ABSTRACT

The equilibrium condition in tidal basins, especially in the Dutch Wadden Sea, which is a multi-basin tidal system, has been the subject of numerous studies in recent decades. This concept is more important when the tidal basin imports sediment from the adjacent coastline and its ebb-tidal delta. In the Dutch Wadden Sea the construction of the Afsluitdijk in 1932 affected the behaviour of tidal basins, especially Marsdiep, to a large extent and disturbed its equilibrium condition. In this study a process-based model (Delft3D) based on the shallow water equations is used to simulate the morphological changes of the Western Wadden Sea for a sufficiently long period for achieving equilibrium (2100 years). The main forcing which is included in the simulations is tidal forcing and different simulations with different initial conditions of the model are carried out. The main parameters of tidal basins are calculated and checked with suggested empirical equilibrium relations in the literature. It is shown that such a process-based model can simulate the morphological evolution of the tidal basins in the Western Dutch Wadden Sea and can model a stable (equilibrium) condition in these basins. This stable condition is however strongly dependent on the initial condition of the model as well as the forcing conditions. Comparing all the results of the simulations in this study, it is concluded that the process-based model results show the morphological evolution towards empirical equilibrium equations suggested in the literature, mainly in line with the relations rather than in terms of exact coefficients.

INTRODUCTION

Barrier islands and tidal inlets are found in many places along the coastlines in the world. A tidal basin system consists of three main morphological elements: a tidal basin, tidal inlet and ebb-tidal delta. These three elements, affected by meteorological and hydrodynamic forces, interact with each other to gain and maintain a (dynamic) equilibrium. Sometimes as a result of human intervention and/or natural phenomena, the effecting forces on the tidal basins change. These changes lead to morphological changes in different elements. First sediment is re-distributed within the elements, and sand is exchanged between elements. But if these changes are larger, the sediment exchange may take place between the tidal basins and adjacent coast and in its turn this causes some morphological changes (and problems) in nearby coastlines.

In the last decades, efforts have been undertaken to identify equilibrium and
stability of tidal inlets, and to model different morphological time scales and spatial scales of tidal basins using behaviour based models (De Vriend et al., 1993). These include, for instance, empirical relationships, such as tidal prism-cross sectional area relationship, (e.g., O’Brien, 1931; Jarret, 1976) and closure criteria (e.g., Escoffier, 1940), and semi-empirical long-term models such as ASMITA (Stive et al., 1998; Stive and Wang, 2003). But better understanding of the underlying processes allows process-based models to find their role in the modelling of tidal basins. These models have been used to simulate the morphological evolution of tidal basins in different time scales (Wang et al., 1995; Hibma et al., 2003; Marciano et al., 2005; Van der Wegen and Roelvink, 2008). These studies show that the process-based morphological models, describing the flow field, resulting sediment transport and bottom changes, perform well in the complicated morphological situation in tidal basins. In this study the Western Dutch Wadden Sea, one of the most investigated tidal basins in the world, is used as a case study and a process-based model based on shallow water equation is used to simulate the morphological evolution of the main morphological features form different initial conditions. The result of this process-based model is compared to the well-known empirical equilibrium equations.

**STUDY AREA**

The Wadden Sea, located at the southeastern side of the North Sea, consists of 33 tidal inlets system along the approximately 500 km of The Netherlands, Germany and Denmark coastlines. The barrier islands of these tidal basin systems separate the largest tidal flat area in the world from the North Sea (Elias, 2006). The part of the Wadden Sea which is along The Netherlands coastline (Dutch Wadden Sea) is shown in Figure 1. The ebb-tidal delta shoals in Dutch Wadden Sea are relatively large while they are associated with relatively narrow and deep channels; the back barrier basins of these tidal inlet systems consist of extensive systems of branching channels, tidal flats and salt marshes. The main area of interest in the current study is the Western part of the Dutch Wadden Sea.

The Wadden Sea is a young geological landscape, which has been subjected to numerous, large- or medium-scale human interventions such as closure of basins, land reclamation, coastal defense structures, sand nourishments and so on. The largest human intervention, which affected the morphology of the Dutch Wadden Sea the most, was the closure of the southern part of the basins, the Zuider Sea. Elias (2006) shows that the Marsdiep basin imports a large volume of sediment from the adjacent coast and ebb tidal delta every year (3-5 Mm³/year). Based on theoretical knowledge and analysis of bathymetry data, a conceptual model for development of the Wadden Sea tidal basins is introduced by Elias et al. (2003). This model describes the morphological development of the Wadden Sea in four different stages (see Figure 2).

In stage 1, which is before the human intervention, it is assumed that the whole system of the Wadden Sea is in a dynamic equilibrium. In this stage the characteristics of morphological elements of tidal basins can be described with empirical relations.
This dynamic equilibrium was disturbed as a result of the effects of the closure of the Zuider Sea in the 1930s. Stage 2 or the "Adaptation period" is the period of large changes. In this stage the natural behaviour of the tidal basin systems is dominated by the human intervention. Therefore, the empirical relations of equilibrium cannot describe the morphological development of the tidal basin systems. This stage has a time scale in the order of several decades and leads the system to reach a stage of "Near equilibrium state". In this stage (stage 3), the adaptation continues but on a long-term time scale. Finally, after centuries, the whole system will gain its new dynamic equilibrium state, clearly different from its original one (stage 4).

It seems that now 75 years after the closure of the Zuider Sea, the condition of the Wadden Sea is somewhere at the end of stage 2 and beginning of stage 3.

The Dutch Wadden Sea is one of the best-monitored coastal regions in the world. Some depth measurements especially in Marsdiep were recorded in the 16th century. Since 1987 Rijkswaterstaat (The Netherlands Directorate-General of Public Works and Water Management) have frequently measured the bed level in the Wadden Sea. The ebb-tidal deltas are measured every 3 years, while the basins are measured every 6 years. Rijkswaterstaat defined the borders between different basins, and the data for each basin is stored in a 20 x 20 m resolution database called Vaklodingen. The available data before that time are less frequent and also less accurate; those data are stored in a 250 x 250 m grid.

MODEL DESCRIPTION AND SETUP

Model description
The model which is used in this study is the 2DH version of the Delft3D model, described in Lesser et al. (2004) in detail. Basically the governing equation of the same model is integrated over depth. This model is a finite difference scheme which solves the momentum and continuity equations on a curvilinear grid with a robust drying and flooding scheme. For this exploratory study, the simplest possible physics (depth-averaged shallow water equations, simple transport formula) are applied. In this study, the empirical relation of Engelund-Hansen is used for sediment transport.

\[ S = S_b + S_s = \frac{0.05\alpha U^5}{\sqrt{gC^3\Delta^2D_{50}}} \]

in which

- \( U \) [m/sec]: Magnitude of flow velocity
- \( \Delta [-] \): Relative density
- \( C [m^{0.5} /sec] \): Chézy friction coefficient
- \( D_{50}[m] \): Median grain size
- \( \alpha [-] \): Calibration coefficient \( O(1) \)

The approach for morphological modelling in this study is called the “online approach” (Roelvink, 2006). In this approach the flow, sediment transport and bed-level updating run with the same (small) time steps (Lesser et al., 2004; Roelvink, 2006).

Since the morphological changes are calculated simultaneously with the other modules, the coupling errors are minimised. But, as described in Lesser et al. (2004), because this approach does not consider the difference between the flow and morphological time step, a "morphological

---

**Figure 3. Model flowchart.**

---

![Ali Dastgheib received the IADC Best Paper Award for a young author at PIANC-COPEDEC VII in Dubai, UAE.](image-url)
factor” to increase the depth changes rate by a constant factor (n) should be applied (Roelvink, 2006). So after a simulation of one tidal cycle in fact the morphological changes in n tidal cycle are modelled. In this model even if a large value is chosen for n, the bed level changes are computed in much smaller time steps than in other approaches.

The drying and wetting areas are also treated in a more straightforward way than, e.g., in the classical tide averaged approaches. Examples of the practical usage of this approach can be found in Lesser et al. (2003, 2004). This method has been used for detail event-scale modelling also (Roelvink et al., 2003) for a case of breaching of a sand dam or narrow barrier island. In the case of long-term morphological modelling of tidal basins and estuaries, this method is used by Van der Wegen and Roelvink (2008). The flow chart of the model is shown in Figure 3.

**Grids**

A local model for the Western Dutch Wadden Sea was set up. Although the main area of interest is Marsdiep, Eierlandse Gat and Vlie, to avoid the effect of boundaries, the model is extended to the tidal divide between Amelander Zeegat and Frisian basins. In this study the aim was to set up a model with a reasonable computational time that can simulate long-term (~ 2000 years) morphological changes. The grid that was generated is a compromise between enough resolution in the inlets (at least 10 at the gorge) and having as few cells as possible (~ 7000 cells total) In this study the average spacing between grid lines inside the basins is about 350 m. The grid cells are smaller inside the basins and they are much bigger at the offshore boundary. The grid mesh covers only the area under the high water and the other parts of the barrier islands are excluded from the model. Based on these considerations the mesh shown in Figure 4 was generated for the study area.

**Forcing**

The main forces acting on a hydro-morphological model for coastal regions are tides, wind, waves and gravitational circulations. However, in this exploratory study the focus was on the effect of tidal forcing and neglects other processes. In order to determine the boundary conditions of this local model, a calibrated model for the vertical tide in the North Sea, called ZUNO, is used.

Referring to Van de Kreeke and Robaczewska (1993), the spring neap cycle was neglected and the dominant forcing by M2 and over-tides was considered. Therefore the ZUNO model was run with the forcing boundary conditions of M2, M4 and M6 until a periodic solution was reached. During this run the tidal level variations at the boundaries of local model were recorded.

From the results of the ZUNO model, the recorded tidal variations at local model boundaries were analysed and M2, M4 and M6 were extracted for these boundaries. These components were used to form boundary conditions for the local model. The boundaries for the local model consisted of three boundaries: One boundary at the seaside and two other lateral boundaries. The seaside boundary was chosen to be a water level boundary, while the lateral boundaries were Neumann boundaries, where the alongshore water level gradient is prescribed (Roelvink and Walstra, 2004). Figure 6 shows the local model configuration.

**Initial bathymetry**

The other parameter that can affect the hypothetical equilibrium condition of a tidal
basin in a process-based model is the initial bathymetry. In this study besides the real bathymetry, two other types of schematised bathymetries also were modelled. The most important point in choosing the bathymetries is the available sediment in the model. The amount of available sediment in all the bathymetries should be reasonably similar to the available sediment in the real bathymetry. For runs with real bathymetry, the bathymetry data for 1998 were used; these data are projected on the grid using triangular interpolation. This bathymetry is shown in Figure 7.

**Flat bathymetry**

An other interesting way to model a tidal basin is to use a flat bathymetry inside the basin without any kind of ebb-tidal delta outside the inlet and to let the model show the mechanism of building and changing the ebb-tidal delta outside the basin and channel and shoal patterns inside. So it was decided to make some schematised bathymetries with flat bed inside the Wadden Sea. The following steps were taken to make such a bathymetry:

- Inside the Wadden Sea was assumed to be flat.
- The effects of tidal basins on the seaside such as ebb tidal deltas were omitted.
- The slope of coastal shelf was made uniform.
- The offshore side of the model was assumed to be flat.

A sample of this bathymetry with the same depth scale of Figure 7 is shown in Figure 8.

To determine the depth of the flat Wadden Sea some analysis on the availability and the distribution of the sediment inside the model was carried out and, based on different criteria, different depths are chosen:

- **Depth = 3.62**: The volume of sediment inside the basins is equal to the real bathymetry plus the available sediment in the ebb-tidal deltas.
- **Depth = 4.54**: The volume of sediment inside the basins is equal to the real bathymetry.
- **Depth = 5.02**: The volume of sediment inside the Marsdiep basin is equal to the real bathymetry plus the available sediment in its own ebb-tidal deltas.

**Sloping bathymetry**

During the attempts to model the morphological evolution of the tidal basins with process-based models in recent studies, sometimes a sloping bathymetry toward the inlet is used as the initial bathymetry (e.g. Wang et al., 1995; Marciano et al., 2005). In this study also, a schematised sloping bathymetry is made for the Wadden Sea. The procedure of this schematisation is as follows:

- The tidal basins are separated based on the borders defined by Rijkswaterstaat in Vaklodingen database.
- In each basin the depth of each grid point is plotted versus the distance from the middle point of the inlet.
- The depth of grid points are classified and averaged according to the distance from the inlet in 2.5 km groups.
- Using the average values, the depth of each point is defined as a function of the distance from the inlet.
- The available sediment of each ebb-tidal delta is distributed uniformly inside the corresponding basin.
- The slope of the coastal shelf is made uniform.
- The offshore side of the model is assumed to be flat.
Different runs
Considering different initial bathymetry conditions, 5 different simulations were carried out, 3 with flat bathymetry with the depths of 3.62, 4.54 and 5.02 m, one with sloping bathymetry (Figure 9) and finally one with the real bathymetry. The bed material in all cases consists of uniform sand with $D_{50} = 200 \mu m$. For bottom roughness a Chezy value of 65 m ½/sec is used.

To choose the morphological factor, it is referred to the Van der Wegen and Roelvink (2008) study. This study shows that in the long-term simulations using high values of morphological factor (up to 400), the main morphological characteristics of the basin are maintained. In this study the morphological factor of 300 is used and by running the model for 7 years of hydrodynamic time, 2100 years of morphological time is simulated.

RESULTS AND DISCUSSION

Relative inter-tidal flat area
The inter-tidal flat area (flat area) is defined as the area of the basin between MLW and MHW. In the literature there are some suggestions for the flat area in equilibrium condition. De Vriend et al. (1989) showed a general relation between the flat area and the total area of the basin:

$$A_f = A_b - \beta \frac{2a}{h_c} A_b^{\frac{1}{3}}$$

in which

- $A_f$ [m²] Flat Area at MLW
- $A_b$ [m²] Total Area of basin
- $\beta$ [-] Constant
- $h_c$ [m] Characteristic channel depth
- $a$ [m] Tidal amplitude

Renger and Partenscky (1974) worked on the same form of relation for inlets in the German Bight. Later Eysink (1991) re-wrote their relation as:

$$\frac{A_f}{A_b} = 1 - 0.025 \cdot A_b^{0.5}$$

- $A_f$ [Km²] Flat Area at MLW
- $A_b$ [Km²] Total Area of basin
Eysink (1991) uses the same form of relation \((A_f/A_b\) as a function of \(A_b\)) to analyse the available data in tidal inlets and estuaries in The Netherlands. He summarised his result as shown in Figure 10.

The result of the model for \(A_f/A_b\) is plotted against the Renger and Partenscky (1974) relation and suggested graph for Wadden Sea basins by Eysink (1991) in Figures 11 and 12 during 2100 years of modelling. Figure 11 shows the results for the simulations with schematised initial bathymetry and Figure 12 shows the results for the simulations with real initial bathymetries for all the basins. This shows that regardless of the initial bathymetry the \(A_f/A_b\) tends to a stability near the range which Eysink (1991) suggested. But the final value of \(A_f/A_b\) in Marsdiep and Vlie basins is far from the value suggested by Renger and Partenscky (1974). This is mainly because of the size of the basin. The relation of Renger and Partenscky (1974) is based on the data of smaller basins than Vlie or Marsdiep.

**Height of flats**

Eysink (1990) claims that one of the first parameters which aims for equilibrium, in relatively short time, is the height of flats which is related to the tidal amplitude. Height of flats, which is usually used in the equilibrium situation, is defined as the average height of the flat areas calculated by the following relation:

\[
h_f = \frac{V_f}{A_f}\]

where

- \(A_f \text{ [m}^2\) Flat Area at MLW
- \(V_f \text{ [m}^3\) Volume of flats i.e. volume of sediment in the region between LW and HW
- \(h_f \text{ [-]}\) Height of flats

To check this hypothesis in the results of process-based modelling, the development of flats from different initial bathymetries in different basins are shown in the Figures 13, 14, and 15. The same results for all three basins simulations from real initial bathymetry are presented in Figure 16.
Figures 13 to 16 show that flat characteristics tend toward some equilibrium values but the flat height is not adjusted as fast as Eysink (1990) claims. In addition, it is shown that these equilibrium values are also dependent on the initial condition. This dependency is less pronounced in flat height but in volume of flats obviously the initial sloping bathymetry developed more flat volume and also it developed more flat area. Therefore the longitudinal distribution of the sediment in initial bathymetry also affects the results for flat characteristics. The final height of flats in all the simulations with flat initial bathymetries are almost the same but far from the equilibrium value suggested by Eysink (1990), which is around 0.4 m. The main reason for this difference is the lack of wave effect in the basin, which leads the channels to be deeper and the flats to be higher.

**Friedrichs and Aubrey graph**

Friedrichs and Aubrey (1988) use a 1-D numerical model to study the influence of geometry and bathymetry of short, friction-dominated and well-mixed estuaries. They suggest that two non-dimensional parameters can be used to characterise the tidal basins. These parameters are responsible for different types of asymmetries.

The first one is $a/h$, tidal amplitude over the depth of the channel with respect to MSL, which shows the relative shallowness of the estuary. The second parameter is $V_s/V_c$.

---

**Figure 13.** Development of flat characteristics in Marsdiep from different initial conditions.

**Figure 14.** Development of flat characteristics in Eirlandse Gat from different initial conditions.

**Figure 15.** Development of flat characteristics in Vlie from different initial conditions.

**Figure 16.** Development of flat parameters for different basins during the simulations with real initial bathymetry.
where Vs is the Volume of inter-tidal storage and Vc is the channel volume. Speer et al. (1991) translated the Friedrichs and Aubrey (1988) results to a graph (Figure 17) which distinguishes the flood or ebb-dominant tidal basins. It is suggested that the border between these two regions can represent the equilibrium condition of the basins (Friedrichs and Aubrey, 1988).

The parameters for the Friedrichs and Aubrey graph are calculated from the result of the model for different basins. These results are shown in Figures 18-21. In all the simulations and all the basins the development of the basin according to this graph is toward the ebb and flood dominant separation line; this development is faster in early years of modelling than at the end. When the basin condition is near that line, it begins to scatter and develop almost parallel with the line. This is shown in the case of Marsdiep for the simulation from initial real bathymetry, Vlie for the simulation with sloping and real initial bathymetry and Eierlandse Gat in all the simulations.

This line in the Friedrichs and Aubrey graph is suggested to be some indicator of equilibrium, so it can be concluded that all the basins from all initial conditions are going toward this equilibrium.

The difference between the value of a/h in different simulations is a result of different initial depths (h) rather than the difference in tidal amplitude (a).

Figure 17. Diagram based on Friedrichs and Aubrey models (Speer et al., 1991).

Figure 18. The Friedrichs and Aubrey diagram for Marsdiep in the simulations with different initial condition.

Figure 19. The Friedrichs and Aubrey diagram for Eierlandse Gat in the simulations with different initial condition.

Figure 20. The Friedrichs and Aubrey diagram for Vlie in the simulations with different initial condition.

Figure 21. The Friedrichs and Aubrey diagram for the basins in the simulations with real initial bathymetry.
CONCLUSION

The process-based model which is used in this study does not simulate one single mega-scale stable (equilibrium) condition in the Western Wadden Sea for all initial conditions for the duration of the simulations. But with each initial condition in many aspects such as some basic characteristics of tidal basins, a mega-scale stable (equilibrium) condition is simulated, which is dependent not only on the given boundary condition but also on the initial condition.

In this study it is shown that the results of this process-based model followed the empirical equilibrium equations for flat characteristics and relative flat area qualitatively, while the results are in very good agreement with the equilibrium suggested based on the Friedrichs and Aubrey graph (1988) in the case of Marsdiep Basin.

REFERENCES


