CHAPTER 147

MORPHOLOGIC RESPONSE OF TIDAL BASINS TO CHANGES

The Dutch Coast: Paper No. 8

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Abstract

This paper is part of a series of papers on a study of the Dutch Coast and describes the method used to determine the sand losses of the North Sea coast to the tidal basins of the Dutch Wadden Sea in the North and the estuaries in the South of The Netherlands.
The sand losses can be caused by sea level rise, sand mining, closure works, natural land accretion in the basins or bottom subsidence due to gas extraction. The results of this study were relevant boundary conditions for the study on the behaviour of the North Sea coast in the vicinity of the tidal inlets (paper No. 9 of the Dutch Coast of Stive, Roelvink and De Vriend of these proceedings).

1. Introduction

In the scope of the study on the consequences of sea level rise on the North sea coast of The Netherlands, a practical method has been developed to assess the morphologic response of tidal basins to natural or man-made changes in such a system in terms of sand volumes. This was necessary to quantify the interaction between the North Sea coast and the tidal basins of the Dutch Wadden Sea in the North and the estuaries in the South (Fig. 1).

The hydraulic conditions in tidal basins are important as dominant energy sources causing sediment transports, erosion and sedimentation, and sorting of sediment to size, mineral density and rollability. Together these phenomena form the basis of a very complex geomorphodynamic system in which also flocculation of silt and clay particles and coagulation of those particles by shell fish and diatoms play an important role.
Today it is not possible yet to simulate the above complex processes sufficiently accurate in a numerical model. However, in spite of the complex and dynamic character of these areas, some systems can be recognized in nature if we look in a broad way neglecting details such as migration of channels and shoals. It appears that we can express certain characteristic quantities in empirical relationships which are useful tools for engineers.

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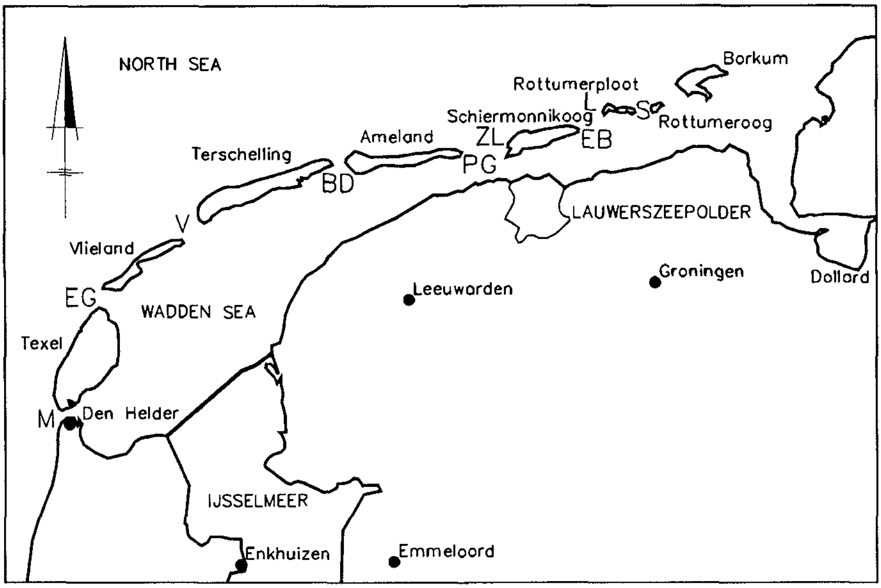


Figure 1a The Dutch Wadden Sea

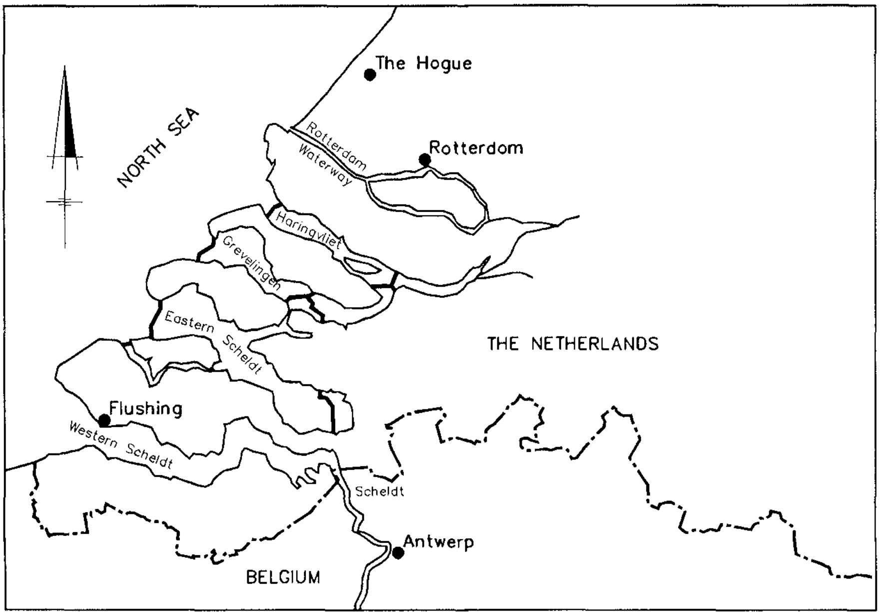


Figure 1b The Dutch Delta Area

2. Morphological relationships

A well known relationship from literature is the relation between the flow area of a tidal inlet and the tidal prism passing that inlet (e.g. O'Brien, 1969 and Bruun and Gerritsen, 1960) or related characteristic quantities such as the mean tidal flow velocity (e.g. Kreeke and Haring, 1979), maximum tidal flow velocity (e.g. De Jong and Gerritsen, 1984) or related shear stress velocities (e.g. Gerritsen and De Jong, 1985).

From data of one tidal channel in the Dutch Wadden Sea presented by De Glopper (1967) it appeared that also along a channel the flow area was related to the tidal volume passing the local cross section. Lateron this was confirmed by extensive investigations of Gerritsen and De Jong (1984, 1985) for various tidal channels in the Dutch Wadden Sea and in the estuaries in the Dutch Delta area in the South.

All results show that a rather good description is presented by the relationship:

$$A_{MSL} = c_A \; V \tag{1}$$

where:
A_{MSL} = flow area below MSL
c_A = empirical coefficient
V = characteristic tidal volume

Also some relation seems to exist between the mean depth of a tidal channel and the tidal volume (Fig. 2). This relationship is less firm and may show deviations due to the occurrence of hard bed layers or man-made bank protections.

Equation (1) does suspect that integration along a channel should result in a relationship for the volume of the entire channel system of a tidal basin. Plotting data of the channel volumes of the different tidal basins of the Dutch Wadden Sea versus their tidal volumes showed such a relation (Fig. 3). A similar relationship was found by plotting channel volumes of the Grevelingen and of various sections of the Eastern Scheldt versus the related tidal volumes (Fig. 4). Data of the Western Scheldt at first glance showed a different picture (Fig. 5). However, the deviation from that of the relationship for the other basins may be explained by the deepening of the River Scheldt and the Western Scheldt in the back of the estuary for a proper access to the Port of Antwerp. In general, the following relationship seems to be valid for the channel volume of a tidal basin or estuary (with minor upland discharge):

$$V_C = c_C \; V^{3/2} \tag{2}$$

where:
V_C = channel volume below MSL
c_C = empirical coefficient

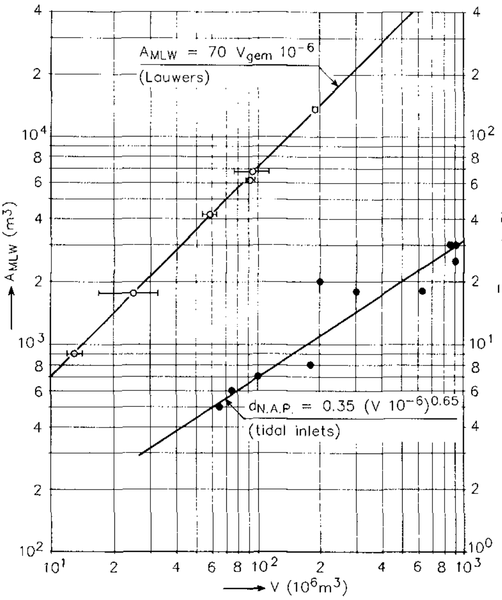


Figure 2 Mean tidal volume versus channel profile and depth

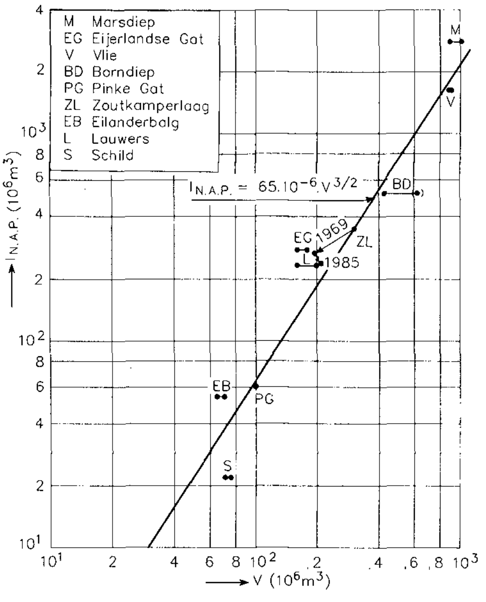


Figure 3 Channel volume versus mean tidal volume tidal basins of the Wadden Sea

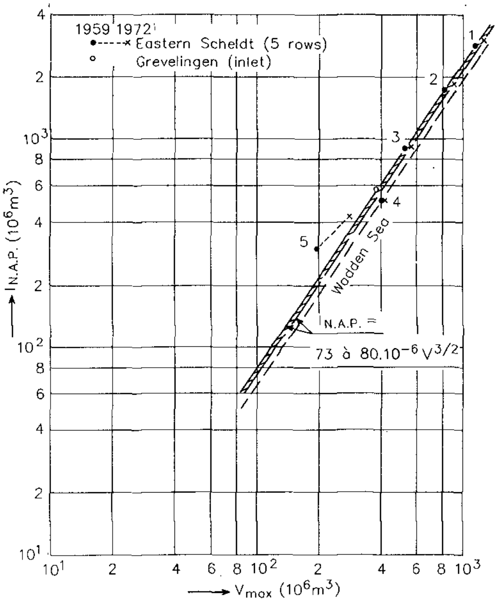


Figure 4 Channel volume - mean tidal volume relation Eastern Scheldt and Grevelingen

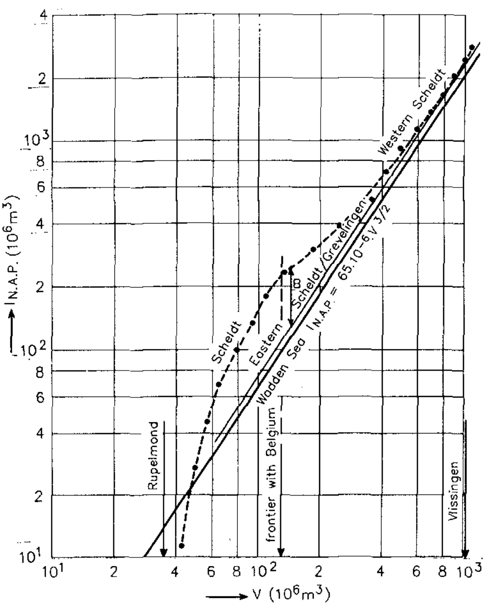


Figure 5 Comparison of channel volume relations Wadden Sea, Eastern Scheldt/Grevelingen and Western Scheldt

Another important relationship is the one for the sand volume stored in the outer deltas in front of tidal inlets which is shown in literature (Bruun, 1978). This relationship is derived for outer deltas in the USA and reads (Fig. 6):

$$V_o = c_o V^{1.23} \tag{3}$$

where:
V_o = sand volume stored in outer delta
c_o = empirical coefficient

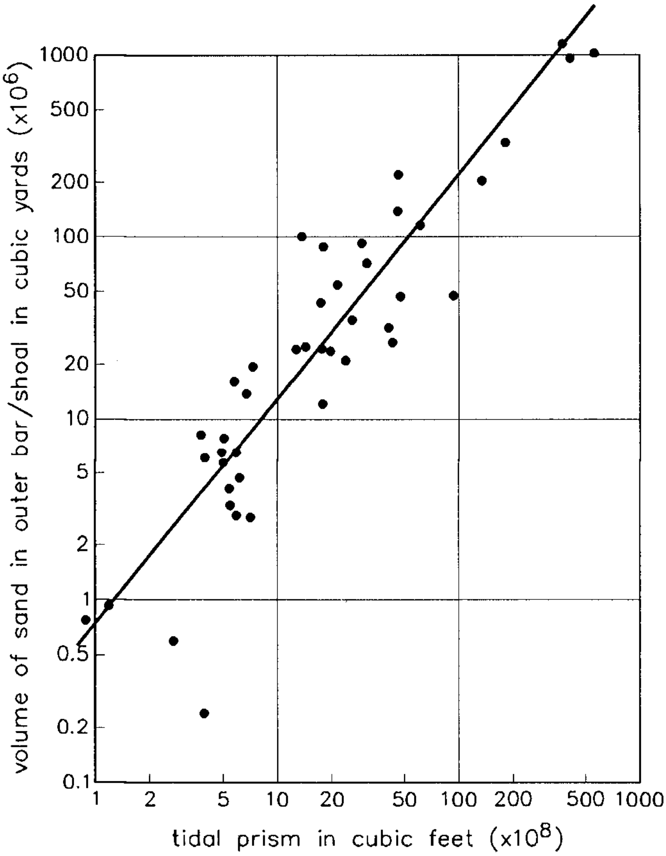
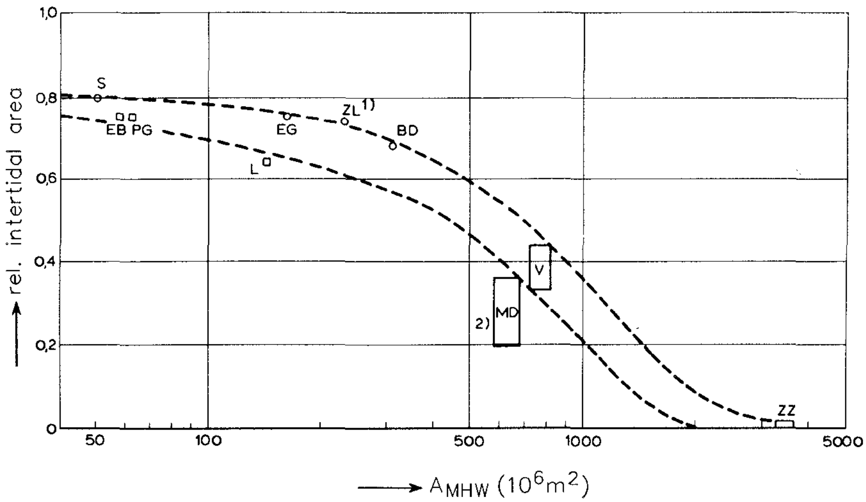


Figure 6 Sand volume outer deltas in America in relation to the mean tidal volume of the inlet

For the time being this relationship has been assumed also valid for the Dutch coast. Its validity will be verified in the near future.

Further, the relative tidal flat area in the Dutch Wadden Sea seems to show a relationship with the size of the basin (Fig. 7).

Also for the estuaries in the South of The Netherlands such a relationship was found which, however, differs from the one for the Wadden Sea. A possible explanation for the trend of the relationships could be the increasing activity of local wind waves in the larger basins (fetch). The difference between the two relationships might be caused by the difference in shape of the basins and the orientation relative to the dominating wind direction. Further investigations on this item may yield a better understanding.



1. Before closure of the Lauwerszee
2. After closure of the Zuiderzee (IJsselmeer); no equilibrium yet?

Figure 7 Relative area of the intertidal zones in the Wadden Sea

Finally, it is believed that the crest level of the tidal flats in between the tidal channels somehow are related to a characteristic tide level (e.g. MSL or MHW), local wave activity and flow conditions. The level is determined by a dynamic balance between sediment transport from the tidal channel to the flats during flood and vice versa during ebb. Also in this respect more investigations could support this hypothesis.

The above relationships are derived for situations where morphology is in a dynamic equilibrium with the hydrodynamic conditions.

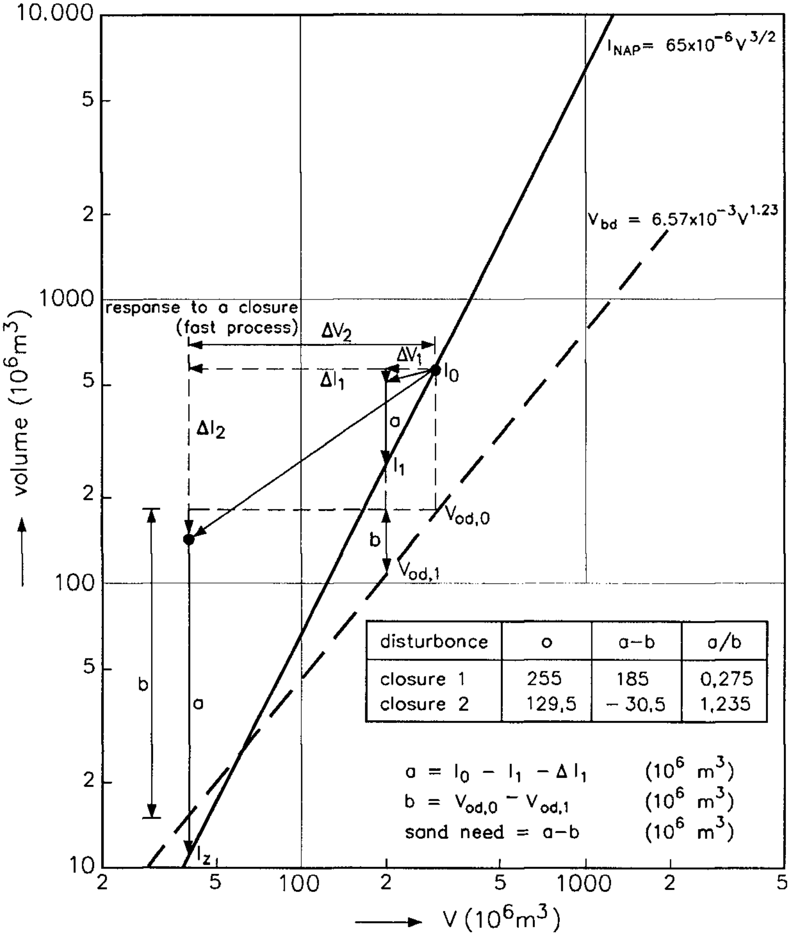
3. Application of relationships in coastal engineering

The relationships are very suitable means to determine in what way Nature will respond to changes in the existing dynamic equilibrium. The equations (1) to (3) allow for a quantification of the ultimate change from the disturbed equilibrium to the new equilibrium. The relations of the relative tidal flat area and the height of the tidal flats may be helpful in the interpretation in what way the developments will occur in combination with knowledge on general sediment transport theories and hydraulics.

For example with Figure 8 it can be demonstrated what will happen in response to closure works. Such works make part of the original basin inactive resulting in a reduction of both the channel volume ΔV_c and the tidal volume ΔV. The new situation will deviate from the equilibrium lines:

- the remaining channel volume is a m³ too big, and
- the sand volume of the outer delta has become a volume of b m³ too big.

The sand of the outer delta lays on the doorstep of the tidal basin and is readily available for the adaptation of the channels in the basin. The rest (a-b m³) has to be supplied from outside.



disturbance	a	a-b	a/b
closure 1	255	185	0,275
closure 2	129,5	- 30,5	1,235

Figure 8 Example of application of morphological relationships

In Figure 9 another example is shown, that is the response of the system to natural accretion of new land mainly by deposition of silt (salt marshes) along the borders of the basin. This is a very slow process causing a gradual reduction of the tidal volume of the basin at a rate ranging from 0.3‰ in the western Wadden Sea, 0.7‰ in the more sheltered eastern part of the Dutch Wadden Sea to 0.5% in the sheltered basin of the Dollard (Eysink, 1979). In the same way as before this results in a demand for sand from the outside.
The Dutch Wadden Sea reached its greatest extension around the year 1500 and decreased in size ever since due to accretion. Therefore, it is realistic to assume that the adaptation of the channel system and the outer delta keep in pace with the accretion process.

Sand borrowing from the outer delta or the tidal channels of a basin does not effect the tidal volume but only locally the flow velocities. It is obvious that in that case the removed sand will be ultimately replaced by sand from the adjacent North Sea coast or its foreshore.

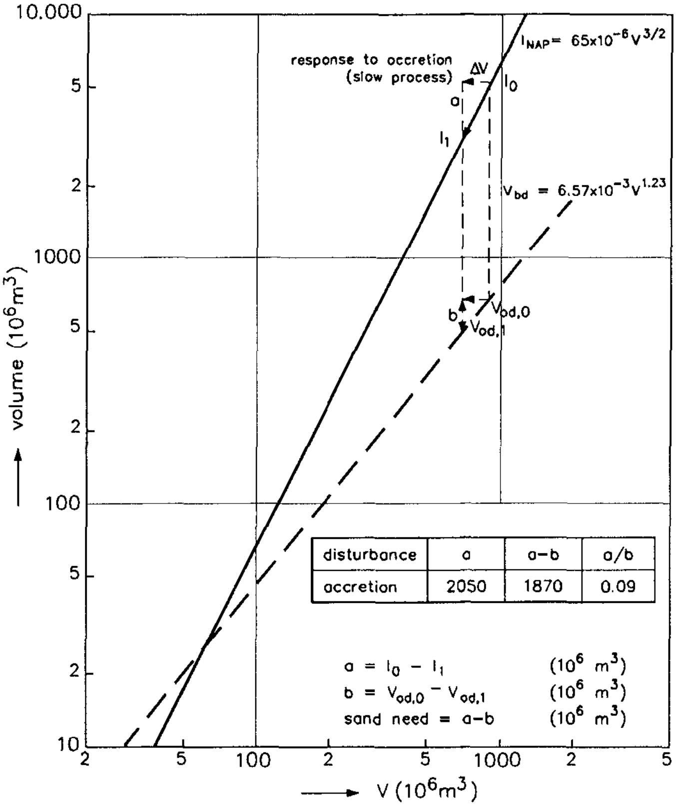


Figure 9 Example of application of morphological relationships

With respect to the effects of increased sea level rise the answers are more difficult to assess. From storage curves of the different basins it follows that, without adaptation of the levels of the tidal flats, the tidal volume will increase and the area of intertidal zones will decrease. The latter effect will be most serious in the Wadden Sea, especially in the western part where the levels of the tidal flats are low (see Table 1). If this scenario is realistic, the channels in the basin will widen and sand will be tranported partly to the outer delta, which will extend, and partly will become available for accretion of the North Sea Coast adjacent to the tidal inlet.

Area	losses in km^2/cm SLR
Wadden Sea-East	3.0
Wadden Sea-West	6.0
Eastern Scheldt	0.2
Western Scheldt	0.02

Table 1 Loss of intertidal zone due to increased sea level rise without adaptation of tidal flats

However, an increase of sea level rise also will effect the level of the tidal flats. In a relative sense the disturbance of the characteristic water depth at the flats will be much greater than in the channels. Hence, the sediment transports in the channel will be far less effected than those on the flats. Consequently, it seems realistic to assume that the response of Nature will be the strongest on the tidal flats. If it is assumed that the levels of the tidal flats can follow the extra sea level rise, this implies that the tidal volume of the basin remains unchanged, whereas the volume of the channels increases. Thus, this scenario results in a demand of sand from outside.

There are indications that the response of tidal flat levels to changes in HW is fast and may follow the sea level rise very closely. However, there is no proof that the latter scenario is fully realistic. Anyway, it is a pessimistic scenario for the North Sea Coast.

4. Model for adaptation histories

The above mentioned relationships only give an indication of the new equilibrium between morphology and hydrodynamic conditions in case of changes. They don't give any information how the adaptation will take place and what time this will take.

Adaptation processes generally show a logarithmic character; examples of this are found in:
- accretion history of the Dollard (Fig. 10),
- adaptation of the Zoutkamperlaag after the enclosure of the Lauwerszee (Postma and Reenders, 1986),
- infill of sand borrow pits (Kniess, 1976).

This shows that the adaptation history can be described by an expression like:

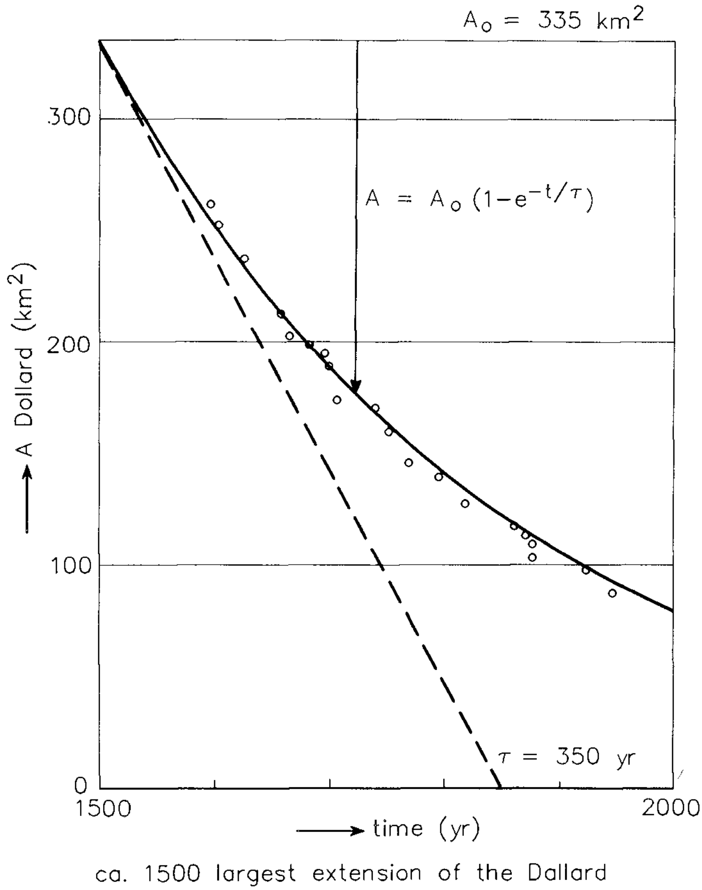


Figure 10 Accretion of the Dollard

$$X/X_o = \exp.(-t/\tau) \tag{4}$$

where:
t = time since disturbance of existing equilibrium,
X = quantity (depth, area or volume) representing difference from new equilibrium,
X_o = initial difference from new equilibrium,
τ = characteristic time for adaptation equal to:

$$\tau = X_o/\Delta X_o \tag{5}$$

where: ΔX_o = initial rate of adaptation.

The initial disturbance of the system X_o can be derived via the change in the hydraulic conditions and the morphologic relations.

The initial adaptation rate can be obtained through monitoring or computations with mathematical models. Then the characteristic time τ can be calculated with equation (5) and the adaptation history can be determined by equation (4). This provides a fair indication of reality.

The above approach can not be applied in case of a (sudden) change in sea level rise as this is a process of gradual and continuous growing disturbance of the existing equilibrium. In this case it is not realistic to assume that this will result in an immediate response of the sea bed in a tidal basin. It is more likely that the sea bed will follow with a certain time lag.
Based on geological and historical evidence it can be stated that the tidal basins are sedimentation areas. This only can occur if the sediment transport capacities inside the basin are slightly less than outside. This could be explained if it is assumed that the bed of the basin lags slightly behind (below) the actual equilibrium level. This hypothesis is based on the principles of a sand trap. The bed lag causes a small overdepth resulting in a small reduction of flow velocities and sand transport capacities inside the basin. Thus sand is trapped to follow the present sea level rise.

If the sea level suddenly rises faster, more sand has to be trapped. Due to the extra sea level rise the overdepth in the basin initially increases. Consequently, gradually more sand is trapped until the sea bed again rises at the same rate as the sea level.

This process can be calculated in a schematic way by using a fictive overdepth. This quantity can be determined based on the percentage of the annual sand influx that is trapped in the basin and the relation between sand transport and flow velocity. If x percent of the sand is trapped, the fictive overdepth is $1-(1-x)^{1/n}$ percent of the weighted mean depth of the basin if the sand transport is proportional to the flow velocity to the power n. If the annual sand influx of a tidal basin is known, the percentage x can be determined for different rates of sea level rise (sedimentation is equal to the area of the basin times the rate of sea level rise). Next, the adaptation of the bed lag to the increased sea level rise can be calculated numerically (Fig. 11).

5. Conclusions

The above approach with proper interpretations are suitable for practical application in coastal engineering. It can be further developed as a conceptual model for areas like the Wadden Sea by implementing also other relations such as those for the tidal flat areas and heights of tidal flats in relation to characteristic hydraulic parameters.

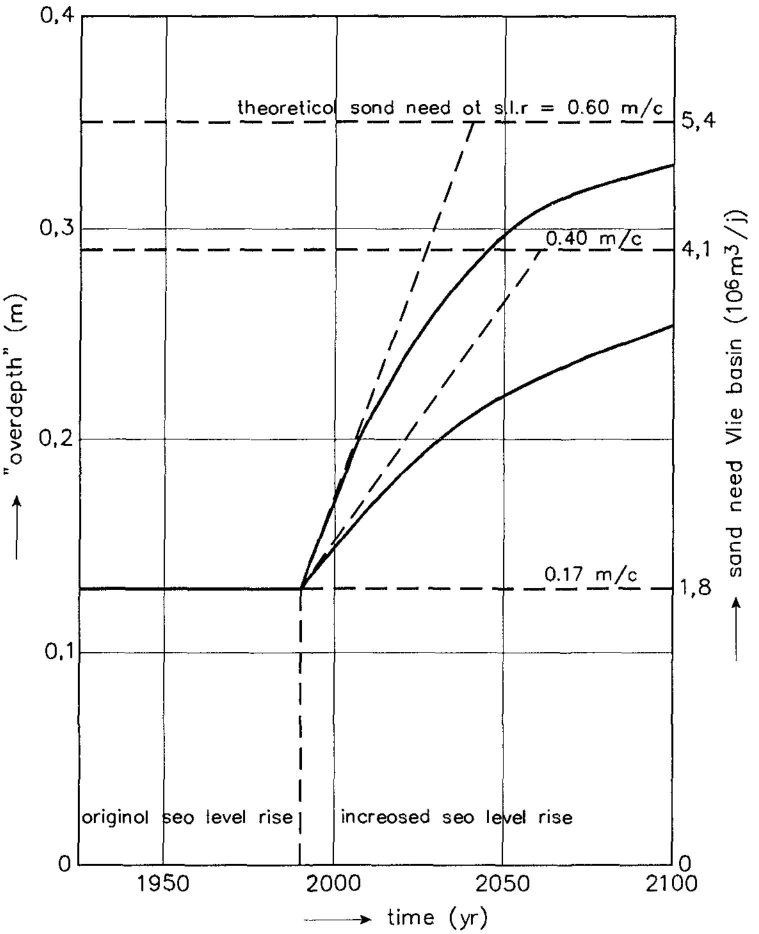


Figure 11 Sand need of the tidal basin of Het Vlie and retardation in the actual deposition rate

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