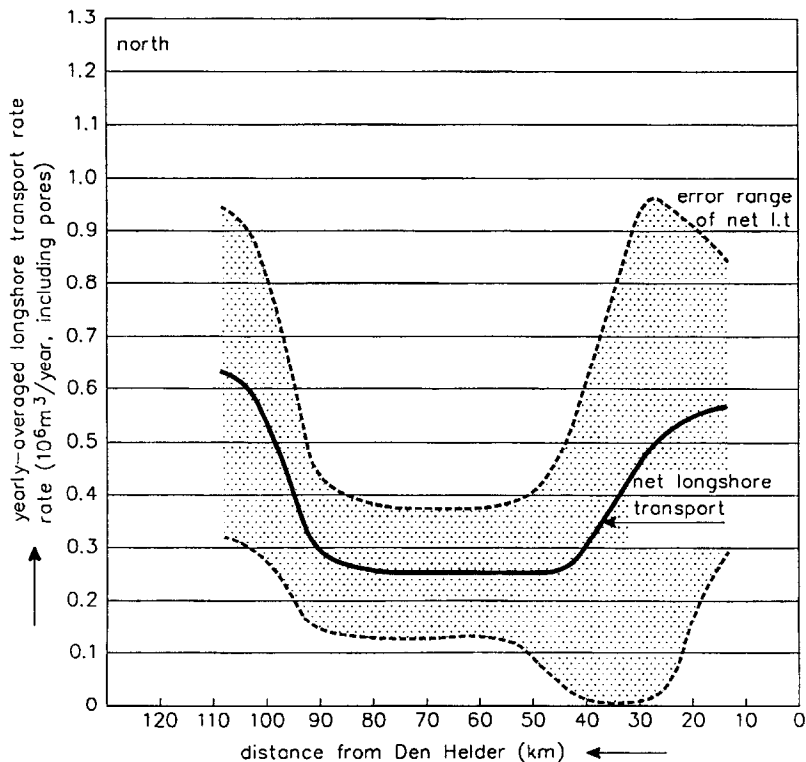


Fig. 11. Yearly-averaged longshore transport rates integrated over the surf zone along the coast.

The net longshore transport rate is approximately constant in the central part of the coast (45 to 85 km from Den Helder). The net transport rates are relatively large in the southern sections 90 to 110 km which is related to the increasing coastline orientation and the profile steepness. The relatively large net transport rates in section 15 to 40 km are related to the increasing tidal asymmetry and profile steepness and to lesser extent by a somewhat more severe wave climate in the north.

Finally, the influence of structures is noted. The results given in Fig. 11 are valid for a natural coast without the presence of structures like harbour barriers. The sand transport rates presented previously need to be corrected to account for the effect of structures.

The harbour barriers near Hoek van Holland and IJmuiden extend considerably beyond the surf zone resulting in an almost full blocking of the total longshore transport process.

The nearshore tidal currents are forced to pass around the barriers resulting in accelerated (converging) flow upstream of the barriers and decelerated (diverging) flow downstream of the barriers. The converging flow upstream of the barriers generates a seaward cross-shore flow component. As a result of this process, sediment material will be carried out of the surf zone into the shoreface zone. Similarly, a landward cross-shore flow component will be generated downstream of the barriers resulting in transport of sediments from the shoreface zone into the surf zone. These current-related cross-shore transport components are dominant in the sections near the barriers. Realistic estimates of the net current-related transport rates across the  $-8$  m NAP contour are in the range of 15 to 50  $\text{m}^3/\text{m}/\text{year}$ . Along the Dutch coast the north-going flood currents are dominant. Consequently, south of the barriers the net cross-shore transport component will be directed seaward. North of the barriers the net cross-shore transport will be directed landward.

## **5. Hindcast of observed morphological data 1964–1992**

### *5.1. Approach*

The sand budget model has been used to hindcast the yearly-averaged sand volume changes and shoreline changes as observed in the period 1964–1992 and to forecast the erosion/sedimentation volumes and shoreline changes during the coming 50 years, including the effects of accelerated sea level rise. Subsidence effects may vary between 0.01 and 0.05 m/century (Rijkswaterstaat, 1987) and are taken into account through the value of relative sea level rise used in the Bruun rule. Various scenarios have been considered. The forecast results are not discussed in this paper (see Van Rijn, 1994).

The hindcast study is focussed on the morphological data of the beach and surf zone between the  $+3$  and  $-8$  m NAP contours, because most of the available sand volume data is related to the beach and surf zone. The shoreface zone between the  $-8$  and  $-20$  m NAP contours will also be considered, although reliable data of volume changes are not available for this latter zone.

The main objective of the hindcast study is to match the observed volume changes with the longshore and cross-shore gradients of the computed sand transport rates taking



the nourishment and dredging volumes into account. This approach is expected to give reasonable results for the (uniform) coastal sections outside the influence zones of structures and tidal inlet channels (Marsdiep near Den Helder). The transport rates in the non-uniform coastal sections near the harbour barriers and Marsdiep-channel will be determined by calibration using the available sedimentation and erosion volumes. Details are given by Van Rijn (1994).

### *5.2. Hindcast results for surf zone between +3 and –8 m NAP contours*

Herein, only the overall sand balance is presented. The results for each subsection along the shore are given elsewhere (Van Rijn, 1994). The sand transport rates and volume changes in the approach channel (near IJmuiden) to the harbour of Amsterdam are not considered.

The overall net long-term sand volume change (derived from profile data over the period 1964–1992) in this zone including beach nourishment is  $125,000 \text{ m}^3/\text{year}$  (sedimentation) between Den Helder and Hoek van Holland, see Fig. 12.

The components contributing to this volume change in the surf zone are:

- Net longshore transport near Den Helder and Hoek van Holland.
- Net cross-shore transport across the +3 m and across the –8 m NAP contours.
- Nourishment and dredging volumes.

The net cross-shore transport across the –8 m contour is considered to be the least accurate component of the sediment balance equation and will, therefore, be taken as the closing volume.

Based on model computations, the net longshore transport near Den Helder is estimated to be about  $500,000 \text{ m}^3/\text{year}$  in northward direction (assuming a porosity factor of 0.4). This value is a realistic value because it is in reasonable agreement with long-term transport rates, based on the estimated volume of coastal erosion in the northern section over the last 400 years (Van Rijn, 1994). The net longshore transport near Hoek van Holland is zero due to the presence of the harbour barriers extending far beyond the surf zone (–8 m NAP) and the presence of a deep approach channel (acting as a sand trap for the tide-related transport). Similarly, the net longshore transport rate near IJmuiden is assumed to be zero.

The net onshore wind-blown sand transport across the +3 m NAP contour is estimated to be  $280,000 \text{ m}^3/\text{year}$  between Den Helder and Hoek van Holland, based on results of earlier studies of the sediment budget of the dune zone (Van Vessem and Stolk, 1990). Their estimates are based on long-term records of dune volume changes obtained by means of analysis of stereometric photographing and topographic levelling methods. A yearly-averaged gain of about  $280,000 \text{ m}^3/\text{year}$  in the dune zone landward of the +3 m contour was obtained. It is assumed to be caused by wind-blown sand transport.

Taking into account the above-given net wind-blown and net longshore transport volumes, the available nourishment and dredging volumes, the net cross-shore transport over the –8 m NAP contour is found to be  $490,000 \text{ m}^3/\text{year}$  in onshore direction as the closing volume.

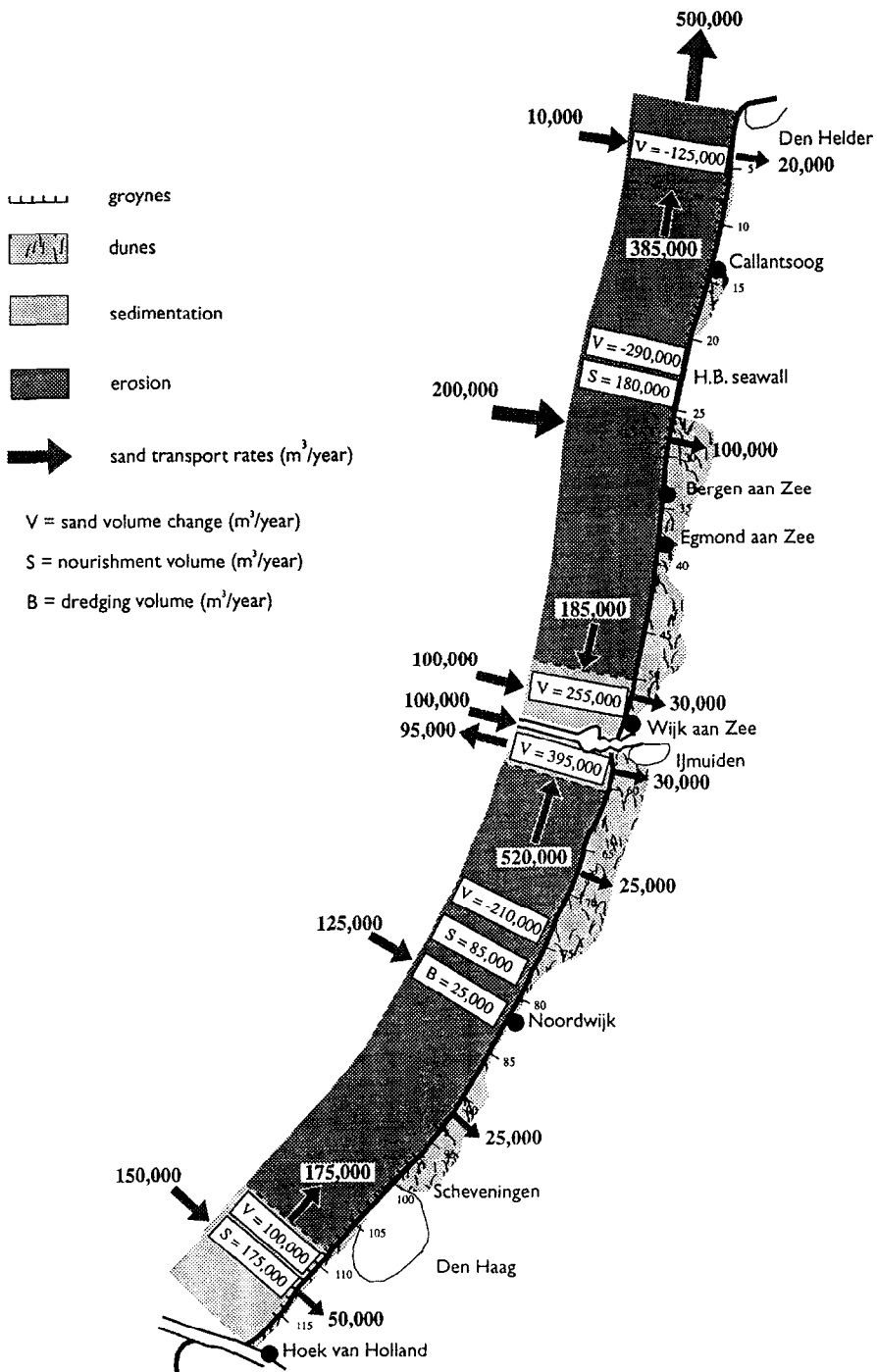


Fig. 12. Sand budget of coastal zone between Den Helder and Hoek van Holland.

The corresponding sand budget is, as follows (see also Fig. 12):

In	: nourishment	= 440,000 m <sup>3</sup> /year
	net onshore transport (− 8 m NAP)	= 490,000 m <sup>3</sup> /year
Out	: net longshore transport (Den Helder)	= 500,000 m <sup>3</sup> /year
	net onshore transport (+ 3 m NAP)	= 280,000 m <sup>3</sup> /year
	dredging Scheveningen harbour	= 25,000 m <sup>3</sup> /year
In–Out	: resulting sedimentation	= 125,000 m <sup>3</sup> /year

The total net onshore transport component of 490,000 m<sup>3</sup>/year over a length of about 120 km represents a value of about 4 m<sup>3</sup>/m/year across the − 8 m depth contour. Most likely, this value will be somewhat lower in the central sections further away from the barriers because the onshore transport component of the sediment exchange taking place in the lee zones directly north of the barriers (over total length of about 15 km) generated by the dominant north-going flood current may be relatively large.

A net onshore transport of about 4 m<sup>3</sup>/m/year may be regarded as realistic given the estimated values of  $0 \pm 10$  m<sup>3</sup>/m/year for the net cross-shore transport at the − 8 m NAP contour.

### 5.3. Hindcast results for the zone between − 8 and − 20 m NAP contours

Reliable sand volume changes are only available in the subzone between the − 8 and − 12 m NAP contours. Based on the measured data, erosion volumes of about 350,000 m<sup>3</sup>/year were obtained for the central sections 8–50 km and 60–108 km.

Dumping of sandy materials was carried out at various locations (seaward of − 15 m NAP):

- 4,200,000 m<sup>3</sup>/year at ‘Loswal Noord’ north-west of Hoek van Holland.
- 700,000 m<sup>3</sup>/year at ‘Loswal Wijk aan Zee’ north-west of IJmuiden.
- 125,000 m<sup>3</sup>/year at ‘Loswal Scheveningen’ north-west of Scheveningen.

An enormous amount of fine sandy material (4.2 million m<sup>3</sup>/year of sediments between 0.1 and 0.2 mm) dredged from the approach channels and harbour basins of Rotterdam is dumped seaward of the − 15 m NAP contour in the section north of the harbour barrier (Loswal Noord).

Dredging (75,000 m<sup>3</sup>/year) was carried out in the central section 60–108 km to obtain sand material for beach nourishment.

The yearly-averaged transport rates at the boundaries were derived by interpolating and averaging of the computed transport rates (see Table 3).

Taking all contributions into account, the sand volume changes were computed yielding an erosion volume of about 700,000 m<sup>3</sup>/year in both central sections, which is equivalent to a layer thickness of 0.5 to 1 mm/year.

## 6. Conclusions and recommendations

The main findings of the present study can be summarized in the following conclusions:

- The net cross-shore sand transport rate at a depth of 20 m in various stations along the coast of Holland is estimated to be in the range of 0 to 15 m<sup>3</sup>/m/year (including pores) in onshore direction (with variation ranges of  $\pm 10$  m<sup>3</sup>/m/year).
- The net cross-shore sand transport rate at a depth of 8 m is estimated to be about zero m<sup>3</sup>/m/year (with variation ranges of  $\pm 10$  m<sup>3</sup>/m/year).
- The net longshore sand transport rate at a depth of 20 m is estimated to be in the range of 25 to 75 m<sup>3</sup>/m/year (including pores) in northward direction (with variation ranges of  $\pm 15$  to 30 m<sup>3</sup>/m/year).
- The net longshore sand transport rate at a depth of 8 m is estimated to be in the range of 65 to 150 m<sup>3</sup>/m/year (including pores) in northward direction (with variation ranges of  $\pm 40$  to 60 m<sup>3</sup>/m/year).
- The maximum net yearly-averaged longshore sand transport rate in the surf zone between the  $-8$  m NAP depth contour and the shoreline is estimated to be about 500,000 m<sup>3</sup>/year (including pores) near Den Helder (loss to tidal inlet Marsdiep).
- The erosion volume in the beach and surf zone ( $3/-8$  m NAP) in the eroding sections between Den Helder and Hoek van Holland is found to be about 730,000 m<sup>3</sup>/year during the period 1964–1992 despite nourishment efforts of about 440,000 m<sup>3</sup>/year.
- The erosion volume in the middle shoreface zone ( $-8/-12$  m NAP) between Den Helder and Hoek van Holland is found to be about 750,000 m<sup>3</sup>/year during the period 1964–1992; all sections except those adjacent to the harbour barriers of IJmuiden show erosion.
- The sedimentation volume in the beach and surf zone ( $3/-8$  m NAP) in the accreting sections between Den Helder and Hoek van Holland is found to be about 855,000 m<sup>3</sup>/year during the period 1964–1992 including nourishment efforts.
- Based on a hindcast study, the total net yearly-averaged onshore sand transport rate due to waves and currents across the  $-8$  m NAP contour between Den Helder and Hoek van Holland is estimated to be about 500,000 m<sup>3</sup>/year including pores.
- The sand budget of the beach and surf zone ( $3/-8$  m NAP) between Den Helder and Hoek van Holland shows a loss (erosion) of 300,000 m<sup>3</sup>/year in the absence of any nourishment and a gain (sedimentation) of about 125,000 m<sup>3</sup>/year including nourishment.

A sediment budget analysis consists of two basic elements: volume changes in each compartment and exchanges of sediment between the compartments, both in cross-shore and in longshore direction. Understanding of the transport pathways requires the application of mathematical models, because synoptic and accurate field data of transport processes generally are not available. The application of transport models yields information of the relative importance of the various transport components and net values and directions. Without modelling results, the observed volume changes can

only be evaluated in terms of gains and losses, but the causes and possible remedial measures can not be overseen. In the present study the overall net transport rates and directions are based on computed yearly-averaged values. Hence, the accuracy of the sand budget results is strongly related to the accuracy of the computed transport rates. However, it has been shown that the observed long-term erosion and deposition volumes in the budget area can be explained in terms of computed net transport rates, the latter being at least within the ranges of the sensitivity computations. This is an encouraging result. Further verification of the model results by direct hydrodynamic and sediment transport observations remains, however, essential.

The primary research task for the coming years is a better understanding of the large-scale sand budget of the surf zone. This requires more accurate information of the total net longshore and cross-shore transport rates at the boundaries of the budget area. Both transport components are now estimated to be about 0.5 million m<sup>3</sup>/year. These values should be verified by performing field experiments in combination with diagnostic mathematical modelling.

## Acknowledgements

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