CHAPTER 148

LARGE-SCALE COASTAL EVOLUTION CONCEPT
The Dutch Coast: Paper No. 9

Marcel J.F. Stive[1], Dano (J.)A., Roelvink[1] and Huib J. de Vriend[1]

Abstract

Using the coastal evolution of the Netherlands in the Holocene up to the present as an example and a test case, a coastal evolution concept is proposed and materialized with which shoreline position changes for different sea level rise scenarios are predicted. The (more generally applicable) model applies to quasi-uniform coastal stretches. It accounts for morphodynamic processes from the shelf to the first dune-row, and integrates over coastal units of approximately 10 km alongshore length. The added value, compared to earlier published concepts or models, lies in the full inclusion of cross-shore and alongshore processes, and in the distinction between a - with respect to sea level rise - instantaneously responding active zone and a noninstantaneously responding central shoreface zone. Relevant differences have been found to exist between coastal cells on the closed and the interrupted coast. An important conclusion is that the cross-shore effective Bruun-effect is only of limited importance. This is especially true in the case of the interrupted coast. Longshore sand transport gradients are very large there. This is mainly related to the sand demand which is placed on coastal stretches adjacent to estuary mouths of those estuaries which tend to follow the sea level rise.

1. Introduction

Since the early 1970's Rijkswaterstaat stimulated Dutch coastal research with the TOW Coastal Research Programme. The Programme was mainly devoted to the study of coastal processes from the coastal engineering perspective. Around 1985 - initiated by coastal erosion management questions in general and by the anticipated increase in relative sea level rise in particular - an interest grew into larger scale, longer term coastal evolution processes. It was realized that the TOW Programme as such (which focussed on coastal evolution processes of typical time- and space-scales of a year and a kilometer) was too limited in scope. In order to gain an understanding of large-scale, long term coastal evolution, a variety of geo-morphological processes with a diversity of time- and length-scales needs to be considered which,

---

1 DELFT HYDRAULICS, P.O. Box 152, 8300 AD Emmeloord, The Netherlands

in turn, calls for the deployment of many specialisms. This approach has been applied in a new research programme, called Kustgenese (Coastal Genesis). In this Programme the fields of geomorphology, hydro- and morphodynamics, physical and historical geography and geology have been linked in order to study and understand coastal evolution at the scales of interest and, subsequently, to arrive at a (physical-mathematical) tool for coastal evolution. This has led to Coastal Genesis Phase I in 1987, reporting on the available knowledge of the physical processes responsible for the reconstructed evolution of the Dutch coastal system (for a summary see Zitman et al, Paper No. 2, these proceedings).

The Kustgenese Programme was more or less interrupted for a period of two year to prepare a Coastal Defence Policy Study for the Dutch Government. This study looks into the near (5 years) and far (several decades) future (Louisse and Kuik, Paper No. 1, these proceedings). A main technical item of the study is the prediction of the coastline development, in which one of the topical aspects is the effect of an accelerating rate of eustatic sea level rise due to the greenhouse effect. The look into the far future more or less forced the researchers (drafted from the Kustgenese team and) responsible for the coastline prediction to materialize their concepts of coastal evolution into a predictive, quantitative tool. This has stimulated a coastal modelling approach which considers larger coastal development scales than sofar has been done in the Netherlands. The approach is described below. First however, a concise sketch of the Dutch coastal system and its Holocene evolution is given, with an identification of the relevant processes and external conditions.

2. Recent Holocene evolution of the Dutch coast

The present Dutch coastal system exists of three typical coastal subsystems, which basically differ with respect to the dominance of particular physical processes (see Figure 1). The complexity of the system is due to the fact that these systems place boundary constraints on one another. In the South of the Netherlands the relics of the Rhine-Meuse Delta are located. Centrally, the closed dune system of the Holland coast safeguards in the most litteral sense the Randstad, which is the commercial center of the Netherlands. In the North the southend of the Wadden region is found, which extends up to Denmark. A sketch of these subsystems and their evolution is as follows.

The central part of the coast of the Netherlands is called the Holland coast. Geologically speaking it is a recent, closed coastal system, since it was only formed during the Holocene some 5000 years ago. It is expected (Beets et al, 1990) that the Pleistocene based lagoon mouth positioned there, closed itself off during periods of a strongly decreasing rate of sea level rise. Its basic contents are a relatively young (1000 to 1600 A.D.) dune system of variable width, covering an older dune system formed approximately 5000 year ago. By and large the coast has retreated over the last 2000 years, near Rotterdam and Den Helder the most and centrally less and less. Now - mostly due to human regulation - it has come to a standstill centrally and it is retreating under control in the North.

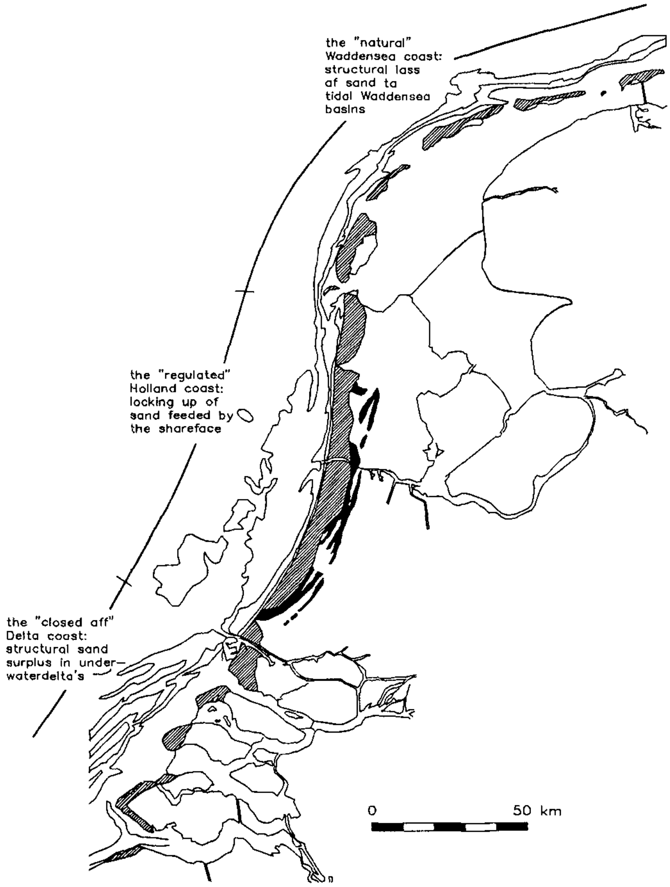

Figure 1 Three subsystems of the coast of the Netherlands

In the South of the Netherlands we find the area which is usually denoted as the Delta-region. It is a region which over the last millennia has experienced considerable variations in opening and closing of the coast, largely related to human agricultural activities. The Delta-works in the region were initiated by the flooding disaster in the region in February 1953. They consist mainly of permanent closure works of the estuary arms, which have the delta now more or less changed into a relic. One of the arms, the Westerscheldt, is still open, being the shipping entrance to Antwerp. The Westerscheldt estuary mouth is a strongly active system of bars and gullies, with important impacts in the form of coastline undulations on the adjacent coastal stretches.

The Dutch Wadden Sea coast consists typically of a system of relatively longstretched barrier islands, with active delta systems. Its present form was more or less reached a thousand years ago, when important breakthroughs were formed towards the former Almere lagoon in the center of Holland thus creating the Zuiderzee. A characteristic feature of the Wadden Sea region is its continuous sedimentation of the tidal flats in order to keep pace with relative sea level rise, and its siltation along the Wadden shores. These processes are responsible for an important influx of sand, which is basically delivered by the adjacent coastal system. This is the cause of a structural retreat of the Wadden island shores.

By studying the evolution of the Dutch coast over the Holocene up to the present, as was done in Coastal Genesis Phase 1, the following aspects were identified as important for the large scale evolution (see also Zitman et al, Paper No. 2, these proceedings):

(1) sediment transport in cross-shore direction is at least as important as longshore transport, where the terminology cross-shore refers to the surfzone and the shoreface: in this respect it is emphasized that what counts is the exchange of sediment between shoreface and surfzone (the diabathic exchange) and the exchange of sediment between longshore coastal stretches both in the surfzone and on the shoreface (the parabathic exchange);
(2) the Subboreal coastal advance (approximately 5000 C14 years BP) and the subsequent formation of the Old Dunes are very likely related to a strong decrease in relative sea level rise (Beets et al, 1990). The physical process responsible for the closing of the coast is similar to that of the behaviour of an underwaterdelta after closure of its tidal basin (Steijn et al, 1989);
(3) the formation of the Young Dunes along the Holland coast some thousand years ago cannot be explained by longshore motions of sediment alone. The external conditions which may have initiated a diabathic exchange may be those related to relative sea level rise fluctuations;
(4) tidal basins or estuary mouths bear important effects on adjacent coastal stretches. For instance the Waddensea tidal basins in dynamic equilibrium keeping pace with sea level rise demand high amounts of sediment (Eysink, Paper No. 8, these proceedings), which are eventually delivered by the adjacent North Holland coast and the barrier island coasts.

3. Coastal evolution concept

The need for a longer term prediction has -more so than before- made us aware of the fact that we have to distinguish between coastal evolution concepts or models on a range of scales. Also, there is a relation between the space scale of a coastal feature and the time scale on which its behaviour is manifest. A schematic relation is given in Fig. 2 for the following three spatial and temporal scales of coastal evolution which we have chosen to distinguish:

(1) Large scale coastal evolution (LSCE) with a morphodynamic length scale of 10 km and a time scale of decades, for which a conceptual model was developed, which is decribed below. The evolution character in this class can vary between mean trend (e.g. geological processes related), fluctuating (e.g. boundary conditions related) and asymptotic (e.g. morphodynamic constraints related) behaviour. This is typically the sort of model with which longer term predictions can be made, needed for a longterm planning of coastal development both due to large scale natural processes, such as an increasing sea level rise or a changing

climate, and to large scale human activities, such as an estuary or tidal basin closing;

(2) Middle scale coastal evolution (MSCE) with a morphodynamic length scale of 1 km and a time scale of years. Important distinctions in this evolution class are cyclic and damping coastline developments. Cyclic developments are for instance due to interactions between geometry and water motions in the low-frequency range, or due to (quasi-)cyclic channel-shoal shift patterns in estuary mouths. Damping developments are mostly due to human interferences like harbour moles, beach nourishments, channeldredging etc. This is typically the sort of model which is used to identify the impact of coastal works on the coastline development;

(3) Small scale coastal evolution (SSCE) with a morphodynamic length scale of 100 m and a time scale of storms to seasons. In this class of development it is the local (on the scale of the wave length) variability of topography and hydraulic conditions which interact to result in short-term, often rhythmic, coastline fluctuations. Generally, these fluctuations seem to have little interaction with the longer-term structural coastline evolution. This is typically the sort of model which is used for the more detailed design of coastal defence works.

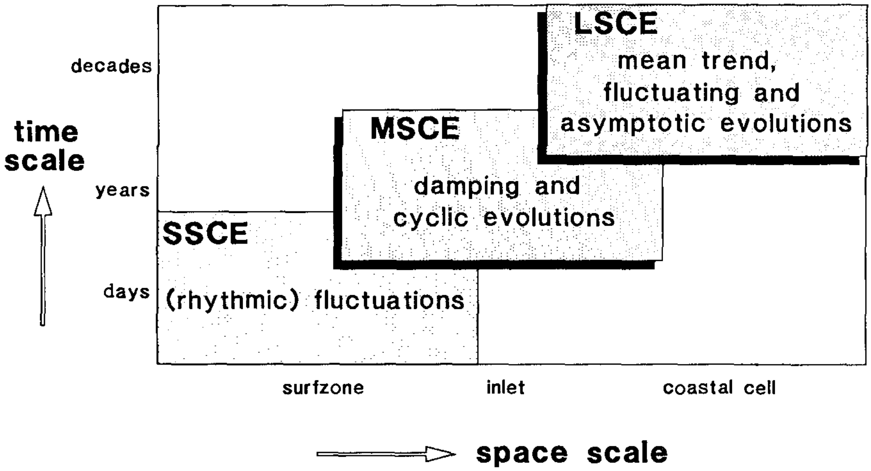

Figure 2 Coastal evolution scales

It is our opinion that the state-of-the-art in deductive modelling (i.e. models deduced from basic physical process knowledge) just about enables us to make predictions of SSCE. While in predictions of MSCE inductive concepts (i.e. modelconcepts inferred from observed or through analogy expected behaviour) commonly are included, this is certainly the case in predictions of LSCE. We share the viewpoint that the two approaches do not exclude one another, on the contrary: "induction is really the inverse process of deduction" (Jevons, 1958). So, in the following formulation of the large scale coastal evolution concept we try to combine our detailed process knowledge with inductive knowledge.

Our concept is in principle derived for the Dutch coast, but is expected to have some generality for sandy dune coasts and barrier island coasts. The concept further applies to (quasi-)uniform coastal stretches or cells of several km´s length, of which it is assumed that the longterm average coastal profile (from the dune to the shelf) and wave, current and sand transport conditions and gradients vary only weakly alongshore. Relatively important interruptions due to river delta´s, harbours, shipping channels, headlands, submarine canyons are either point sources or a principal boundary to the cells. Cross-shore three units are distinguished, i.e. the active zone (the upper shoreface, extending from the first dune row to 8 m waterdepth), the middle and lower shoreface (from 8 m to 20 m water depth) and the inner shelf (below 20 m water depth). The waterdepths mentioned are approximate figures for the Holland coast and depend in general largely on the wave climate. We define the important transition of the active zone to the middle shoreface as the level above which profile changes occur as observable from profile measurements over one average year. Alongshore we distinguish two types of coastal cells, i.e. cells on the closed coast and cells on the interrupted coast. The former category is formed by those coastal stretches which develop unaffected by coastal interruptions due to estuary or tidal basin mouths, under offshore hydro-meteo conditions which are relatively slowly varying alongshore. In contrast, the latter category is strongly affected by these interruptions; a tidal basin in dynamic equilibrium keeping pace with the sea level rise, for instance (see Eysink, Paper No. 8, these proceedings), may be the cause of a structurally retreating coastline in adjacent coastal stretches. It is found that alongshore gradients of net sediment transport, wave-induced as well as tidal, may differ by an order of magnitude between these categories. The variety of physical processes which may act on these two categories of coastal cells is summarized in Figures 3 and 4. Also, an indication is given of the relative frequency and intensity of the processes.

The morphodynamic processes are integrated over the three distinguished units, resulting in transport gradients over their control volume, under adoption of the following inductive concepts:

- The active zone has, averaged over the longer term, a steady profile form relative to the position of the mean sea level. This determines the vertical position of the profile. It is noted that this is basically the assumption behind the Bruun-rule. However, here we only adopt this inductive concept to be valid for the active zone, while it is furthermore only one of the factors determining the horizontal position of the active zone and thus of the shoreline. The horizontal position is principally determined by the sediment balance, which takes account of the vertical motion (sea level rise driven), alongshore gradients (wave and current driven) and cross-shore gradients (transport over the "foot" of the active zone and (winddriven) over the first dune row);
- The middle and lower shoreface is a morphodynamically weakly varying zone, where the gross changes over a decade are such that they can be derived from initial sediment transport considerations (Roelvink and Stive, Paper No. 5, these proceedings). This is typically the zone where at the most seaward boundary the transports are tide-dominated and at the shoreward boundary wave-dominated;

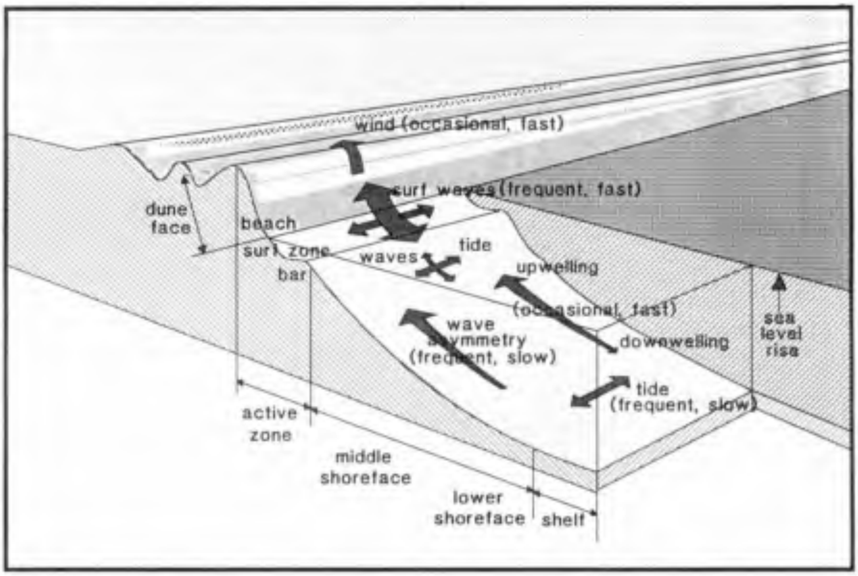

Figure 3 Overview of sediment transport processes in a coastal cell along the closed coast

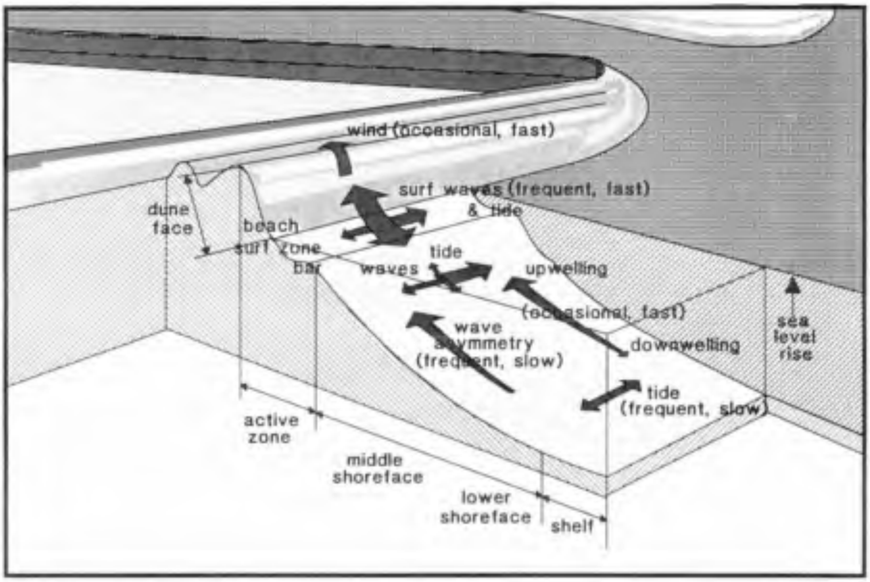

Figure 4 Overview of sediment transport processes in a coastal cell along a coast interrupted by a coastal inlet

- The inner shelf is morphodynamically negligible for the scales under consideration, and is assumed to stay unchanged.

An overview of the general behaviour and possible displacements of the several cross-shore profile zones is given in Table 1.

PROFILE ZONE	BEHAVIOUR AND DISPLACEMENT
Active zone	• Yearly averaged, steady profile form • Upward profile displacement with sea level rise • Shoreward horizontal profile displacement due to: - upward profile displacement with sea level rise - aeolian transport over first dune row - positive alongshore transport gradient (alongshore loss) - downwelling transport on shoreface • Seaward horizontal profile displacement due to: - wave asymmetry and upwelling transport on shoreface - negative alongshore transport gradient (alongshore gain)
Upper shoreface	• Inclining or declining depending on: - horizontal nearshore zone displacement - declining or inclining shoreface
Central and lower shoreface	• Declining (and eroding) in case of: - dominance of wave asymmetry and upwelling transport - negative alongshore transport gradient • Inclining (and accreting) in case of: - dominance of downwelling transport - positive alongshore transport gradient
Inner shelf	• Steady average level with undulations due to: - ripples induced by instantaneous currents and waves - megaripples or ridges induced by large scale circulations

Table 1 Large scale evolution of a coastal stretch; general case

Two of the typical evolutions of the cross-shore units that can occur according to the above overview, are actually found on the Holland coast (see Figure 5). On the central part of the Holland coast alongshore net losses in the active zone are small enough that the net shoreface feeding of the active zone (due to wave asymmetry and density flow driven upwelling) can also compensate for the losses due to vertical profile movement with sea level rise and wind induced transport. This causes the active zone to move seaward and the middle shoreface to flatten. As a result, the transition between the active zone and the middle shoreface steepens. On the northern part of the Holland coast alongshore losses in the active zone are so large that despite compensation due to shoreface feeding appreciable regression occurs. The regression is so strong that the transition between the active zone and the middle shoreface flattens, even though the central shoreface flattens as well. The actual quantitative confirmation of these effects can be found in Knoester (1990), where e.g. long term evolution data (1896-1975) of the -7 m and the -10 m depth contour are presented.

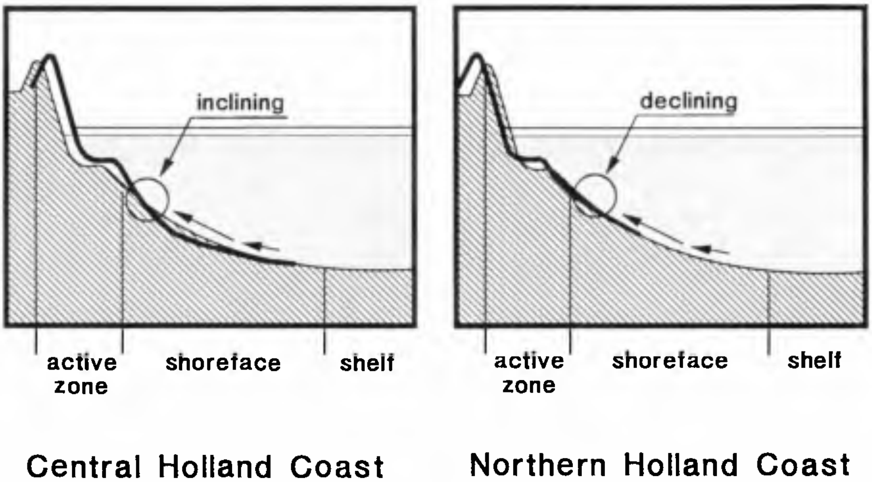

Figure 5 Typical behaviour of the transition between the active zone and the middle shoreface

In accordance with the above concept of LSCE the "present" (i.e. averaged over the last 5 to 10 years) dynamic coastal sediment budget for the whole of the Dutch coastal system has been drawn up (see Figure 6). As explained it is based on a combination of deductive physical process knowledge and inductive concepts, with the latter supported or verified by observations. On the considered time and space scale the dynamics of the model are of a weakly varying character. With hydro-meteo scenarios involving wind, wave, tide, surge level and mean sea level predictions for the next decades as input parameters it was used as a basis for predictions (Louisse and Kuik, Paper No. 1, these proceedings).

Results of the actual coastline predictions are omitted here, since they are not considered to be of interest in this context. One of the most generally interesting results though is the relative importance of the several sources and sinks that contribute to the displacement of the active zone (and therewith of the shoreline). A quantification of the several effects as found for the Holland coast gives the following result:

Effect	Closed coast	interrupted coast
sea level rise direct (Bruun-effect)	15% > 40%	5% > 10%
sea level rise indirect (estuary-pull)	-	55% > 61%
feeding by shoreface	65% > 46%	25% > 20%
dune formation (loss over first dune row)	10% > 7%	5% > 3%
longshore drift (wave-driven)	10% > 7%	10% > 6%

Table 2 Relative importance of absolute contribution to active zone displacement on the Holland coast for a sea level rise of 0.2 m/century > 0.6 m/century (Note: ">" stands for changing to)

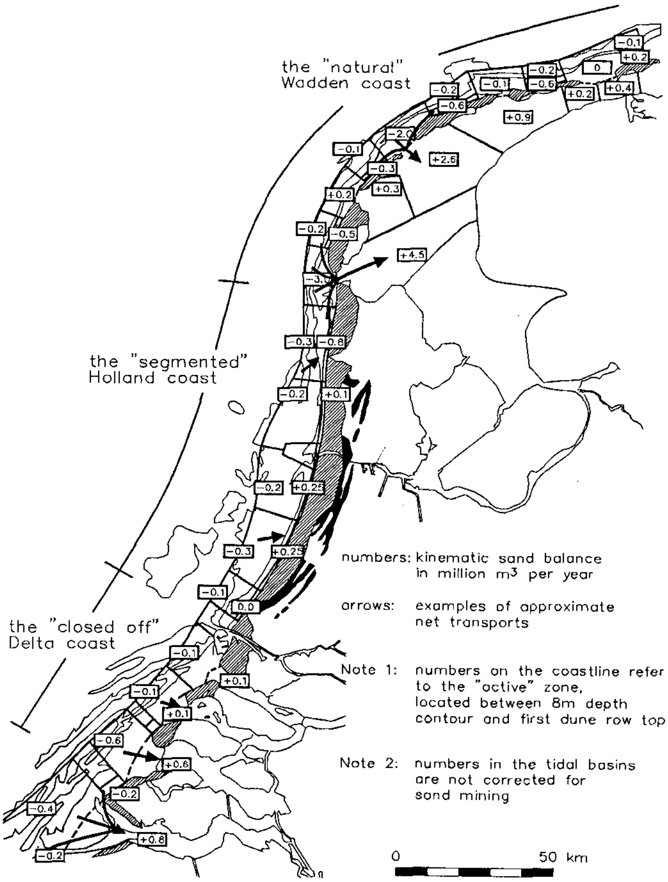

Figure 6 Present sand balance of the Dutch coastal system

From these results, several conclusions may be drawn of which two are mentioned. Firstly, it follows that the Bruun effect is generally of minor importance. Only in the case of a triplication of the present rate of sea level rise on the closed coast sections does it become important. Secondly, wave-driven longshore drift is of minor importance in general. In the following section these conclusions are brought in as contributions to the ongoing discussion of the relevance of sea level rise for coastal erosion.

4. Discussion

The above presented coastal evolution model contains important elements of earlier published work. Without striving for completeness, and certainly not fully aware of all the existing literature in this field, the following categories of references are mentioned. For the "Bruun Rule" aspects reference is made to Bruun (1962), Edelman (1968, 1970) and Dean and Maurmeyer (1983). For the exchange processes between the shoreface and the active zone reference is made to Niedoroda et al (1984) and Wright (1987). For a discussion of coastline recession models and especially the relative importance of cross-shore and longshore effects reference is made to Everts (1985), Pilkey and Davis (1987) and Galvin (1989).

The conceptual model presented here, however, does contain several aspects which make it differ from and more extensive compared to earlier suggested models or concepts in the following sense:
- in cross-shore direction the model includes not only the active zone, which instantaneously follows the relative sea level rise, but also the (central) shoreface which responds non-instantaneously to the relative sea level rise;
- the model takes full account of longshore effects, not only those induced by wave-induced longshore drift variations, but also those induced by coastal inlet systems.

Especially, the quantification of the several effects makes the presented model contribute importantly to the ongoing discussions on the effects of relative sea level rise on coastal recession. From the present application to the Dutch coastal system, it is found that the cross-shore Bruun effect is generally less important than other effects such as shoreface feeding or alongshore effects due to estuary inlets. Since the Dutch coast covers a variety of systems, these conclusions may be of more universal value than the length of the Dutch coast in first instance would seem to justify.

Finally, it needs to be mentioned that the results of these studies enabled the Dutch coastal researchers to identify several research aspects for further study, for instance:
- the morphodynamic behaviour of the shoreface, with specific emphasis on the sediment exchange with the active zone;
- the degree of profile invariance of the active zone relative to mean sea level.

These and other questions are being addressed in the framework of the Coastal Genesis Programme Part II. In this context it is important to point out the following. The resulting coastline development is assumed to be due to a superposition of the abovementioned three scales of evolution. Here, there is a fundamental research question. This concerns the assumption that smaller scale phenomena are not interacting with or iniators of larger scale phenomena. The degree to which this is indeed true will largely determine the degree of predictability of coastal evolution.

References

Beets, D.J., Valk, B. van de, and Stive, M.J.F. (1990).
Holocene evolution of the Holland coast.
Manuscript submitted for publication.

Bruun, P. (1962).
Sea-level rise as a cause of shore erosion.
J. Waterways and Harbors Division, ASCE, Vol. 88, No. WW1, pp. 117-130.

Dean, R.G. and Maurmeyer, E.M. (1983).
Models for beach profile responses.
In Komar, P.D., ed., Handbook of Coastal Processes and Erosion, Chemical Rubber Company Press, pp. 151-166.

Edelman, T. (1968).
Dune erosion during storm conditions.
Proc. 11th Int. Conf. on Coastal Eng., ASCE, New York, pp. 719-723.

Edelman, T. (1970).
Dune erosion during storm conditions.
Proc. 12th Int. Conf. on Coastal Eng., ASCE, New York, pp. 1305-1307.

Everts, C.H. (1985).
Sea level rise effects on shoreline position.
J. Waterway, Port, Coastal and Ocean Eng., ASCE, Vol. 111, No. 6, pp. 985-999.

Eysink, W.D. (1990).
Morphologic response of tidal basins to changes. Paper No. 8.
Proc. 22nd Int. Conf. on Coastal Eng., ASCE, New York.

Galvin, C. (1989).
Beach erosion and beach erosion data.
Paper presented at OAS Seminar on erosion, pollution and recovery of the coastal zone and its resources in Latin America and the Carribean, Buenos Aires.

Jevons, W.S. (1958).
The principles of science. A treatise on logic and the scientific method.
Dover Publications, New York, 786 pp.

Knoester, D. (1990).
Morphology of the Holland coast (in Dutch).
Rijkswaterstaat, Tidal Waters Divison, Report GWAO-90.010.

Louisse, C.J. and Kuik, A.J. (1990).
Coastal defence alternatives in The Netherlands. Paper No. 1.
Proc. 22nd Int. Conf. on Coastal Eng., ASCE, New York.

Niedoroda, A.W., Swift, D.J.P., Hopkins, T.S. and Chen-Mean Ma (1984).
Shoreface morphodynamics on wave-dominated coasts.
Marine Geology, 60, pp. 331-354.

Pilkey, O.H. and Davis, T.W. (1987).
An analysis of coastal recession models: North carolina coast.
Proc. Symposium on Sea-level fluctuation and coastal evolution, Spec. Publ. No. 41, Soc. of Economic Paleontologists and Mineralogists, pp. 59-68.

Roelvink, J.A. and Stive, M.J.F. (1990).
Sand transport on the shoreface of the Holland coast. Paper No. 5.
Proc. 22nd Int. Conf. on Coastal Eng., ASCE, New York.

Steijn, R.C., Louters, T., Spek, A.J.F. v.d. and De Vriend, H.J. (1989).
Numerical model hindcast of the ebb tidal evolution in front of the Deltaworks.
Proc. Int. Conf. Hydr. and Envir. Mod. Coastal, Estuarine and River Waters, Bradford, England.

Wright, L.D. (1987).
Shelf-surfzone coupling: diabathic shoreface transport.
Coastal Sediments, pp. 25-40.

Zitman, T.J., Stive, M.J.F. and Wiersma, J. (1990).
Reconstruction of the historical development of the Dutch coast. Paper No.2.
Proc. 22nd Int. Conf. on Coastal Eng., ASCE, New York.