Modelling accumulation of fine grained material in the Hörnum tidal-basin using representative wave situations

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Abstract

The morphology of tidal-basins is influenced by tidal currents and waves as well. It is essential to apply input-filtering for long-term morphodynamic modelling, which means the reduction of the input-parameters to those relevant for the purpose of investigation. Thus representative tidal and wave conditions are crucial for long term predict.

Concerning tidal currents the concept of a representative tide, often referred as a morphological tide has been developed by LATTEUX [1995]. The morphological tide is the tide, that produces the same morphological changes as a series of tides. Concerning waves STEIJN [1992] introduced the concept of multiple representative waves. The determination of a representative wave reaches a much higher level of sophistication. The reason for that is twofold:

- The wave climate in time is much more variable than the occurrence of different tides.
- The morphological effect of different waves is qualitatively much more differentiated than the morphological effects of different tides.

The representative wave situations were determined on base of a morphological matrix. The morphological matrix contains the morphological changes for different wave situations, so that the morphological effects evoked by these situations can be combined with each other to reach maximum agreement with a reference condition. The paper focuses on the construction of representative wave situations.

The study area is the Hörnum tidal basin, situated in the German Bight. It is approximately 400 km² in size has a tidal range of 2m, which means low mesotidal conditions. The ebb-delta is exposed to the waves of the North Sea, whereas the inner part of the basin is affected by local wind waves.

Calculations are presented, that differ in the applied wave-situations alone. The results are compared with the observed long-term morphodynamic trend in the Hörnum tidal basin.

1 Introduction

In recent years it has become possible to calculate the morphodynamic behaviour of large coastal areas with 2D-morphodynamic models. Due to progress in computational power models can work more sophisticated, in particular regarding

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model resolution, direct interaction between hydrodynamics (tidal currents and waves) and morphodynamics and also multi-fractional transport. Nevertheless it is still not possible to run long-term simulations on real time. Thus there is the need to apply input-filtering and to some extent process-filtering.

In tidal-basins the tides are the morphological dominant factor. Applying input-filtering by use of a morphological tide has become state of the art.

But also wave-action can not be neglected in tidal-basins for long-term runs. Although wave heights are rather small, they play an important role to stir up sediment, which is deposited on the flats during calm weather conditions. To simulate the behaviour of the system properly, concepts have to be developed to account for wave action as well.

2 The project area

The Hörnum tidal-basin is situated south-east of the Island of Sylt in the Inner German Bight. The area is approximately 400 km² large and the depth ranges up to 30m in the Hörnum tidal-channel south of the Island Sylt, as shown in figure 1. Approximately 50% of the basin are intertidal flats. This is a considerably low value in comparison with other tidal basins in the region, for example the Dithmarscher bay, where 80% of the area are intertidal flats. The basin was subject to human interference: In 1927 a dam was constructed, that connected the Island Sylt with the mainland. This dam reduced the tidal prism of the basin because it obstructed a residual current into the Lister tidal-basin to the north. The tidal range is approximately 2m. Wave action in the basin is mainly due to local wind seas, because higher waves break on the ebb-delta and are further flattened by refraction.

The morphological evolution of the area is documented since 1955, where the first complete bathymetry of the area was measured. The following bathymetries are dated from 1974, 1978, 1981, 1986, 1987 and 1997. The analysis of the data indicates only a weak morphodynamic signal, which is superimposed by inaccuracies in the data.

To detect a clear morphodynamic signal in the data relevant parameter were derived, in particular the trend and the standard deviation using 6 data sets.

The analysis of the standard deviation reveals three areas of high morphological activity:

- The tidal channels are more active than the flats. This is caused by the higher current velocities and the larger depth-gradient at the channel-sides.
- The activity in the north-eastern part, which is more closely related to the construction of the dam is considerably higher than in the north-western branch, called the Eidum-deep.
- The third region of high morphological activity is the ebb-delta. Wave-action on the delta, influence by longshore-transport along the island Sylt and sediment exchange processes between the delta and the tidal-basin are responsible for the high morphological activity.

The analysis of the trend of the data showed, that in the eastern-part, especially in the end-parts of the channels and branches, a trend for accumulation is dominating.
There is also a weak tendency for the channels to become deeper and more narrow. At the ebb-delta there is a strong indication for a southward shift of the delta. This is probably caused by a net sediment input from the longshore transport along the island of Sylt, which leads to a shifting of the delta.

![Bathymetry of the Hörnum-tidal-basin with sections I-III](image)

**3 The 2D-Morphodynamic-Model TIMOR**

TIMOR [ZANKE 1995] vouches for Tidal MORphodynamics and is a 2D-morphodynamic-model which solves shallow water equations on a Finite-Element grid. Morphodynamics are calculated by applying the bottom-evolution equation:

\[
\frac{\partial z}{\partial t} = \frac{\partial q_{tx}}{\partial x} + \frac{\partial q_{ty}}{\partial y} + E - S
\]

**equation 1**

with:  
- \(z\) : bottom elevation  
- \(q\) : transported quantity in i-direction  
- \(E\) : source term for erosion  
- \(S\) : sink term for deposition
Bed-load transport can be calculated by different formulations. (In the simulations presented in this paper the formula of MEYER-PETER-MÜLLER [1949] is used.) Suspended sediment is calculated by applying an entrainment formulation according to VAN RIJN [1984]. A vertical distribution of suspended sediment according to the Rouse-profile is used, leading to a 2.5D formulation of suspended sediment. The model calculates multi-fractional transport with (by now) up to 12 particle-size-classes. The model is capable to represent biological production due to micro-organism. Details of the model are described in [ZANKE 1995]. The model is coupled with the 2D – wave-energy model SWAN, described in [RIS, 1997].

4 Determination of representative wind situations

For long-term modelling it is essential to apply input-filtering. Concerning computational time in real-time-calculations it is not possible to consider all occurring natural conditions. It is necessary to apply input-filtering, i.e. the reduction of input parameters to those relevant for the purpose of investigation [DE VRIEND 1993].

Concerning tidal currents the concept of a representative tide, often referred as a morphological tide has been developed by [LATTEUX, 1995]. The morphological tide is the tide that produces the same morphological changes as a series of tides. It aims to reduce the natural input conditions. He found, that the tide being somewhat higher than the mean tide is the morphological tide. A similar investigation has been carried out for the Hörnum tidal-basin leading to a 2% - 5% increased tide, depending on the specific year (calm or stormy) [HIRSCHHÄUSER, ZANKE 1999].

The determination of a representative wave reaches a much higher level of sophistication. The reasons for that are twofold:

- The wave climate in time is much more variable than the occurrence of different tides.
- The morphological effect of different waves is qualitatively much more differentiated than the morphological effects of different tides. Different tides produce more or less similar morphological patterns.

The question arises how to reduce all occurring wave-situations for the purpose of morphodynamic modeling to a small number of representative waves or representative wind situations, which account for all occurring situations and produce from morphodynamic point of view the same results as the totality of all occurring situations. Those situations should be used as boundary conditions for non-linear morphodynamic calculations. In the following representative wind situations will be discussed instead of representative waves, because the Hörnum tidal-basin is much more dominated by local wind waves than by swell waves at the outer boundary. Most of those waves break at the ebb-delta.

To find representative wind situations a morphological matrix was generated. The idea of a morphological matrix is the to have a matrix with morphological changes for each wind situation, so that the morphological effects evoked by different wind situations can easily be combined with each other to reach maximum agreement with a reference condition.
To find the representative wind situations on base of a morphological matrix a reference condition has to be defined and the particular wind situation vectors have to be weighted to reach maximum agreement with the reference condition.

The main advantages of this procedure are as follows:

- It proves to be the best choice of representative situations from morphological point of view, because the situations were derived from their morphological effect alone.
- It offers the opportunity to detect in which parts of the area the filtering procedure will probably produce the largest error and thus offers the opportunity to discuss the results in that area more cautiously.
- It can easily be refined by considering more situations.

The main disadvantage of the procedure is, that the combination of different situations is based on linear superposition.

![Frequency of occurrence for different wind situations (10 year period)](image)

**figure 2: Wind distribution at Westerland (Island Sylt)**

To generate the reference condition, wind-situations in the Hörnnum tidal-basin were separated into eight directional and five wind-velocity classes. For each of the forty wind situations a fully coupled morphodynamic run was carried out over one tide to account for different water levels as well. In the following the morphodynamic change for one particular run was weighted by its frequency of occurrence. By summing up all the individual morphodynamic changes for the 40 wind-situations weighted by their frequency of occurrence an artificial reference condition was generated. The need to generate an artificial reference condition was given, because the natural morphodynamic trend was strongly superimposed by inaccuracies in the data.
The frequency of occurrence for the wind situations is given in figure 2. The representative wind situations are determined by the following equation:

\[
RS(n, a_j, h_j) = \min \left( \frac{\sum_{i=1}^n h_{\text{ref},i} - \left( \sum_{j=1}^n a_j \cdot h_{j,i} \right)}{\sum A_i} \right)
\]

equation 2

with: \( RS(n, a_j, h_j) \) : Representative situations
\( h_{\text{ref},i} \) : bottom change at node i (reference condition)
\( A_i \) : patch area of node i
\( h_{j,i} \) : bottom change at node i (wind situation j)
\( a_j \) : multiplication factor for wind situation j

The representative situations are determined by calculating the minimum difference to the reference condition by weighting the situations with a multiplication-factor \( a_j \). Now it is necessary to specify the needed accuracy or the number of situations, which should be included. In the following table 1 the representative wind situations for up to four considered situations are given with their multiplication factors:

<table>
<thead>
<tr>
<th>Number of considered situations</th>
<th>S</th>
<th>SW</th>
<th>W</th>
<th>NW</th>
<th>Relative Volumetric Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.7 *W7.5m/s</td>
<td></td>
<td></td>
<td></td>
<td>23.2%</td>
</tr>
<tr>
<td>2</td>
<td>0.55 *SW7.5 m/s</td>
<td>0.15*NW12.5m/s</td>
<td></td>
<td></td>
<td>18.7%</td>
</tr>
<tr>
<td>3</td>
<td>0.3 *SW7.5m/s</td>
<td>0.15*W12.5m/s</td>
<td>0.25*NW7.5m/s</td>
<td></td>
<td>16.4%</td>
</tr>
<tr>
<td>4</td>
<td>0.3*S7.5m/s</td>
<td>0.05*SW12.5m/s</td>
<td>0.1*W12.5m/s</td>
<td>0.35*NW7.5m/s</td>
<td>13.0%</td>
</tr>
</tbody>
</table>

table 1: Combination of wind situations to get the minimum relative volumetric error compared with the reference condition

The relative volumetric error is defined as:

\[
\Delta V_{\text{rel}} = \sum_{i=1}^n \frac{A_i \cdot \Delta h_i - \Delta h_{\text{ref},i}}{\sum A_i \cdot \Delta h_{\text{ref},i}}
\]

equation 3

with: \( \Delta V_{\text{rel}} \) : relative volumetric error
\( \Delta h_i \) : depth change calculation i
\( \Delta h_{\text{ref},i} \) : depth change reference calculation
\( A_i \) : area

The accuracy of the representative situations rises with the number of considered situations: It decreases from 18.7 % for two considered situations to 13.0% for four considered situations.

The multiplication factors for the representative situations differ from their frequency of occurrence. This can easily be explained, because they stand for a whole set of
situations. It is furthermore not surprising, that the summation of the multiplication factors always reaches less than one, because calm situations, which evoke weak morphological reaction, do not appear in the representative situations.

Generally it can be stated that the best agreement with the reference condition is achieved, when the considered wind situations are more or less symmetrical to the west and a combination of stronger 12.5 m/s winds and more common 7.5 m/s winds is used.

5 Accumulation of fine grained material in the Hörnum tidal-basin

The accumulation of fine grained material is a generally accepted phenomenon in tidal-basins. One of the main questions is, whether the amount of imported fine-grained material is sufficient for growth of the flats with rising sea-level. Between the North Sea and the adjacent tidal basins a considerable exchange of material takes place. The amount of these exchange determines the capability of the tidal flats to grow with rising sea level. The material is mainly a result of primary production and thus strongly dependent on seasonal variations. It is partly mineralized on the tidal flats.

A preliminary estimation of the sediment demand in the Hörnum tidal basin was carried out: In the region the rise of the mean sea level is 25 cm in a century, resulting in 10 cm rise in 40 years. The sediment demand for the next 40 years can be estimated in three different ways:

1. Accumulation in the whole basin \( (A_B) \): \[ S = A_B \cdot 2.5 \frac{mm}{a} \cdot 40a = 29 \text{Mio. m}^3 \]

2. Accumulation on the flats only \( (A_{FL}) \): \[ S = A_{FL} \cdot 2.5 \frac{mm}{a} \cdot 40a = 13.7 \text{Mio. m}^3 \]

3. Accumulation according to regime theory: \[ S = \text{ca.9 Mio. m}^3, \text{ with respect to the present state, which means that according to the equations of Niemeyer[1995], Ferk[1995] and Renger[1976] the Hörnum tidal basin is not in equilibrium at present, but will have a demand of ca. 9 Mio. m}^3 \text{ to sustain the similar geometry as today.} \]

The 3rd assumption should be the most realistic one.

This amount \( S \) can be related to the mean tidal volume entering the area \( (P) \), leading to a mean accumulation relevant concentration \( c_a \). It is the mean concentration difference between the incoming and the outgoing current. The density\( (\rho) \) of the material and the porosity\( (p) \), when it comes to accumulation have to be considered. According to samples taken by Bartholdy and Pheiffer Madsen [1985] in the Gradyb tidal basin, a factor of around 1000 for \( \rho \cdot p \) seems to be reasonable, thus:

\[
c_a = \frac{S}{P} = \frac{9 \text{Mio. m}^3}{520 \text{Mio. m}^3 \cdot 705 \text{tides} \cdot 40a} \cdot 2650 \frac{kg}{m^3} \cdot 0.4 = 0.65 \text{mg/l}
\]

\text{equation 4}
In table 2 actual accumulation relevant concentrations $c_a$ from other locations in the Wadden Sea are listed:

<table>
<thead>
<tr>
<th>Location</th>
<th>$c_a$ [mg/l]</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dollard</td>
<td>3.1</td>
<td>Van Es [1977]</td>
</tr>
<tr>
<td>Dutch Wadden Sea</td>
<td>0.35-1.04</td>
<td>Delft Hydraulic Laboratorium [1980]</td>
</tr>
<tr>
<td>Jade</td>
<td>1.8</td>
<td>Eisma [1981]</td>
</tr>
<tr>
<td>Gradyb</td>
<td>1.5</td>
<td>Bartholdy and Pheiffer Madsen [1985]</td>
</tr>
</tbody>
</table>

**table 2: Actual accumulation relevant concentration $c_a$ [mg/l] in different areas of the Wadden Sea**

A comparable value of the Hörnum tidal basin is not available. At first sight it seems that the sediment demand of the Hörnum tidal basin is in the range of the measured values of other tidal basins. On the other hand, the Dollard, the Jade and the Gradyb are areas of considerable deposition, whereas this is at present not documented for the Hörnum tidal basin, although a dam was built in 1927 that reduced tidal prism.

![Mean grain size distribution Hörnum tidal basin](image)

**figure 3: Sediment composition of the Hörnum tidal basin (Mean of more than 500 samples taken from all parts of the area)**

Additionally it is an area, where the rate of the intertidal area is rather small in comparison with other tidal basins in the region. The reason therefore might be in the origin of the Hörnum tidal basin: In contrast to other tidal basins in the German bight the core of the barrier island Sylt is composited of relatively coarse material, and the basin is located in large distance to the Elbe, Weser and Ems estuaries, which contribute considerable to the availability of fine grained material in the North Sea. Looking at the sediment composition in the Hörnum tidal basin in figure 3, it becomes obvious that the basin is short of certain grain sizes ($d=0.21$mm and $d=0.35$mm),
which is an indication that this material is rare in the source material of the barrier island and consequently points up that transport paths are of a limited extent. It can be assumed that a high amount of fine material is demanded to build up tidal flats, because only this material can be transported in suspension and come to deposition in a sheltered area. Considering this, it seems that the flats of the Hörnum tidal basin might be ranked at the lower edge of the Dutch Wadden Sea $C_a$-values, which means that the flats might not grow in the same order as the mean sea level.

6 Calculations

Three calculations were carried out to investigate the accumulation of fine grained material in the Hörnum tidal basin under different conditions:

1. TIDE: The water level boundary condition was chosen according to mean tide.
2. WAVE: A representative wave situation was determined according to the procedure described earlier. The estimated representative situation is with westerly winds of 5-10m/s. The wave situation can be characterized as a moderate wave climate. The water level boundary condition is according to the mean tide.
3. STORM: A stormy period in October 1996 was chosen. Wind velocities reached up to 25m/s. The water level set-up at Hörnum gauge was up to 2m.

The main idea is to investigate, in how far fine grained material which is imported from the North sea comes to deposition and to which amount it is exported again. The fine grained material was handled as a sediment with a density of 2650 kg/m³ and a diameter of 0.04mm, corresponding to a particle fall velocity of 0.000032m/s. The suspended concentration of this material was chosen as 7mg/l at the beginning of the calculations as a “background” concentration in the whole area, according to data documented by Postma [1981]. This material was absent in the bottom-layer in the beginning of the calculation, so that it could be identified easily, when it comes to accumulation. Additionally a material with the same physical properties was added to the bottom-layer with a spatial different portion according to the maximum occurring velocity [Hirschhäuser et al. 1998] to investigate the influence of different conditions on fine grained material already available in the basin.

6.1 Depth changes

The calculations were carried out over a period of at least 3 tides, which was the period for comparison of the results. In figure 4 the depth changes after 3 tides are plotted. It can easily be seen that in calculation TIDE the change of morphology is rather small. Only at the southward edge of the Island Sylt there are considerable morphological changes. The flats undergo only marginal changes because tidal currents are not strong enough to transport high amounts of material. This calculation can only be representative for very calm weather conditions. It must be noted that the deposition of fine grained material does not contribute much to the morphological change on the short term because of the low concentrations, the reason why the
response of this material is analysed separately because of its influence on the longer term response.

The morphological changes in calculation **WAVE** shown in figure 5 strongly exceed those from calculation **TIDE**. Especially on the ebb-delta, where the waves are breaking and suspending a lot of material and in the Hörnum tidal channel the changes are considerable. The western edge of the ebb-delta is eroded by the waves coming from the west. This material is transported in suspension and comes to deposition inside the basin but also in the central part of the Hörnum tidal-channel. The region of erosion is confined to the area above the 8m depth contour. Outside this region the bottom-orbital velocity is not sufficient to pick up large amounts of material.

Also on the flats noticeable morphological changes occur. Some of the channel banks are shifted slightly to the east, a result of the waves coming from the west.

The morphological changes are most pronounced in calculation **STORM** (s. figure 6). This situation shows the influence of an extreme event. Wind velocities reached up to 25m/s, changing from southwest- to northwest-direction, which is typically for storm events in that area. The water level set-up was up to 2m.

The topography deepens more than 1m at the base of the ebb-delta. The bottom-orbital-velocity is even capable to suspend material which is beneath the 8m depth contour-line. The eroded material deposits partly in the channels between the ebb-delta.

Also the flats are subjected to significant morphological changes. The wave height in the basin reaches up to 1.2m. In general the channel banks are eroded and material is deposited in the channel, where the bottom-orbital-velocities are sufficiently small. Due to the high water table and consequently higher waves more material is transported.

Some of the material is deposited on the upper flats in the southern part of the basin. In general the morphological changes have similar patterns as in calculation **WAVE** but they are much more pronounced.
6.2 Response of the fine grained sediment fraction

The analysis of the response of the fine grained fraction to different hydrodynamic conditions was the aim of this study. The exchange of fine grained material between a tidal basin and the open sea plays an important role concerning the growth of the tidal flats. In general these exchanges have a high seasonal variability because of the variability in primary production. Concerning the exchange of fine grained material three different mechanisms work in combination with their accompanying hydrodynamic conditions in the investigated conditions:

- A general accumulation in the whole basin when wave action is neglected, leading to a net import of material.
- Erosion of material seawards of the tidal inlet, leading to a higher import of material.
- Erosion of material inside the tidal basin, leading to a higher export of material.

6.2.1 Calculation TIDE

The fine grained material deposits in the whole basin, as can be seen from figure 7. Especially the channels are subjected to deposition of this material, because larger water depth means that more material is settling down and additionally the flats fall partially dry, so that deposition can not take place all the time. Remarkably is the accumulation seaward of the ebb-delta. Tidal currents are very small in this area so that a pronounced increase of that fraction takes place, if wave action is neglected.

As expected the sediment balance shows a net import of fine grained material over the three tides, with only little variance in time, which is demonstrated in figure 18 and discussed later on.

It has to be noted that the system does not reach an equilibrium after three tides. It is shown in figure 10, that the portion of fine grained material rises in the beginning, but after some tides this material is eroded and transported to the flats.
6.2.2 Calculation WAVE

Due to the wave action the fine grained material does not come to settlement at the ebb-delta (s. figure 11). Furthermore the settlement seaward of the ebb-delta is much smaller in comparison with calculation tide. This can be explained by the weak bottom shear-stress induced by the waves.
In general a greater part of the material is kept in suspension, leading to smaller concentrations in the bottom layer. On figure 12 it can be seen that during the 3rd tide the material settles down in the end-breaches of the channels and a dynamic equilibrium situation is reached in the rest of the basin. The reason for the lesser portion of fine material in the bottom layer of the channels compared with calculation TIDE might be in the general deposition which takes place in this part of the basin in calculation WAVE, which can be seen on figure 5. This means that the relative increase of the fine portion is smaller, if also coarser material comes to accumulation.

This scenario leads to the strongest import of fine grained material in the basin (s. figure 18). The reason for this import is, that material is eroded at the ebb-delta and transported by suspension inside the basin. Settlement of fine material is only possible inside the basin, where bottom shear stresses are smaller. On the other hand there is clear evidence that on the longer term material is transported over the watershed (section II) into the neighbouring tidal basin due to the slightly easterly currents induced by the wind, indicated in figure 19. During calm weather conditions (Calculation TIDE) there is a net current inside the basin through section II.

6.2.3 Calculation STORM

Calculation STORM leads to a completely different situation of the hydro- and morphodynamics. A comparison to the other conditions concerning the tides is not possible, because the duration of the first flood is lengthened due to the strong wind forcing and the presumed water level at the open boundary. The water balance is not in equilibrium after 36.5h (3 tides), which means that the mean water level in the basin is still higher than at the beginning of the calculation. This leads to a net water volume import into the basin during the first 12.5 h of more than 400 Mio. m³ as can be seen in figure 19. Because of this, it is not surprising that the net import of suspended sediment during this period reaches a peak value. But the net current inside the basin is not the only reason for the strong import of sediment: It is shown in
figure 13 that almost the whole material seaward of the basin is entrained and transported in the basin. But high waves inside the basin also lead to an entrainment. When the weather situations becomes calmer the suspended sediment with its high concentration is transported out of the basin due to the ebb-dominance of the current. After 3 tides the situation is near an equilibrium. During the last two tides, a part of the imported material is exported, attributed to a net current out of the basin combined with still large quantities of material in suspension because of increased currents and wave heights. Especially the transport of material through section II is considerable. This is induced by high waves and high water table, leading to strong currents over the watershed.

In the 3rd tide an export of material takes place and the portion of the fine grained material in the bottom layer decreases, as can be seen in figure 14, which means that the loss of material can not only be attributed to the net current outside the basin.

The storm situation is the an extreme event. It is not easy to compare this event with the others because the period of the tide changes significantly during this period leading to a shift of the tidal currents and thus to a large sediment import or export in 12.5h. In general the calculation indicates that deposition increases at the beginning of the storm event with large amounts of material eroded seaward of the inlet but most of this material is exported with falling water level which leads to a smaller deposition after all.

6.3 Distribution of fine grained suspended sediment eroded from the bottom layer

An intercomparison of the suspended sediment concentration of fine grained material eroded from the bottom layer represented by a material with the same physical properties as the ‘background material’ was carried out. The portion of this material in the bottom layer at the beginning of the calculation was determined by a procedure depending on the shear stresses evoked by tidal currents.
The suspended sediment concentration of this material at high water is shown in figure 15, figure 16 and figure 17.

For calculation TIDE it can be seen that the largest concentrations appear in the channel, because there are larger velocities leading to erosion. This material is transported convective in suspension on the flats, where the currents are not strong enough to erode material. In comparison with the other two calculations concentrations are rather small (an order of magnitude).

**figure 15:** Suspended sediment concentration $d=0.04\text{mm} \text{[mg/l]}$ at high tide; calculation TIDE (the material was available in the bottom layer at the beginning of the calculation)

**figure 16:** Suspended sediment concentration $d=0.04\text{mm} \text{[mg/l]}$ at high tide; calculation WAVE (the material was available in the bottom layer at the beginning of the calculation)

**figure 17:** Suspended sediment concentration $d=0.04\text{mm} \text{[mg/l]}$ at high tide; calculation STORM (the material was available in the bottom layer at the beginning of the calculation)

During calculation WAVE the fine grained material is eroded by the waves on the flats, where this fraction is available in appreciate amounts and transported by the flood current to the east. This leads to a pronounced maximum of the suspended concentration in the eastern part of the basin.

Looking at the suspended sediment concentration in calculation STORM (s. figure 17) a similar situation becomes evident: The largest concentrations are in the eastern part. But there is also an increased concentration in the north-western part of the basin, south of the Island Föhr (probably induced by convective transport of wind-
induced current) and seaward of the barrier Island Sylt, attributed to the higher bottom-orbital velocities, leading to decreased deposition.

6.4 Determination of the accumulation relevant concentration under different conditions

The aim of this study was to investigate the accumulation of fine grained material under different conditions. To compare the results of the morphodynamic calculation with values of other authors a sediment balance of the fine grained material has to be carried out. The suspended sediment transport of the fine fraction not available in the bottom layer at the beginning of the calculation through three sections, plotted in figure 1.

The net suspended sediment transport was calculated over 3 tides (approximately 36.5h) using the following relationship:

\[
S = \int q \cdot c \cdot dt
\]

equation 5

It is plotted in figure 18. The largest net import of sediment is estimated during calculation WAVE. The different mechanisms mentioned earlier have to be considered interpreting the net sediment balance:

The first mechanism (general accumulation in the whole basin ) is working in each of the calculations, but can be analysed separately in calculation TIDE. There is a considerable accumulation attributed to this mechanism.

The erosion of material which was deposited seawards of the tidal inlet is only possible if waves of sufficient height are present. This mechanism intensifies the overall accumulation but is on the other hand accompanied by wave action inside the basin and thus erosion of material inside the basin. Comparison of calculation WAVE and STORM makes evident that under moderate conditions an increase of the accumulation takes place, whereas under extreme conditions the effect of erosion of material inside the basin is dominating, leading to the smallest net accumulation in calculation STORM.

Looking at the sediment balance for each section it is obvious that the main part of the material is delivered through the tidal inlet. Thinking of the negative hydrodynamic balance under mean tidal conditions this can only be explained by a partial deposition of the material in the basin. Under wave conditions the erosion of material seaward of the inlet becomes significant. This is confirmed by the larger sediment input in calculation WAVE in comparison with calculation TIDE. On the other hand the changed hydrodynamic situation leads to a sediment export through section III between Amrum and Föhr, attributed to relatively high sediment concentrations because of erosion at the ebb-delta which is transported through the section III, induced by the net current export.

Using equation 4 the mean accumulation relevant concentration \(c_a\), can be calculated, using the mean tidal volume of the calculation plotted in figure 19.
It is between 0.05 mg/l for calculation STORM and 0.42 mg/l for calculation WAVE. For the STORM calculation it has to be considered that the hydrodynamic balance is not in equilibrium, which means that there might be almost no net accumulation after the storm has passed.

In general this means that under moderate wave conditions the accumulation in the Hörnum tidal basin is largest. The accumulation relevant concentration $c_a$ for calculation WAVE seems to be a realistic value in comparison with the values given in table 2. On the other hand it must be stated, that in none of the calculations the accumulation relevant concentration $c_a$, required for growing of the flats according to mean sea level rise of 0.65 mg/l is reached. A reason for this might be due to the relatively low background concentration of 7 mg/l.

7 Summary

A morphological study of the Hörnum tidal basin was carried out to investigate the accumulation of fine grained sediments under different conditions. The accumulation of fine grained material is of major importance for the growth of the tidal flats with rising mean sea level.
Concerning the next 40 years a sediment demand of the Hörnum tidal basin of 9 Mio.m³ was estimated to sustain its present morphological equilibrium according to regime-theory. Relating this amount to the mean tidal volume entering the Hörnum tidal basin leads to a accumulation relevant concentration \( c_a \) of 0.65mg/l. Looking at accumulation relevant concentration \( c_a \) of other tidal basins it is questionable if the Hörnum basin can undergo accumulation of this order.

Three morphodynamic calculations were carried out to investigate the influence of different hydrodynamic conditions on the accumulation of fine grained sediment. The calculations show maximum accumulation concentration \( c_a \) of 0.42mg/l during moderate wave conditions (westerly winds of 5-10m/s, estimated as the representative wave situation). The accumulation relevant concentration \( c_a \) of the calculation TIDE, neglecting WAVE action was estimated as 0.17mg/l and for an storm event as 0.05mg/l.

The estimated values are smaller than the required accumulation relevant concentration \( c_a \) of 0.65mg/l, which confirms that the flats of the Hörnum tidal basin might not grow in the same order as the rising sea level.

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