

Sea-level rise and shore nourishment: a discussion

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ABSTRACT

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The role of sea-level rise in the long-term evolution of the world's coastlines is generally acknowledged in a qualitative sense. Hence it is logical that it is taken into account in the design of shore nourishment schemes. However, because of the large-scale character (in both time and space), it is difficult to quantify its impacts. The state-of-the-art in deductive modelling does not allow for an approach based purely on mathematical physics. Therefore, an alternative approach is proposed, utilizing conceptual models which are made quantitative and validated with the aid of inductive ideas, such as those inferred from observed or through analogy expected behaviour.

An example is a conceptual LSCE model in which sea-level rise is one of the "sinks" acting on the active zone of a coastal cell. This model describes the coastal evolution at the time scale of the sea-level rise. At a somewhat smaller time scale, say the lifetime of an individual nourishment, a profile behaviour model, deductive or inductive and defined for a specific site and a specific class of situations and phenomena, can be the appropriate answer. With the aid of these design tools one does not have to fall back in the too simple and usually false assumption that shoreline retreat before and after a nourishment is the same. This allows us to include the increased effects of an accelerated sea-level rise to predict the longevity of shore nourishment. Thus, the conceptual model approach appears to be promising.

Designing shore nourishment specifically to compensate for the effects of sea-level rise requires a good understanding of the coastal evolution on the longer time and space scales. Because of the uncertainties associated with these large scales this requires flexibility which, fortunately, can be achieved by combining shore nourishment with appropriate monitoring. Thus, shore nourishment is an effective mechanism to prevent shore retreat due to long-term sea-level rise.

1. INTRODUCTION

Sea-level rise is not a new phenomenon. On the contrary it is one of the most apparent manifestations of the current interglacial (last 10,000 year). It is, however, a phenomenon which at present rates manifests itself on a geological time scale, so that until very recently, i.e., upon the "discovery" of the (acceleration of the) greenhouse effect, limited attention was given to it in

the context of coastal engineering. Worldwide (or eustatic) sea-level rise is now projected to rise between 0.31 m and 1.10 m by the year 2100, with the most likely scenario being a rise of 0.66 m (IPCC, 1990). This compares with an estimated eustatic rise of between 0.1 m to 0.2 m in the last century. Thus, sea-level rise is of growing interest, also in the field of "soft" engineering (e.g., Weggel, 1986; Leatherman and Gaunt, 1989; Dean, 1991). It is for this reason that a broad retrospection of shore nourishment in general and beach nourishment in particular cannot be made without giving some attention to the role of relative sea-level rise. It should be noted that existing nourishments are already counteracting the effects of contemporary sea-level rise (cf. Bird, 1985), although these effects are small compared to those expected in the next century.

We prefer to use the term *shore nourishment* rather than *beach nourishment*. This is in acknowledgement of the fact that an important part of the sand used to maintain a shoreline resides beneath low water, a fact which is not always fully appreciated. Thus, in order to counteract shoreline recession a nourishment should be designed to nourish the complete "active profile", including the subaqueous portion. Because of the activity of this profile — of which the seaward boundary is discussed in the paper — a local nourishment will in the longer term contribute to the whole of the active profile. This implies that one may either feed the beach or the nearshore, the longer term effect is the same, i.e., to feed the shore. In this context it should be noted that feeding the nearshore rather than the beach will result in a positive post-nourishment profile adjustment of the subaerial beach, in fact the subaerial beach may accrete and probably more importantly the cost of sand delivery is significantly reduced (e.g., Bruun, 1990).

This discussion concentrates on two aspects:

- the implications of an accelerated sea-level rise for the design of shore nourishment measures;
- shore nourishment as a measure to counteract the erosive effects of relative sea-level rise.

This discussion limits itself to sea-level rise effects in the behaviour of sandy coasts, barrier islands and bay systems. The effects of sea-level rise on the behaviour of estuaries and tidal basins are only discussed in a limited and indirect manner.

2. ROLE OF SEA-LEVEL RISE IN HOLOCENE COASTAL EVOLUTION

Bird's (1985) worldwide inventory indicates that approximately 70% of the world's sandy coastlines have shown retreat over the past few decades; less than 10% have shown net progradation, while the remaining 20 to 25% have remained approximately stable. While shore retreat on a geological time scale is undoubtedly connected with eustatic sea-level rise, it is more or less

generally assumed that even the relatively small rate of sea-level rise of the last century is driving this worldwide tendency of shore retreat (cf. Vellinga and Leatherman, 1989). It must be borne in mind though that both the sea-level rise relative to the land and its effects are rather site specific. Besides the eustatic sea-level rise, local contributions can for instance be due to glacial rebound, subsidence, compaction, and changes in ocean circulation. Additional (and often dominating) causes of erosion can be due to longshore or cross-shore losses, which in their turn can be due to a variety of causes such as the physical geometry (e.g., headlands, submarine canyons), hydraulic boundary conditions (e.g., related to waves, tides, wind) or human interference (e.g., harbours, erosion-mitigating structures). At a high level of aggregation these latter losses can be summarized to be represented by the terminology "sediment availability". The following three literature references illustrate and confirm this description.

With respect to the behaviour of barriers, Curray (1964) summarized the effects of both relative sea-level changes and sediment availability on the displacement of the coastline in a qualitative way as follows. In the case of absence of a net source or a net sink for sediment regression occurs in the case of a falling sea-level or emergence and transgression occurs in the case of a rising sea-level or subsidence. With a net source of sediment the transition between regression and transgression shifts towards low levels of rising relative sea-level, and alternatively with a net sink of sediment towards low levels of falling relative sea-level.

Also, Swift (1976) adopts this basic "model" and adds to it by giving valuable specifications of the shifts mentioned above. He relates the presence of either a sink or a source for the upper shoreface to either longshore or cross-shore processes. In the longshore process sediment discharge by rivers is one of the more important factors, while for the cross-shore process the relative importance of storm and fair weather conditions is described.

For a larger variety of sedimentary environments the reasonably well-documented Holocene coastal evolution of the Netherlands (cf. Zitman et al., 1990; or Beets et al., 1990) gives a qualitative picture of the role of sea-level rise (Van der Valk, 1990), see Table 1.

Thus, the influence of relative sea-level rise is generally acknowledged, but the more precise quantification is a matter of discussion. In this context it is noteworthy that there is a large amount of literature devoted to the description and subsequent discussion of concepts to quantify the effect. One of the most well known concepts is that of Bruun (1954, 1962), which basically states that the shore profile is vertically invariant in space and time relative to mean sea-level. If no sediment sinks and sources are introduced this determines the profile shift in a simple way. Valuable extensions of the concept and discussions on the validity of the concept have been made by Dean (see Dean, 1990, for a review). Here, it will be argued and discussed in more detail

TABLE 1

Effects of sea-level rise on sedimentary environments in the western Netherlands (adapted from Van der Valk, 1990)

area	rate of sea-level rise	
	fast	slow
river	vertical architecture	horizontal architecture
peat-bog	drowning	spreading
tidal basin/estuary	drowning	surface stabilization
barrier	retreat	depending on sediment availability: nil: transgressive med: static high: regressive

furtheron that the Bruun concept is not a valid approach in general. In this context it is also important to note that time is required for equilibrium to be established. Often this point is not considered by coastal scientists. Hands (1983) noted that (a) the Bruun rule requires a lag if it is to predict shoreline behaviour and (b) the depth of the active profile increases as one considers longer time scales. Both of these conclusions are of relevance when considering shore nourishment in relation to sea-level rise.

Another important point that should be stressed here is that the time scale on which present sea-level rise influences coastal evolution in general and coastal erosion in particular, is relatively large. This is not generally true for coastal response in cases of larger rates of sea-level rise, since rapid sea-level rise induces rapid coastal response in general. Present coastal evolution on smaller time and space scales is dominated by other causes (Stive et al., 1990). In summary, 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. 1 for the following three spatial and temporal scales of coastal evolution:

(1) Large-scale coastal evolution (LSCE) with a morphodynamic length scale of 10 km and a time scale of decades. 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. Quantitative models in this class are typically the sort with which longer-term predictions can be made. They are needed for long-term 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 develop-

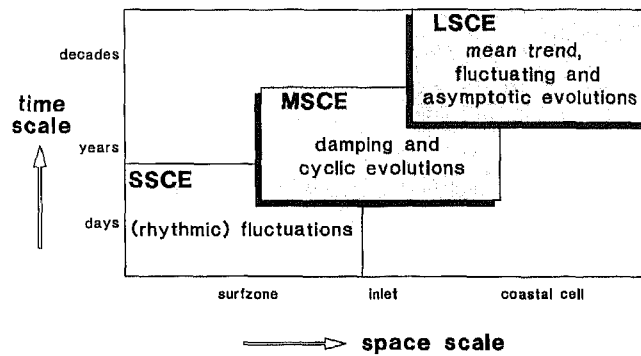


Fig. 1. Scales of coastal evolution (after Stive et al., 1990).

ments 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, channel dredging etc. Quantitative models in this class are typically the sort 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. Quantitative models in this class are typically the sort which is used for the more detailed design of coastal defence works.

So, the important points are that the present and the projected sea-level rise manifests itself in LSCE, while shore nourishment on today's scales does so in MSCE. Nourishment on large space scales (> 10 km length) is becoming more common, but the design life of individual nourishments will probably remain medium scale (≤ 10 year) to maintain the most favourable cost-benefit ratio. The importance of this statement is that it is only useful or appropriate to judge sea-level rise effects in the context of shore nourishment from the large-scale viewpoint. This implies that sea-level rise is considered as a mean background effect, which in general will show little dynamic interaction with a shore nourishment measure. In one way this makes the inclusion of the effect simple, but the problem that arises is that we lack purely deductive models to predict coastal evolution on the larger scales. Both these aspects will be discussed in the following sections.

3. MODELLING COASTAL EVOLUTION

State-of-the-art

As stated by Stive et al. (1990), the state-of-the-art in deductive modelling (i.e., models deduced from basic physical process knowledge) just about enables one to make predictions of SSCE. While in predictions of MSCE inductive concepts (i.e., model concepts inferred from observed or through analogy expected behaviour) commonly are included, this is certainly the case in predictions of LSCE. So, in predictive modelling of MSCE and certainly of LSCE detailed process knowledge should be combined with inductive knowledge. This generally implies that a quantitative model which is used for the prediction of the effects of sea-level rise needs to be based upon, adjusted to and validated for a specific site or situation.

These conclusions indicate that quantitative models for the prediction of sea-level rise effects on coastal evolution and to a somewhat lesser degree also for the prediction of a shore nourishment measure can not be considered unconditionally reliable. This fact has led some coastal researchers to the conclusion that quantitative modelling on the MSCE scale (let alone the LSCE scale) is out of the question (cf. Pilkey, 1990). We do not share this viewpoint (see also De Vriend, 1991). On the contrary, if one combines general small-scale knowledge with local, observed and through analogy estimated behaviour, a conceptual evolution model of a coastal stretch or cell can be formulated. This enables the qualitative evaluation of measures and effects. If long-term data are available, the evolution model could be made quantitative by using the data to calibrate and validate the model. If the calibration and validation period of the model is an order of magnitude larger than the prediction period of the model, reliable prediction results may be expected. A lack of good monitoring of beach nourishment performance helps to sustain the disbelief in a quantitative approach. The authors would strongly recommend that all shore nourishment projects be regularly monitored for their life, preferably simultaneously with an unnourished, similar nearby coastal section.

There are few examples of LSCE prediction modelling efforts, largely because of the fact that this type of a model crucially depends on the availability of long-term coastal evolution data. An — as yet unpublished — example is that of Cowell and Roy (1988; pers. commun., 1991). Another example is that formulated in the framework of the National Coastal Defence Study of the Netherlands (Stive et al., 1990). Because of the explicit attention for the effects of sea-level rise on LSCE and because of the expected wider generality of the model for sandy dune coasts and barrier island coasts, we will give a short summary of this conceptual model. Besides, we will outline a tentative

profile behaviour model, which we will use for illustration purposes in the next sections.

Conceptual quasi-equilibrium model

The conceptual model applies to (quasi-)uniform coastal stretches or cells of several km's length, of which it is assumed that the long-term 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 water depth), the *middle and lower shoreface* (from 8 to 20 m water depth) and the *inner shelf* (below 20 m water depth).

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. 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 (wind driven) 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 (cf. Roelvink and Stive, 1990). This is typically the zone where at the most seaward boundary the transports are tide dominated and at the shoreward boundary wave dominated.

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

It is noted that the first concept is basically the assumption behind the Bruun rule. However, here this inductive idea is only adopted 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 waterdepths mentioned are approximate figures (relative to Mean Sea Level) for the Holland coast and depend in general largely on the wave climate. The important transition of the active zone to the middle shoreface is defined as the depth above which profile changes occur as observable from profile measurements over one average year. In the absence of profile data the depth definition d_1 of Hallermeier (1981) will provide a good first estimate of the transition depth. The depth of the transition from the shore face

to the inner shelf is a little more arbitrary, given the gradational nature of the transition. It is deeper than the depth definition d_i of Hallermeier (1981) (which is only about 15 m on the Dutch coast) because of the long time scales associated with its definition.

Thus, this conceptual model contains the spatial and temporal scales of the shore system. It is seen that sea-level rise is only one of several factors which determine the shoreline position. More quantitative directions of how to incorporate sea-level rise and the other effects in the design of a beach nourishment measure are addressed in the next section.

Profile behaviour model

Profile behaviour modelling lies somewhere between this inductive quasi-equilibrium model and deductive fully dynamic MSCE models. The concept can be explained as follows.

Suppose we wish to describe the long-term profile evolution of a certain coast in a certain type of situation (e.g., rising sea-level plus nourishment scheme), and we have a sufficiently long record of the medium-term profile behaviour in such a situation, observed or simulated with a well-validated MSCE model. Then, we can filter out the shorter time scales and map the remaining long-term behaviour onto a simple parametric model, making use of whatever data assimilation techniques we deem necessary. The result is a profile behaviour model for a particular stretch of coast and a particular type of situation, which can be used for design and policy-making purposes.

One class of behaviour models, proposed by De Vriend and Roelvink (1988) and actually very similar to the n -line concept (Perlin and Dean, 1983; De Vroeg et al., 1988), is based upon the diffusion-type equation:

$$\partial X/\partial t - \partial/\partial z [D(z)\partial X/\partial z] = S(z,t) \quad (1a)$$

in which $X(z,t)$ is the cross-shore position of the profile, with respect to the position of the equilibrium profile; z is the vertical coordinate, t the time, $D(z)$ the diffusion coefficient (to be calibrated), and $S(z,t)$ the source term.

The boundary condition at the top of the profile reads:

$$\partial X/\partial z = 0 \quad \text{at } z = z_{\max} \quad (1b)$$

which allows for the upper part of the profile to maintain its shape.

The vertical variation of the diffusion coefficient allows us to represent two observed phenomena: the variation of the morphological time scale with the vertical position (cf. De Vroeg et al., 1988) and the asymmetry in the long-term residual sand displacement across the profile. The calibration of this parameter is the key element of the model definition: all information, on site-specific aspects as well as on shorter-term dynamics, is stored in it.

The boundary condition at the lower end of the profile is still a point of concern. Here we will use:

$$X=0 \quad \text{at } z=z_{\min} \quad (1c)$$

which complies with the assumption that the inner shelf remains morphologically inactive at the time scales under considerations.

The numerical solution of this model is fairly standard and easy to implement. Sea-level rise is not included via the source term, but via a simple coordinate transformation (the z -grid moves along with the sea-level, except for the lowest point, and the increasing gap is filled with additional grid points).

The choice of X as a dependent variable eliminates the possibility to deal with ridges and runnels, but as long as these are situated in the active zone, they are MSCE features, which are not found back in the filtered profile evolution. Hence the concept has the potential to cover a rather wide and practically relevant range of sites and situations. Taking the equilibrium profile as a reference implies (1) that this profile has to be defined, and (2) that this profile, rather than $X(z,t)$, includes the effects of "autonomous" cross-shore transport mechanisms, which are invariant to profile changes.

This model, though hardly beyond the stage of an idea, seems potentially able to describe the long-term dynamic response of seaward facing profiles relative to sea-level rise and shore nourishment (De Vriend and Roelvink, 1988). In any case, it seems good enough to provide some illustrations to the present argument.

MSCE models

Many examples of reasonably successful predictive modelling of MSCE are known in the context of harbour moles related updrift and downdrift accretion and erosion. The so-named one-line modelling approach based upon the Pelnard-Considère theory is often applicable in this situation. In general, we expect that the one-line theory — including its features like sinks and sources inclusion — is a powerful tool in hindcasting and predicting coastal evolution on the MSCE scale. This logically should include shore nourishment as well, which indeed is in agreement with the recommendation of the Manual on Beach Nourishment (CUR et al., 1987). However, a strong disbelief in prediction of the behaviour of shore nourishment schemes is expressed by an evaluation of U.S. nourishment schemes (Leonard et al., 1990). Amongst others based on this study Pilkey (1990) concludes that all but one of the nourished beaches of this list "have eroded much faster ($1\frac{1}{2}$ times to 12 times) than their natural counterparts. *Not surprisingly, storms seem to be the major factor determining beach longevity on the East Coast.*" However, careful reading of Leonard et al. (1990) demonstrates that much of the data is at best semi-quantitative and only the sub-aerial portion of the shore nourishment is

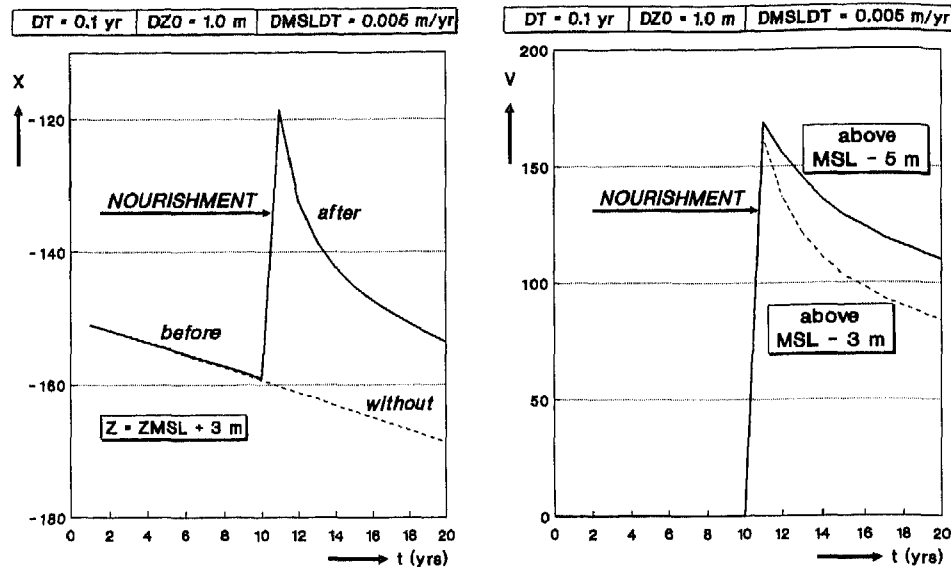


Fig. 2. Time evolution of the dune foot position (left) and the nourished volume in the active zone (right) before and after a beach nourishment.

considered. Where precise numbers are quoted their validity has been questioned (Houston, 1990). Thus one could see Leonard et al.'s conclusions as indicative of the poor monitoring of U.S. nourishment schemes, and we would further claim that Pilkey's (1990) conclusion is based on the — in some sense naïve — assumption that the initial shoreline retreat after a beach nourishment is an indication of the true sediment shortage in the relevant section.

In order to illustrate this, Fig. 2 shows some results from the parametric behaviour model, for a beach nourishment on a coast subject to sea-level rise. The diffusion coefficient, derived from an MSCE model of the Dutch coast (De Vriend and Roelvink, 1988), ranges from $5 \text{ m}^2/\text{s}$ in the upper part of the profile to virtually zero at the lower end. Even this simple model predicts a higher rate of shoreline (dune foot) retreat after the beach nourishment than before. Note that also the total volume of nourished sand that is retained in the active zone, V , decreases with time, though at a much lower rate. The missing sand is transported from the active zone to the middle and lower shoreface, physically and also “mathematically”, as we assume the boundaries between the zones to follow the rising sea level.

4. THE ROLE OF SEA-LEVEL RISE IN THE DESIGN OF SHORE NOURISHMENT

From the above discussion it follows that the assumption that shoreline retreat before and after a nourishment is the same, is too simple. One of th

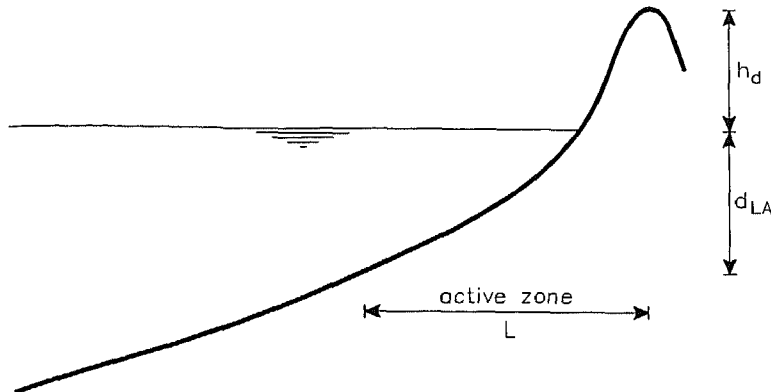


Fig. 3. The active profile.

most obvious reasons for this is that a nourishment wherever it is placed (as long as it is in the active zone) ultimately contributes and thus spreads over the whole of the active profile (cf. the equilibrium profile model of Dean (1983, 1991) predicts similar behaviour assuming the grain sizes of the native and borrow material are the same). The authors support the approach which is standard in the Netherlands and which assumes that the net losses from the "active" coastal region before and after are the same (Pilkey, 1990, calls this the Dutch approach). If we now first disregard any finite-length effects of a nourishment and also long term response of the shoreface below the active profile, we may determine the required nourishment volume from a LSCE viewpoint as follows.

In line with the earlier description of the active profile we assume that this active profile is of fixed shape and vertically steady relative to Mean Sea Level (see Fig. 3 for definitions). Its effective height includes the height of the dune face. The volume change per unit shore length and per unit time, V , may now be derived to be given by:

$$V = c_p(d_{LA} + h_d) \approx \partial MSL / \partial t L - (q_{x|sea} - q_{x|dune}) - \partial Q_y / \partial y - s \quad (2)$$

where:

- c_p = the displacement rate of the active profile and shoreline,
- d_{LA} = the depth of the active profile,
- h_d = the height of the dune face,
- $\partial MSL / \partial t$ = the rate of change of mean sea level,
- L = the horizontal extent of the active profile,
- $q_{x|sea}$ = the net cross-shore sediment transport on the seaward boundary,
- $q_{x|dune}$ = the net cross-shore sediment transport on the dune top,
- $\partial Q_y / \partial y$ = the gradient of cross-shore integrated alongshore transport,
- s = a source term, e.g., due to shore nourishment.

The minimum required nourishment volume s_{\min} should neutralize the other terms, so that V becomes zero. In general, with the small relative rates of sea-level rise of the last centuries (e.g., 0.2 m/century in The Netherlands), the direct effect of sea-level rise as expressed in the first term (the so-called Bruun effect) is small — but not negligible — compared to the other terms on an eroding coast. A fourfold increase of this rate (as would occur by the year 2070 in the most likely “Business as Usual” Scenario of IPCC, 1990) would have a noticeable effect on erosion rates. It is important to note that the direct effect of sea-level rise can be small relative to indirect effects related to, e.g., tidal basin response, which are represented in the third term (cf. Stive et al., 1990). This term also contains the usually larger effects which are the more general causes of shoreline erosion, i.e., those induced by alongshore variations of the alongshore sediment transport due to coastal structures or shoreline curvature. Finally, the second term would include possible long-term losses from the active zone to the middle and lower shoreface and/or to the hinterland. Alternatively, the reverse situation, i.e., gains to the active zone, is possible as well.

The actual required nourishment volume should be based on s_{\min} and augmented or reduced by taking account of the following other effects:

- (i) alongshore spreading of a nourishment which occurs due to the finite length of a nourishment (cf. Dean, 1983; CUR, 1987); and
- (ii) required over- or underfill depending on whether the borrow sediment is finer or coarser than the native sediment (cf. US Army Corps of Engineers, 1984), or alternatively correcting for differences in the borrow and native grain sizes using the equilibrium profile concept (Dean, 1983, 1991).

5. SHORE NOURISHMENT TO COUNTERACT THE EFFECT OF SEA-LEVEL RISE

At the long time scale of interest, shore nourishment must be a repetitive process if the shoreline is to be maintained in its original position. As such, this section focuses upon designs comprising a number of nourishment cycles, a design concept which is still in its infancy in practice.

Designing shore nourishment schemes to counteract the effects of sea-level rise implies that longer time scales will have to be considered than is commonly done for present nourishment schemes. Therefore, processes which existing schemes ignore may become significant. For instance — what depth of closure is appropriate? In the foregoing section the considered shore region is that of the active zone, implying that the closure depth is at the foot of the active zone. This may be a reasonable assumption when considering medium term schemes, but some sand must also be provided to the middle and lower shoreface considering the longer time scales which are involved in the context of sea-level rise (see Fig. 4). A conservative assumption would be to provide enough sand to raise this entire zone, with the active zone, in pace with the

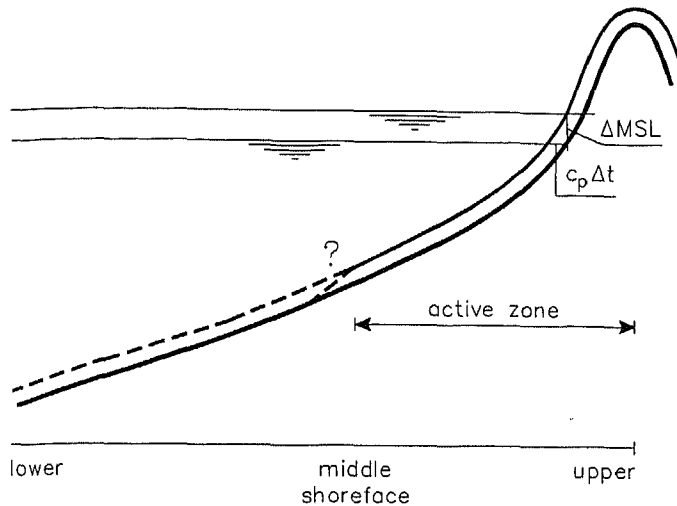


Fig. 4. The shoreface profile.

rate of sea-level rise. However, as described in section 3 the response of the middle and lower shoreface differs from that of the active zone. There are gradients of change across this zone which are only secondarily influenced by sea-level rise. Clearly, this undermines the necessity to raise the entire zone along with the sea-level. Besides, the inherent morphological time scale of the lower shoreface is so large (Van Alphen et al., 1990), that the profile is not likely to ever approach its equilibrium state there. So, even if the equilibrium profile follows the sea-level, this provides little information on the actual profile.

On the other hand the time scales are not so large, that the evolution of the active zone can be predicted without taking the lower and the middle shoreface into account.

This is readily illustrated by the example shown in Fig. 5, which was again produced with the parametric behaviour model. It concerns two repetitive nourishment scenarios, on a ten year constant volume nourishment cycle: (1) a beach nourishment between $\text{MSL} + 3 \text{ m}$, and (2) a shoreface nourishment between $\text{MSL} - 5 \text{ m}$ and $\text{MSL} - 8 \text{ m}$. The nourished quantities are chosen such, that the shoreline position is just about maintained. For the given parameter setting this means, that the volume of shoreface nourishments has to be some 25% higher than for the beach nourishments.

Both schemes may seem satisfactory, but upon closer inspection it appears that, in the beach nourishment case, the middle and lower shoreface cannot keep pace with the active zone and build up an ever increasing sand deficit. Consequently:

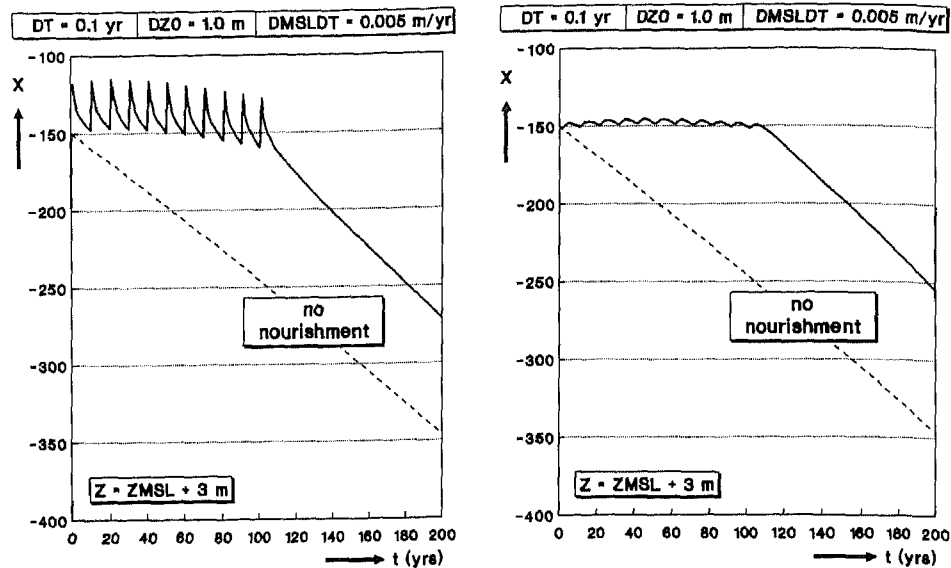


Fig. 5. Effect of repetitive beach (left) and shoreface (right) nourishment schemes of finite duration.

- (1) the efficiency of the scheme decreases with time, because an ever larger part of beach nourishment is lost to be shoreface; and
- (2) the longer the scheme is maintained, the faster the rate of enhanced shoreline retreat when it ceases.

Since the shoreface nourishments supply more sand to the middle and lower shoreface, the sand deficit remains smaller there and the above problems are less severe.

This case also illustrates, that we have to be aware of the response of the whole coastal profile when designing a long-term nourishment scheme. As long as this is not the case, it is recommended to use the inherent flexibility of "soft" engineering, by making the scheme adjustable and by including a monitoring programme into it. Especially where the middle and lower shoreface are concerned, this monitoring is not a trivial task, because the phenomena of interest (e.g., sand deficit) can easily lie within the error band of the observations. A profile behaviour model like the one presented herein can be of use to specify what parameters of the profile we need to monitor to quantify a possible sand deficit.

6. SUMMARY AND CONCLUSION

Relative sea-level rise is a basic, natural background process in coastal evolution. Besides eustatic sea-level rise regional effects can be quite important.

The qualitative role of sea-level rise for the evolution of the world's coastlines is generally acknowledged. It is thus logical to conclude that sea-level rise needs to be accounted for in designing shore nourishment schemes, particularly as this factor is likely to be more significant in the next century.

Very closely connected with the large-scale character of sea-level rise is the problem of quantification of the sea-level rise impacts. An important problem in this context is that the state-of-the-art in deductive modelling does not allow for an approach based on purely mathematical physics. It is suggested that it should be well possible to develop conceptual models which are made quantitative and validated with the aid of inductive tools, such as those inferred from observed or through analogy expected behaviour.

This may lead to a Large-Scale Coastal Evolution (LSCE) concept in which sea-level rise is one of the "sinks" acting on the active zone of a coastal cell, both reflected in a term which takes account of the direct effect (known as the Bruun effect) and one which takes account of the indirect effect (e.g., related to tidal basin response). These conceptual models are supposed to describe the coastal evolution at the time scale of the sea-level rise. At a somewhat smaller time scale, say the lifetime of an individual nourishment, the quasi-equilibrium approach is not sufficient. There a profile behaviour model, deductive or inductive and defined for a specific site and a specific class of situations and phenomena, can be the appropriate answer. With the aid of these design tools one does not have to fall back on the too simple and usually false assumption that shoreline retreat before and after a nourishment is the same. So, once we have a quantification of the net losses from the active zone for the present sea-level rise effects, we may include the increased effects for an accelerated sea-level rise to predict the longevity of shore nourishment. Determination of the direct and indirect effects of sea-level rise is vital to allow accurate prediction of future shoreline recession and estimates of the shore fill quantities required to counteract such changes.

Designing shore nourishment specifically to compensate for the effects of sea-level rise implies the consideration of longer time and space scales than is presently the case. The uncertainties this produces require flexibility which can be achieved by combining shore nourishment with appropriate monitoring. Thus, shore nourishment provides an effective solution to counteract shoreline retreat caused by long-term sea-level rise.

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