Morphodynamics of ebb-tidal deltas: a model approach

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Abstract

The results of 2DH numerical models of the Frisian Inlet (located in the Dutch Wadden Sea) are discussed to gain further knowledge about the physical mechanisms causing the presence of both ebb-tidal deltas and of channels and shoals in tide-dominated inlet systems. A hydrodynamic model, extended with sediment transport formulations, was used to verify earlier conceptual models that deal with ebb-tidal delta characteristics. The model does not confirm their hypothesis concerning the observed spatial asymmetry of ebb-tidal deltas and suggests that long-term morphological simulations are needed to understand this aspect. Furthermore, the model indicates that the initial formation of the ebb-tidal delta is mainly due to convergence of the tidally averaged sediment flux related to residual currents, whilst the net sediment transport in the basin is mainly caused by tidal asymmetry. A second model (accounting for feedbacks between tidal motion and the erodible bottom) was used to simulate the long-term bathymetric evolution of the Frisian Inlet under fair weather conditions. This model reproduces the gross characteristics of the observed morphology: the presence of a double-inlet system with two distinct ebb-tidal deltas having different sizes and the presence of channels and shoals. The role of the 'Engelsmanplaat', a consolidated shoal in the middle of the Frisian Inlet, was not found to be crucial for the morphodynamic stability of this inlet system.

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1. Introduction

It has been noted by Davis (1996), Hubbard, Oertel, and Nummedal (1979) and others that significant parts of the world’s coastal system consist of series of barrier islands separated by inlet systems. The behaviour of water motion and morphology in these areas is strongly controlled by offshore wave and tidal forcing. The present study focuses on a specific class of inlet systems: those characterised by both strong shore-parallel tidal currents and strong currents in the strait. Such systems are found in the Dutch Wadden Sea (Ehlers, 1988). They have a complex bathymetry, consisting of an ebb-tidal delta and a network of channels and shoals. Typical tidal velocity amplitudes in the channels are of the order of 1 m s\(^{-1}\). Most of the channels on the ebb-tidal delta of tide-dominated inlets have an upstream orientation with respect to the direction of tidal propagation in the outer sea (Sha, 1989).

Ebb-tidal deltas play an important role in the exchange of water and sediment between the backbarrier basin and the coastal zone (cf. Fenster & Dolan, 1996). This observation motivated the main objective of the present study, i.e. to identify and understand the physical mechanisms causing the presence of an ebb-tidal delta on the seaward side of a tide-dominated inlet and why channels on this delta often have a preferred upstream orientation.

A conceptual model to explain the observed asymmetry of ebb-tidal deltas of tide-dominated inlet systems was formulated by Sha (1989). He attributed this property to the interaction between shore-parallel tidal currents and tidal currents in the strait. This would cause an overshoot of the tidal flow on the downstream side of the inlet, resulting in weaker and more eccentric tidal currents than on the upstream side. A definition of tidal eccentricity is given in Pugh (1987). As a result, sediment deposition (and thus shoal formation) would take place...
on the downstream side of the inlet, thereby forcing the main channels on ebb-tidal deltas to have an upstream orientation. Shoals forming in this area would then migrate under the influence of waves and aeolian processes. This model is simple and transparent, but it is based on conceptual ideas rather than physical analysis. It is therefore important to test these ideas with process-oriented models, based on physical laws for the water motion, sediment transport and bottom changes. Such quasi-realistic models for tidal inlets are nowadays available (see Cayocca, 2001; Ranasinghe, Pattiaratchi, & Masselink, 1999; Wang, De Vriend, & Louters, 1992; Wang, Louters, & De Vriend, 1995). Up to now, such models have not been used to test the conceptual ideas of Sha (1989). Moreover, these models are so complex that it is difficult to gain fundamental knowledge about the physical processes involved.

This motivates the use of less complex models in which highly schematised tidal inlet systems and simplified equations of motion are used. In order to test the concepts discussed above, such a model should at least be able to describe the eccentricity of horizontal tidal currents. Van Leeuwen and De Swart (2002) analysed tidal properties and patterns of sediment erosion–deposition for idealised inlet geometries, using the HAMSOM model developed by Backhaus (1985), which they extended with sediment transport routines. They found indications that the mechanism of Sha (1989) is not fully supported by their numerical experiments, but did not consider to what extent their findings were representative of realistic tidal inlets. Besides, they neither investigated the possible formation of an ebb-tidal delta nor that of channels and shoals in this area.

Therefore, in this paper, a similar simplified model as that discussed by Van Leeuwen and De Swart (2002) is analysed, but with emphasis on understanding tidal properties and net erosion–deposition of sediment on the seaward side of a prototype tide-dominated inlet, the Frisian Inlet. In order to study the long-term morphological evolution of tidal inlets, the feedback from the changing bottom to the water motion has to be taken into account. As this facility is not yet available for the simplified model, such simulations are carried out with a full morphodynamic model, called Delft3D. The latter has already been successfully used by Wang et al. (1992, 1995) to model water motion and morphological evolution of the Frisian Inlet on timescales of several years. In this paper, results of longer time periods are presented which reveal the development of an ebb-tidal delta.

In the following section, the characteristics of the Frisian Inlet system are presented, followed by a description of the numerical models and the results with regard to the initial formation of channels and shoals. Next, the long-term evolution of the bathymetry is investigated with the Delft3D model, followed by a discussion of the results and the conclusions.

2. Material and methods

2.1. The Frisian Inlet

The Frisian Inlet is located in the Dutch Wadden Sea, between the barrier islands Ameland and Schiermonnikoog (Fig. 1). It consists of a wide basin (nowadays its length and width are approximately 10 and 20 km, respectively). Most of the bottom material is fine sand (mean grain size of 200 μm). In the inlet, a supra-tidal shoal (called the Engelsmanplaat) is located. It consists of consolidated sediment that is much more resistant to erosive forces than sand. Therefore, the Engelsmanplaat causes a rather effective separation of two sub-inlet systems called the Pinkegat (on the west)
and the Zoutkamperlaag (on the east). Both subsystems have their own ebb-tidal delta: the size of the delta of Pinkegat (with a seaward extension of about 3 km) is about half that of Zoutkamperlaag. Horizontal water motion in this area is mainly driven by tides, with the semi-diurnal M\textsubscript{2} constituent being the dominant component. Characteristic sea surface amplitudes are about 1 m and maximum tidal currents are of the order of 1 m s\textsuperscript{-1}; the tidal wave propagates along the coast from west to east at about 15 m s\textsuperscript{-1}. Significant wave heights in this area are about 1 m. This system is a mixed-energy tide-dominated inlet system according to the classification of Gibeaut and Davis (1993) and Hubbard et al. (1979).

Presently, on both ebb-tidal deltas and in the inner basin, a complex pattern of channels and shoals is observed. Recent field data of the water motion at various locations in the Frisian Inlet were discussed by Van de Kreeke and Dunsbergen (2000). They reported small (positive and negative) values of the eccentricity of tidal currents in the basin. Only one station was situated on the ebb-tidal delta, so that the spatial distribution of eccentricity in this area cannot be reconstructed from data.

2.2. The HAMSOM model with added sediment transport routines

Experiments with a fixed bathymetry were carried out with the HAMSOM model (HAMburg Shelf Ocean Model), extended with routines to compute sediment fluxes and erosion–deposition of sediment at the bed. The HAMSOM model, developed by Backhaus (1985), calculates the water motion by solving the shallow water equations. Here, the depth-averaged version of the model was used.

For the sediment transport, a suspended load parameterisation is used which contains advective and diffusive contributions and explicitly accounts for settling lag effects. For further details, see Van Leeuwen and De Swart (2002). The erosion–deposition is given by the divergence of this flux. Here, the depth-averaged version of the model was used.

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2.3. The Delft3D-MOR model

The extended HAMSOM model was applied to a highly schematised tidal inlet system, consisting of a rectangular inner basin that is connected by a strait to the adjacent sea. Fig. 2 shows the default geometry and default depth profile. The geometric (and other parameter) values are representative for the Frisian Inlet system and were obtained from the data presented by Oost and De Boer (1994). Note that the central axis of the strait does not coincide with that of the inner basin. The default bottom neither contains an ebb-tidal delta, nor any channels and shoals: the depth is constant in the basin (2 m) and increases linearly in the outer sea in the offshore direction. The motivation for this choice was to investigate whether the interaction between tidal currents and this initial bathymetry (to be expected after a storm-induced flooding of the backbarrier area) would result in the formation of features like an ebb-tidal delta and channels and shoals. The water motion was forced by prescribing an eastward propagating semi-diurnal (M\textsubscript{2}) tidal wave, with a constant amplitude of 1 m, at the open boundaries (the dashed lines in Fig. 2). Tidal residual currents and overtides are generated internally by nonlinear shallow water terms and bottom friction. Forcing by waves is not included. For numerical details, see Stronach, Backhaus, and Murty (1993).
the tidally averaged sediment flux \( \langle F \rangle \), as denoted by Eq. (1). The formulation for the volumetric sediment flux per unit width, \( \langle F \rangle \), is discussed later on.

The geometry used resembles that of the Frisian Inlet. The conditions at the open boundaries were taken from a larger scale model that simulates the entire Dutch Wadden Sea (Hibma, personal communication). Only \( M_2 \) elevations were used, which had an amplitude of 1.14 m. Forcing due to wind and waves was neglected.

3. Results

3.1. Initial patterns: water motion

The concepts of Sha (1989) were tested by carrying out numerical experiments with the extended HAMSOM model. The simulations covered a period of several tidal cycles. At each gridpoint, a Fourier analysis was made of the tidal velocity components of the last two tidal periods (representing non-transient behaviour). From this, the characteristics of the \( M_2 \) tidal ellipse (long axis, eccentricity, orientation and phase) and the residual current were computed.

The first aspect of the hypothesis of Sha (1989) to be verified with the process-oriented HAMSOM model is that during flood an overshoot of the tidal current occurs on the downstream side of the inlet, due to phase differences between shore-parallel tidal currents and currents in the strait. The model results (not shown) indeed reveal such phase differences, but no overshoot of the tidal current on the downstream side of the inlet is found. These results are consistent with those of Van Leeuwen and De Swart (2002) who used a different inlet geometry and a different bathymetry.

The second statement of Sha (1989) is that tidal currents are weaker and more eccentric on the downstream side of the inlet than on the upstream side. This was tested with the extended HAMSOM model by computing the long axis and eccentricity of the \( M_2 \) tidal current ellipses. The results, shown in Fig. 3, indicate that large tidal currents occur at the transition basin–outer sea with local maxima in the vicinity of the two barrier islands. Nearly circular tides are found at the downstream side of the inlet, but their amplitudes are not much smaller than those of the currents on the upstream side. The results obtained with the process-oriented model thus confirm some aspects of the conceptual model.

The last aspect of the water motion that is discussed concerns the residual flow. The motivation for doing this is that it is one of the important factors that cause net sediment transport. Within the context of the adopted (suspended load) sediment flux formulation, the other important factors are tidal asymmetry (joint action of \( M_2 \) and \( M_4 \) tidal currents), settling lag effects (sediment concentration lags tidal currents because particles have a finite settling time) and diffusive processes. The physical concepts of these transport mechanisms are discussed in Ridderinkhof (1997), Van de Kreeke and Robaczewska (1993) and references therein. In Fig. 4, the residual currents are shown. In the strait, these currents are found to be directed to the open sea. The residual flow in the outer sea is in the direction of tidal wave propagation.

The results of Fig. 4 can be understood from the fact that the tide in the strait is a partially standing wave, hence the phase difference between tidal elevations and tidal velocities is less than 90°, in particular near the inlet. The tidal wave transports mass into the basin (the so-called Stokes drift) and mass conservation implies that there must be a residual current in the opposite direction to compensate for this mass flux. Seaward of the strait, the residual current directed along bathymetric

![Fig. 3](image-url) Contour plots of the \( M_2 \) long axis (maximum tidal current, in m s\(^{-1}\)) (left) and of the \( M_2 \) eccentricity (right) computed with the extended HAMSOM model.
contours is caused by tide–topography interaction (see Zhang, Boyer, Pérenne, & Renouard, 1996).

3.2. Initial patterns: sediment fluxes and erosion–deposition

The net sediment flux was computed with the extended HAMSOM model by using the suspended load formulation. The sediment erosion–deposition was obtained from the divergence of this flux. Fig. 5 shows the resulting net volumetric sediment flux per unit width (left) and erosion–deposition of sediment at the bed (right). Noticeable are the landward-directed flux in the basin and the seaward-directed flux in the strait and nearby outer sea. A net transport of sediment from the strait to the open sea is found, as well as a tendency to form an ebb-tidal delta. Initial adjustments of the bathymetry also occur in the basin.

Fig. 5(b) shows that in the strait net erosion occurs, particularly on the sides. This indicates the tendency to form two channels. On the seaward side of the inlet and near the basin boundaries, net deposition of sediment is observed, with the most significant changes occurring near the downstream island. The model results do not clearly confirm the idea of Sha (1989), that on the downstream side of the inlet preferred deposition occurs. In particular, in the area where tidal eccentricity is large (Fig. 3(b)) erosion, rather than deposition, is found. The initial pattern of erosion–deposition does not show that channels tend to develop with a preferred upstream orientation.

To test the sensitivity of the model results to the sediment flux formulation used, additional model runs were performed with the following expression for the volumetric sediment transport per unit width:

\[
\mathbf{F} = \frac{0.05 \mu^4 \mathbf{u}}{\sqrt{g} C_z (s - 1)^2 d_{50}}
\]

This is the total-load formulation of Engelund and Hansen (1972), with \( \mu \) being the depth-averaged velocity vector, \( C_z \) the Chezy coefficient, \( g \) the acceleration due to gravity, \( s \approx 2.65 \) the ratio between grain density and fluid density and \( d_{50} \) the mean diameter of the grains. Compared with the suspended load sediment flux, the Engelund–Hansen flux does not account for settling lag effects and has no diffusive components. Results obtained with the Engelund–Hansen formulation (not shown) agree well with those found with the suspended load flux. Thus the model results are robust with respect to changes in the sediment transport formulation. The presence of an area near the strait where divergence of...
the sediment flux occurs (Fig. 5(b)) is a common feature in tidal inlets; this area is called a bedload parting zone (Harris, Pattiaratchi, Collins, & Dalrymple, 1996).

The results mentioned above also imply that settling lag effects and diffusive processes are not dominant factors in forcing net sediment fluxes. Thus, the two possible mechanisms that remain are: the joint action of stirring by tides and subsequent transport by residual currents, and tidal asymmetry. The relative contributions of both mechanisms to the total net transport can be quantified by the dominance index \( I_D \) (Van der Molen & De Swart, 2001),

\[
I_D = \frac{|F_{\text{res}}| - |F_{\text{asym}}|}{|F_{\text{res}}| + |F_{\text{asym}}|}.
\]

Here \( |F_{\text{res}}| \) and \( |F_{\text{asym}}| \) are the magnitudes of the transport related to residual currents and tidal asymmetry, respectively (Van de Kreeke & Robaczewska, 1993). Note that \( I_D \) can attain values between −1 and 1; positive (negative) values imply that sediment transport related to residual currents (tidal asymmetry) prevails. A contour plot of this dominance index is shown in Fig. 6. It reveals the importance of combined tidal stirring and transport by the residual current on the seaward side of the inlet and the dominance of tidal asymmetry in the basin.

The model results presented here indicate the tendency of the inlet system to form an ebb-tidal delta. The underlying process is that sediment, being mainly eroded in the strait, is transported (by the joint action of tidal stirring and residual currents) towards the outer sea and is deposited seaward of the strait. Besides, part of the sediment that is eroded in the strait is transported into the basin (by tidal asymmetry) and is deposited on the landward side of the barrier islands.

### 3.3. Long-term simulations

The long-term development of bottom patterns in a tidal inlet system was studied with the Delft3D model. The initial bathymetry and all parameter values were the same as those used in the previous section. The Engelund–Hansen formulation (2) was used to compute the volumetric sediment flux per unit width.

First, the initial patterns of the water motion, sediment fluxes and erosion–deposition were computed with the Delft3D model (not shown) and compared with those of the extended HAMSOM model (Section 3.2). The two models yielded similar results, thereby confirming the validity and versatility of the extended HAMSOM model. The subplots in Fig. 7 show the evolution of the bathymetry from the initial stage up to 500 years. At first, there is no ebb-tidal delta but the results of the previous section already showed that sediment is deposited in the area seaward of the inlet. After 100 years, depths have clearly decreased here, so an ebb-tidal delta does indeed develop. At this stage, its spatial pattern is still rather symmetrical and two channels are forming in the inlet, near the tips of the two barrier islands.

After 200 years, it becomes clear that two distinct ebb-tidal deltas develop. The channels in the inlet are still deepening and protruding further into the basin. Besides, a clear asymmetrical pattern develops: the eastern channel in the neighbourhood of Schiermonnikoog is becoming larger and deeper than the western channel. With the deepening of the channels, the ebb-tidal delta is extended, the eastern delta becoming larger than the western one. The orientation of the ebb-tidal deltas is changing as well. The delta of the eastern tidal inlet system becomes upstream-oriented, whilst the other one becomes downstream-oriented. Thus, the entire system becomes asymmetrical. After 300 years, this degree of asymmetry further increases and even channel branching can be observed in the eastern part of the basin. After 400 years, the seaward extension of the ebb-tidal delta slows down and after 500 years, a kind of large-scale morphodynamic equilibrium is reached.

The asymmetrical patterns only appear after a long time. This suggests that the evolution of the asymmetry of the ebb-tidal delta is a long-term, non-linear process that involves the feedback between tidal motion and the erodible bottom. In these simulations, the ‘Engelsmanplaat’, a consolidated shoal in the middle of the Frisian Inlet, was not incorporated. Nevertheless, a clear double-inlet system develops. Apparently, the Engelsmanplaat does not play a crucial role in the stability of the Frisian Inlet.

A comparison of the results of the long-term model simulation after 500 years (Fig. 7) with the observed bathymetry of the Frisian Inlet system, as shown in Fig. 1, reveals some remarkable similarities. Both the
model and the field data show the presence of two separated subsystems, the Pinkegat on the west and the Zoutkamperlaag on the east. The model also yields an eastern ebb-tidal delta, which is larger than the one located more to the west. The orientations of these deltas correspond with those observed in the Frisian Inlet: an upstream-oriented Zoutkamperlaag and a downstream-oriented Pinkegat (although the orientation of the Pinkegat varies with time). Also the branching of the main ebb channel in the eastern inlet is reproduced by the model. On the other hand, many features that are present in the original Frisian Inlet system are not captured by the model. The Zoutkamperlaag shows a sequence of channels branching into smaller and shallower channels towards the land, which is not seen in the model results. This is not surprising as their extents are smaller than the grid size (about 200 m) of the numerical model. Furthermore, towards the end of the simulation, the model shows a tendency to form multiple channels on the ebb-tidal delta, which is not realistic. It should also be noted that storm events were not included in the long-term simulation.

4. Conclusions

In this paper, results have been presented of numerical experiments with process-oriented models applied to tidal inlet systems. The first objective was to verify a conceptual model, formulated by Sha (1989), stating that the formation and spatial asymmetry of ebb-tidal deltas in tide-dominated inlet systems is due to the interaction between shore-parallel tidal currents and currents in the strait. The second objective was to identify the dominant physical mechanisms causing the initial formation and long-term behaviour of the ebb-tidal deltas and channels and shoals in a prototype tide-dominated inlet system, the Frisian Inlet, located in the Dutch Wadden Sea.

The results indicate that tidal currents are slightly weaker and more eccentric on the downstream side of the inlet than on the upstream side, which is consistent with the conceptual model of Sha (1989). No overshoot of the tidal current is observed during flood and no clear tendency for preferred sediment deposition on the downstream side of the inlet is found. The conclusion is that the concepts of Sha (1989) are only partly

Fig. 7. Bathymetry, computed with the Delft3D model, at time $t = 0$ and after 100, 200, 300, 400 and 500 years. Initially, the depth in the basin is 2 m and it increases linearly in the outer sea. The black lines represent the coastal boundaries. The forcing consists of tides only, waves and storm events are not accounted for.
confirmed by the model results. The precise formulation of the sediment transport is not a key issue: both a suspended-load and total-load formulation yielded almost the same results. The two important mechanisms controlling the net transport in this case are the combined stirring of sediment by tides and subsequent transport by residual currents and tidal asymmetry. The first mechanism dominates on the seaward side of the strait whereas tidal asymmetry is the dominant factor in the basin. Deposition of sediment occurs on both the seaward and landward sides of the barrier islands.

The long-term development of the bathymetry was investigated with the Delft3D model, applied to the Frisian Inlet. It was found that the system develops into a double-inlet system with two clearly recognisable ebb-tidal deltas which both have an asymmetrical shape. The eastern delta is characterised by an upstream-oriented main channel and has a larger dimension than the western delta, which has a downstream-oriented channel. In the initial phase (a few hundreds of years), the ebb-tidal deltas rapidly extend seaward, but after about 300 years the increase of their sand volume is much slower. Despite this behaviour, channels are still developing, indicating that the final state is not steady. The fully developed bathymetry computed with the numerical model has many similarities with the observed bathymetry of the Frisian Inlet. This includes the presence of two ebb-tidal deltas, the eastern one being larger than the western one, as well as channels on the delta and branching of channels in the eastern part of the basin. The orientation of the main channel on the western ebb-tidal delta is downstream-oriented, a property which is usually attributed to the action of waves and wind (FitzGerald, 1996; Sha, 1989). Since the water motion in the present model is only driven by tides, this puts such a statement in a different perspective. In the model simulations, the possible effect of the ‘Engelsmanplaat’, a consolidated shoal in the middle of the Frisian Inlet, was not accounted for. It was suggested by Wang et al. (1992) that the Engelsmanplaat could be an important factor for the morphodynamic stability of the Frisian Inlet. This statement is not confirmed by the model results presented here, which show smooth behaviour even in the absence of this shoal.

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