RESPONSES OF THE DUTCH COASTAL SYSTEM TO THE (SEMI-) CLOSURES OF TIDAL BASINS

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Abstract: During the last century, various engineering works in the Dutch coastal system have been carried out for flood defence and/or land reclamation purposes. Among these engineering works, two of the tidal inlets in the Dutch Wadden Sea and three of the estuaries in the southwest delta were entirely or partly closed or semi-closed. These closures of the tidal basins have been impacting the development of not only the (semi-) enclosed basins themselves, but also the adjacent coast and tidal basins. They influence the large scale morphological development and the sediment budget, and thereby impacting the maintenance of the coast by sand nourishment. On smaller scale they influence the developments of the channels, inter-tidal flats and other morphological elements. Especially the influence on the morphological development of the inter-tidal flats has impacts on the ecological system. In this paper we evaluate the effects of all these closures to the morphological development of the various parts of the Dutch coastal system. The evaluation is mainly based on analysis of field data. Bathymetric data have been collected since 1926. Further use is also made of the results of earlier modelling studies. Special attention will be paid to the influence of the location of the closure and the type of the closure. It is shown that the total sediment deficit for establishing the new morphological equilibrium caused by a closure is very much dependent on the location of the closure relative to the mouth of the tidal basin. We will also show the different environmental problems caused by the different types of closures. We believe that the lessons learned from the evaluation can also be relevant for elsewhere in the world.

Key words: Dutch Coast, Tidal Basins, Closures, Sediment Budget, Coastal Maintenance, Ecological Impact

1. INTRODUCTION

The Dutch coastal system consists of the North Sea coast, a series of Wadden Sea tidal inlets in the North and various estuaries in the Southwest delta area. During the last century, various engineering works in the Dutch coastal system have been carried out for flood defence and/or land reclamation purposes. Among these engineering works, two of the tidal inlets in the Dutch Wadden Sea and three of the estuaries in the southwest delta were entirely or partly closed or semi-closed (Fig.1). The first closure is the Afsluitdijk, a dam of 30 km finished in 1932 and separating the former Zuiderzee from the Wadden Sea. The last of this series closures is the Eastern Scheldt Storm Surge Barrier, finished in 1986 which semi-closed the Eastern Scheldt Estuary.

These closures differ in type and location within the corresponding basins. Three of the five are fully closed dams: the Afsluitdijk, the closure of Lauwerszee and the closure of the Grevelingen. Haringvliet is closed by a dam in combination with sluices which only allow discharge of fresh water from the upstream river. The Eastern Scheldt Storm Surge Barrier only closes the basin under extreme conditions and it allows tidal flow through although with reduced cross-section. The two closures in the Wadden Sea only close the landwards part of the tidal basin. The closures in the Southwest delta area practically close the entire corresponding basin, but their locations relative to the mouth of the basin also differ from each other.

These closures of the tidal basins have been impacting the development of not only the (semi-) enclosed basins themselves, but also the adjacent coast and tidal basins. They influence the large scale morphological development and the sediment budget, and thereby impacting the maintenance of the coast by sand nourishment. On smaller scale they influence the developments of the channels, inter-tidal flats and other morphological elements. Especially the influence on the morphological development of the inter-tidal flats has impacts on the ecological system.
In this paper we evaluate the effects of all these closures to the morphological development of the various parts of the Dutch coastal system. The evaluation is mainly based on analysis of field data. Bathymetric data have been collected since 1926. Further use is also made of the results of earlier modelling studies. Special attention will be paid to the influence of the location of the closure and the type of the closure. It will e.g. be shown that the total sediment deficit for establishing the new morphological equilibrium caused by a closure is very much dependent on the location of the closure relative to the mouth of the tidal basin. We will also show the different environmental problems caused by the different type closures. We believe that the lessons learned from the evaluation can also be relevant for elsewhere in the world.

2. Closures in the Wadden Sea

2.1 Closure of Zuiderzee

The Afsluitdijk, a 30 km dam separating the former Zuiderzee from the Wadden Sea, was finished in 1932. After the closure part of the Zuiderzee is reclaimed and the remaining part became a freshwater lake, the IJsselmeer.

Figure 2 shows schematically how the closure dam influences the vertical and horizontal tide. Before the closure the basin was relatively long compared to the tidal wave length. There was a place in the system where the tidal flow before the closure was minimal. The closure dam is located just seawards of this place. As the tidal range in the remaining basin became higher, the tidal prisms at the inlets (Texel Inlet and Vlie) became even slightly larger than before the closure.

Although the closure has not caused significant changes of the total tidal prisms of the basins it has induced morphological changes inside and outside the basins, especially the two large basins Marsdiep and Vlie. Figure 3 shows the sediment budget of the three inlet systems. Note that the ebb-tidal delta is also included in the area indicated by ‘coast’. Inside the two large (remaining) basins Marsdiep and Vlie sedimentation has taken place since the closure. The sedimentation rates are much higher than necessary for keeping pace with the relative sea-level rise. See also the total changes in the period 1927-2000 given in table 1. Outside the basins, i.e. the coastal areas erosion occurs and the total amount is more or less the same as the sedimentation inside the basins (Elías, 2006). Apparently the closure has caused sediment deficits in the basins, which has driven sediment import from the coastal area into the basins.
Figure 2: Influence of the closure of the Zuiderzee on the tide (from Elias et al., 2003)

Figure 3: Sediment budget of the three inlet systems influenced by the closure of Zuiderzee (Elias et al., 2009). On the vertical axes cumulative sedimentation since 1927 in million m$^3$ is given.
Table 1 Total changes in sediment budget in the period 1927-2000 (ebb-tidal delta forms part of coast)

<table>
<thead>
<tr>
<th></th>
<th>Coast ($10^6$ m$^3$)</th>
<th>Ebb-delta ($10^6$ m$^3$)</th>
<th>Basin ($10^6$ m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marsdiep (MD, Texel Inlet)</td>
<td>-240</td>
<td>-189</td>
<td>198</td>
</tr>
<tr>
<td>Eierlandse Gat (ELD)</td>
<td>-26</td>
<td>5</td>
<td>-28</td>
</tr>
<tr>
<td>Vlie Inlet</td>
<td>-175</td>
<td>-161</td>
<td>198</td>
</tr>
</tbody>
</table>

The erosion of the coast area has caused retreat of the coastline, especially around the Texel Inlet. Since 1990 the Dutch coastline is maintained by sand nourishment. The coast around the Texel Inlet is an area requiring the largest volume of sand nourishment.

The morphological development within the basins has also caused movement of the tidal divide, i.e. more or less the boundaries between the basins, between Marsdiep and Vlie. The movement is eastwards, enlarging the Marsdiep basin at the cost of the Vlie basin.

In the closed part of the basin, i.e. IJsselmeer, mud supplied by the IJssel River flowing into the basin accumulates. Locally this has resulted in a polluted lake bottom.

2.2 Closure of Lauwerszee

The Lauwerszee was closed in 1969 by a dam and it is nowadays a fresh water lake, Lauwersmeer. Before the closure it was a part of the Frisian Inlet basin, which is divided by the Engelsmanplaat into Zoutkamperlaag and Pinkegat (Figure 4). The closure caused a decrease of the basin area of the Frisian Inlet by about one third.

Figure 4 Frisian Inlet and Closure of Lauwerszee

Figure 5 Influence on tide and sediment transport at centre of Zoutkamperlaag Inlet
Figure 5 shows the effects of the closure on the water level, flow velocity and sediment concentration at the center of the Inlet Zoutkamperlaag as calculated by Wang et al (1995) using a 2DH model. The closure caused a small increase of the tidal range. However, due to the decrease of the tidal basin area the tidal prism and thereby the magnitude of flow velocity decreased significantly. The tidal asymmetry changed such that it became more flood-dominant favouring sediment import.

Since the closure (1969) the tidal basin of Zoutkamperlaag has been accumulating sediment and the ebb-tidal delta has been eroding. The sedimentation in the basin and the erosion of the ebb-tidal delta are more or less in balance. As a consequence the closure has not caused erosion problem of the adjacent coasts, in contradiction to the closure of the Zuiderzee. Although in less extent the closure has also caused movements of tidal divides enlarging the tidal basin of Zoutkamperlaag.

An environmental problem induced by the closure is the erosion of the Engelsmanplaat, the large inter-tidal flat between the Pinkegat and the Zoutkamperlaag. This is due to the fact that the tidal flow in the Zoutkamperlaag channel, which is a building force for the flat, became weaker due to the closure. The eroding force for the flat, the wave action did not change due to the closure.

![Graph]

Figure 6 Sediment budget of Zoutkamperlaag.

2.3 Discussion

It is interesting to compare the two closures in the Wadden Sea. The closure of the Zuiderzee takes away a major part of the original tidal basin, whereas the closure of the Lauwerszee takes away a relatively smaller part of the basin. However, the closure of the Lauwerszee caused a significant decrease of the tidal prism and the closure of the Zuiderzee did not. The reason is that the Friesian Inlet is a short basin and the Zuiderzee was originally a long basin and the special location of the Afsluitdijk.

For the effect of morphological development both closures have in common that they caused sedimentation in the remaining tidal basins, and erosion outside the inlet. The difference is that the closure of the Zuiderzee caused serious erosion of the coasts adjacent to the inlet and the closure of the Lauwerszee did not. This can be explained by the fact that the equilibrium size of the ebb-tidal delta is related to the tidal prism. As the tidal prism did not decrease after the closure of the Zuiderzee, the equilibrium size of the ebb-tidal delta remains the same. This means that there is no sediment surplus in the ebb-tidal delta. The sediment deficit in the tidal basin can be easiest satisfied by eroding the coast, as the size of the ebb-tidal delta will effectively increase when the coastline retreats. In other words by eroding the coast and the ebb-tidal delta at the same time the effective size of the ebb-tidal delta can remain the same. In the case of the closure of the Lauwerszee the tidal prism decreases. This caused a sediment deficit in the basin, and at the same time a sediment surplus in the ebb-tidal delta area. The sediment deficit in the basin can then simply be satisfied by eroding the ebb-tidal delta. It is thus important to realize that the tidal basin and the ebb-tidal delta form a sediment sharing system. The closure of the Lauwerszee does not cause a sediment deficit in this sediment sharing system as a whole, whereas the closure of the Zuiderzee did cause a sediment deficit of this sediment sharing system.
3. CLOSURES IN THE DELTA AREA

3.1 Overview of the closures

The Delta works consist of a series of engineering works as shown in Figure 7. We consider the three closures at the mouths of the three estuaries: Haringvliet, Grevelingen and Eastern Scheldt. An overview of the characteristics of these three closures is listed in Table 2. In the following two sections the effects of these closures on the development of the area seawards of the closures and the effects in the enclosed basins are discussed.

<table>
<thead>
<tr>
<th>Closure</th>
<th>Type</th>
<th>Closed basin</th>
<th>Position</th>
<th>Year of closure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haringvliet</td>
<td>Sluices, freshwater discharge</td>
<td>Fresh water reservoir</td>
<td>More landwards</td>
<td>1969</td>
</tr>
<tr>
<td>Grevelingen</td>
<td>Dam, Fully Closed</td>
<td>Salt water lake</td>
<td>Near mouth</td>
<td>1971</td>
</tr>
<tr>
<td>Eastern Scheldt</td>
<td>Storm surge barrier, Tidal flow</td>
<td>Estuary / Bay</td>
<td>Near mouth</td>
<td>1986</td>
</tr>
</tbody>
</table>

3.2 Developments outside area

The influence of the Delta Works is reflected by the changes in Delta topography. The most important factors influencing the morphological geometry at the ebb-tidal delta’s are: (1) the relative influence of waves versus tidal flow, (2) the average wave direction and (3) the interaction between tidal flow offshore and in the near shore channels (Sha and Van der Berg, 1993). The sedimentation-erosion pattern is shown in Figure 8.

The Haringvliet and the Grevelingen have in common that they are closed for tidal flow by the Delta Works. The Haringvliet Sluices only allow discharge of fresh water from the former estuary during periods with high river discharges. The Brouwersdam even forms a complete closure for the estuary. In both ebb-tidal delta areas the influence of the tidal flow has significantly decreased after the closures, whereas the wave influence has not changed much. The morphological developments in the two areas also show similar patterns: erosion at the outer edge of the deltas (shore face), formation of sand bars that retreat landwards at the north side of the deltas, and sedimentation in the former tidal channels. The development can mainly be explained by the disappearance of the tidal flow in the cross-shore direction, and thus a significant decrease of the tidal volume. A smaller tidal volume means a smaller ebb-tidal delta and smaller tidal channels for the new equilibrium. This
explains the erosion at the shore face and the sedimentation in the tidal channels. That this has resulted in an opposite overall sediment balance is due to the difference in relative position of the closures. The Haringvliet Sluices are located relatively landwards, partly also due to the construction of the Maasvlakte (extension of the Rotterdam harbour area). This means that the area outside the Sluices with sediment deficiting channels is relatively large. So the sedimentation in the channels is dominating with respect to the shore face erosion, resulting into a positive overall sediment balance. The Brouwersdam is located relatively seawards, making the shore face erosion dominant with respect to the sedimentation in the channels, and resulting into a negative overall sediment balance. The morphological development in these two areas is in fact tending to establish an ongoing smooth coastline, because of the disconnection with the estuaries.

The influence of the tidal volume on the morphological development can also be observed at the Eastern Scheldt delta. The delta front propagated seaward from 1969 to 1980 due to an 8% increase in tidal volume by the closure of Volkerak in 1969. After the construction of the storm surge barrier in 1986 the tidal volume decreased causing erosion of the shore face (Aarninkhof and Van Kessel, 1999). The three remaining channels (Hammen, de Schaar van Roggenplaat and the Roompot) that form inlets in the barrier deepened, and the lee side of the dam accreted. The other channels decreased in size and found a new orientation due to the reduction and rotation (more in the along shore direction instead of cross-shore) of the tidal flow.

3.3 Impact to the (semi-) closed basins

For the effect within the closed basin only the most important environmental problems are discussed. The problems appear to be mainly dependent on the type of the closures.

The Haringvliet estuary is closed by sluices which only allow fresh river water flowing out and no flow from the sea to the former estuary can occur through the sluices. The basin thus became a fresh water reservoir. As the cross-sectional area of the former estuary is too large for only discharging the river water, accumulation of fluvial sediment occurs in the basin after the closure. In the first years after the closure the quality of the fluvial sediment was poor. Therefore polluted sediments are now present in the bottom of the basin, which forms an environmental problem.

In case of Grevelingen the former estuary was fully closed by a dam, and became a salt water lake. The only exchange of water between the lake and the sea takes place via a siphon structure. Due to the lack of sufficient refreshment of the water in the basin water quality problem starts to occur in the basin in the recent years.

The Eastern Scheldt has kept its estuarine characteristics because it is semi-closed by a storm surge barrier. Under normal conditions the barrier is open allowing tidal flow through it. Only during severe storms the barrier is closed protecting the area behind it from the high sea. However, the construction of the barrier did reduce the cross-sectional area. In order to limit the decrease of the tidal range in the estuary the basin area has been reduced by additional engineering works. The end result is that only limited change of the tidal range occurs after the closure. However, the tidal prism
and the strength of the tidal flow have significantly decreased. As a consequence the inter-tidal flats in the estuary suffer from serious erosion (Figure 9). This is an environmental problem as the inter-tidal flats are used by birds for finding food and resting when they are dry.

4. CONCLUSIONS

Five closures or semi-closures of tidal basins in the Dutch coastal system are considered in this paper. The two closures in the Wadden Sea separate part of the corresponding basin from the Wadden Sea. The three closures in the delta area close or semi-close practically the entire corresponding tidal basin, but they differ in the exact location with respect to the coastline and in the type of closures varying from fully closed to allowing tidal flow under normal conditions. The effects of these closures have been analyzed from two management points of view, viz. the maintenance of the coast and the environmental problems in the remaining and/or the closed basin.

From the coast maintenance point of view, the ebb-tidal delta and the remaining tidal basin together form a sediment sharing system. The sediment deficits and/or surpluses in the two elements together determine if the tidal inlet / estuary will be a source or sink for the coastal system after the closure. It is concluded that the position of the closure structure with respect to the coastline is important for this aspect. When only a part of the tidal basin is closed, as in the case of the two closures in the Wadden Sea, also the tidal wave length is a relevant length scale to consider. The Texel Inlet became a sink of sediment after the closure of the Zuiderzee causing serious erosion in the adjacent coasts. The sediment deficit in the basin of the Zoutkamperlaag and the sediment surplus in its ebb-tidal delta keep practically in balance. When almost the entire basin is closed as in the cases of the closures in the Delta area, the area outside the closure becomes a sink of sediment when the closure is relatively landwards located and vice versa.

The type of environmental problems in the remaining and/or closed basin caused by the closure mainly depends on the type of the closure. When the closed basin becomes a fresh water lake/reservoir, accumulation of fluvial sediment can cause pollution of the bottom, as in the case of the closures of Zuiderzee and Haringvliet. If the refreshment of the water in the closed basin is too limited, as in the case of Grevelingen, water quality problem can occur on the long-term. When the tidal flow is weakened, as in the case Zoutkamperlaag after closure of Lauwerszee and the eastern Scheldt Estuary, serious erosion of the inter-tidal flats can take place.

REFERENCES


