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ADVANCES IN MORPHODYNAMICS OF TIDAL RIVERS AND ESTUARIES

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Abstract: Using examples from research project and studies on the morphological evolution of sandy estuaries and coastal lagoons in The Netherlands, the added value of simultaneously applying different methods of analysis or prediction is demonstrated. Where the methods overlap, they mutually validate each other, where they are complementary, they provide more complete information that may reduce uncertainty.

INTRODUCTION

Many estuaries around the world are at the same time economically important links between land and sea, providing access to harbours and inland waterways, and valuable natural environments, providing shelter, feeding and breeding grounds and nurseries to a wide variety of species.

In the past, these functions could mostly be combined without much trouble, but now that man is interfering with these systems at an ever larger scale and is putting ever higher demands on navigability for ever larger ships, many estuarine ecosystems are stressed to the extreme. Mitigating measures are taken and rules and regulations are implemented in order to protect these systems. Their design, implementation and monitoring requires thorough knowledge of the physical and biological processes that make an estuary function, more than in the case of an intrusive engineering structure (e.g. a barrier or a dam) that drastically changes the estuary, anyway. In other words: we will have to enhance our knowledge and prediction capabilities regarding the (quasi-)natural behaviour of estuaries if we want to have a sustainable management of these systems.

Using examples from estuarine research in The Netherlands, the present paper shows the potential of a balanced research methodology, in which different methods provide for each other's validation and thus increase the efficiency of research efforts.

RESEARCH METHODOLOGY

Traditionally, there are three categories of hydraulic research methods, viz. field work, laboratory experiments and numerical modelling. These may be subdivided, e.g. field work into long-lasting monitoring programmes and short field campaigns, laboratory experiments into scale model simulations and fundamental process-oriented experiments, numerical modelling into code development and applications, but that does not affect this main categorisation. In recent years, a fourth category has come up, viz. behaviour analysis (cf. Blondeaux, 2001). Starting from a mathematical description of the basic physics, elementary modes of behaviour under more or less idealised conditions are investigated using analytical or semi-analytical mathematical techniques, such as linear and non-linear stability analysis, or characteristics analysis.

This fourth category has come up strongly in the analysis of morphological phenomena, such as bed undulations and channel/shoal formation. As far as estuarine morphology is concerned, Seminara and his group in the University of Genoa have done pioneering work (e.g. Seminara and Tubino, 2001), and so has the group around De Swart at Utrecht University (e.g. Schuttelaars and De Swart, 1999, 2000). Although many of the analyses concern small perturbations to a basic state, they give good insight into the mechanism underlying these morphological processes.

None of these four categories is suitable as a sole predictor of estuarine morphology in a real-life situation in all its natural and human-induced complexity. Field campaigns usually don't cover extreme design conditions, and – although new technologies such as remote sensing offer new perspectives – it is difficult to obtain a comprehensive picture of the system's behaviour from monitoring a few parameters. Scale models suffer from scale effects, especially in the case of morphological experiments, and process-oriented experiments usually focus on one aspect of a much more complex reality. Numerical models in the hands of good experts are quite powerful tools, but their schematisation and validation needs special attention. When such models are utilised in a predictive mode, assessing the uncertainty range in the output may be problematic. Behaviour analyses have to stick to highly idealised situations, in order to allow for analytical solutions. Moreover, their mathematical complexity makes them difficult to access to non-specialists.

In fact, the categories represent different ways of looking at a phenomenon or a problem. Therefore, there is much added value in the combination of methods from different categories. Validation of numerical models against field or laboratory data is a classical one, with data-model integration and data-driven modelling as modern variations. Another example is the combination of a numerical model with a behaviour analysis. In the following, we will see examples of such combinations.

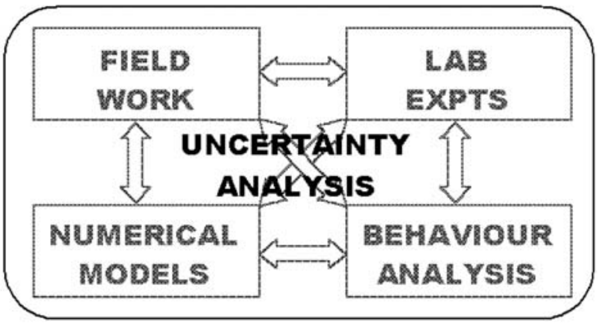

Fig. 1 The table has four footings and a blade

Using the metaphor of a table(Fig.1), four interconnected footings (representing the four categories of methods) provide stability (robust conclusions). We must not forget, however, that the table also has a blade, representing a common feature of all methods: uncertainty analysis. So far, this type of analysis has been underexposed in the fields of water management and geomorphology. Most models are utilised in a deterministic setting, even though they describe natural systems with many uncertain and more or less randomly varying inputs, and even when exploring future responses to human interventions or changing environmental conditions. Probabilistic prediction of estuarine morphology is still very rare and will therefore not be discussed here.

ESTUARIES AND COASTAL LAGOONS IN THE NETHERLANDS

The Netherlands, though being a small country of just above 4×10^4 km^2, encompasses two important estuarine systems and a major coastal lagoon. The largest of the estuarine systems, located in the southwest of the country (Fig. 2), forms the combined mouth of the Rhine-Meuse-Scheldt river complex and is usually indicated as the Delta area. After the floods of 1953, this area has been subject to large human interventions, such as the construction of dams and storm surge barriers. Most of the estuaries in the northern part of the Delta area have thus been separated from the sea and now form reservoirs that are being filled up by river sediments. The Western Scheldt, which provides access to Antwerp harbour, has been kept open, but the fairway to Antwerp has been deepened several times since the 1950's and requires a significant amount of maintenance dredging. The Ems-dollard, the smaller estuarine system in the extreme northeast of the country, provides access to Emden and the River Ems. The northern part of the country is bounded by a large barrier island system sheltering a coastal lagoon called the Wadden Sea. This internationally protected nature reserve extends along the north of Germany through to Denmark and is separated from the North Sea by a series of barrier islands.

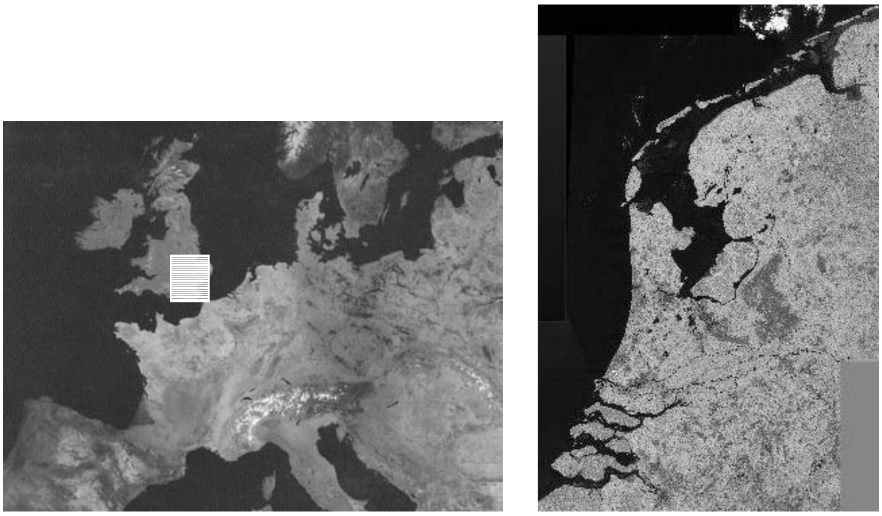

Fig. 2 Geographical location of The Netherlands and its main estuarine systems

SAND-MUD SEGREGATION IN A FORMER ESTUARY

In 1970, the Haringvliet-Hollands Diep estuary, in the north of the Delta area, was closed off by a dam, including a sluice system to discharge the flow from the rivers Waal and Maas, which partly debouch into this estuary (Fig. 3). Since the closure, the estuary has gradually filled up with river sediments, partly sand, which entered the area as a sheet from upstream, and partly polluted cohesive sediment, which was deposited somewhat further downstream.

Fig. 3 Landward part of the Haringvliet/Hollands Diep estuary; the large diagonal branch is the Nieuwe Merwede, connecting the Hollands Diep (bottom left) to the Merwede (top right), which changes into the Waal further upstream; the river near the bottom is the Bergsche Maas, which is connected to the Maas further upstream

Coarse and fine sediments arrive in a time-varying (discharge-dependent) mixture from the rivers upstream, but are segregated in the settling area, primarily due to the difference in settling velocity. As time proceeds, the estuary fills up and the settling area gradually shifts further downstream. This means that, sooner or later, muddy areas will be covered by a sand sheet (Fig. 4), and that finally the rivers debouch straight into the sea.

In terms of bottom quality, it means that polluted sediments will be covered by a layer of clean sand, which may give the impression that the bottom quality problem has vanished. Now that there are plans to reopen the gates and re-allow a certain amount of tidal motion into the estuary, we have to consider the possibility that polluted sediment packages will be uncovered and create new problems.

In order to be able to predict those effects, Van Ledden and Wang (2001) developed a sand/mud interaction model and tested it against measured data from the Nieuwe Merwede-Hollands Diep-Haringvliet system. The results, shown in Fig. 4, agree well with measured data, especially in the reproduction of the regional segregation of sand and mud and in the occurrence of a deposition minimum at the south-westerly end of the Nieuwe Merwede. Exact agreement was not sought, because this would have required running the model with input time series of tides and sea levels.

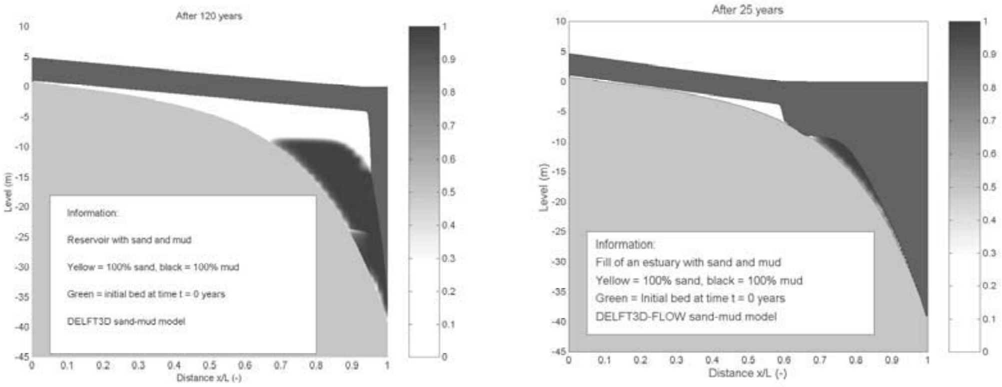

Fig. 4 Computed segregation of sand (light hump) and mud (dark hump) in a reservoir, after 25 years and after 100 years (Van Ledden and Wang, 2001)

In all cases, a comparison of patterns in the measured data and the model results (in this case: segregated deposition areas with a deposition dip in between; mud deposits covered later on by a sand layer) is suitable for a first validation of the model. Point-by-point quantitative comparisons can wait till a later stage. Moreover, one may wonder how much point-by-point tuning of the model would contribute to the predictive value under natural (so uncertain) conditions. From the point of view of the data, the model helps separating signal and noise (e.g. due to spatial and seasonal variations) in the measured data, and hence interpreting these data.

Clearly, this tests primarily the deposition part of the model. Van Ledden (2003) describes other successful tests in more complex situations, such as the Wadden Sea.

LONG-TERM MORPHOLOGICAL EVOLUTION OF THE WESTERN SCHELDT

The building of engineering works is usually a strong driver of field monitoring programmes. In the case of the Western Scheldt (Fig. 5), the continual deepening of the fairway to Antwerp harbour has been a reason for monitoring since the 1950's.

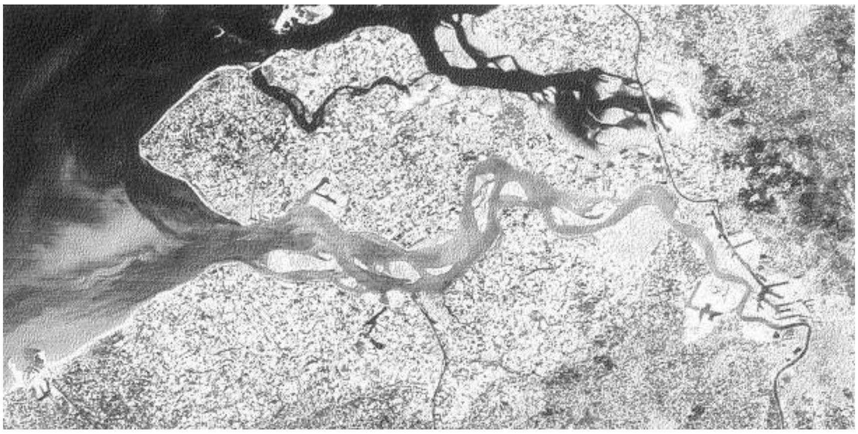

Fig. 5 Overview of the Western Scheldt estuary (to the right: Antwerp harbour)

The dredged material used to be deposited on the marshes next to the channel and there was a concern about (1) an overall inefficiency of the dredging operations by short-circuiting of dredged material, and (2) a loss of character of the estuary, becoming manifest by a consistent degradation of the secondary channel system, a decrease of the intertidal area and an increase of the supratidal area.

One of the analyses of the monitoring data concerned the development of shoals and bars in the central part of the Western Scheldt (Jeuken, 2000). Fig. 6 gives a typical snapshot of the bed topography in that zone, and, for comparison, Fig. 7 gives a result from a long-term morphological simulation with a 2-D depth-averaged Delft 3D-model of an idealised straight estuary of constant width, of dimensions similar to those of the Western Scheldt (Hibma et al., 2003a). The patterns are quite similar, especially when taking into account the differences in overall geometry.

This illustrates that 2-D and 3-D morphological modelling is about spatial patterns, rather than point-by-point comparisons of measured data and computational results. This means that models should be validated either by qualitative comparisons, or by comparing measured data and model results expressed in terms of pattern properties.

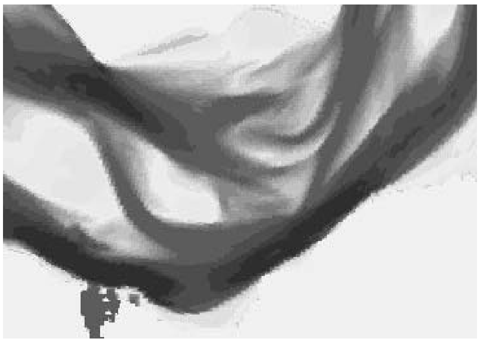

Fig. 6 Measured bed topgraphy in the Western Scheldt (Jeuken, 2000)

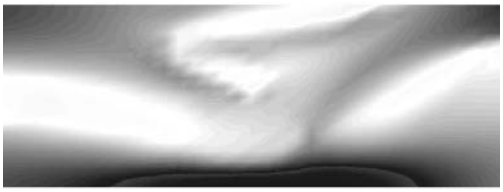

Fig. 7 Computed bed topgraphy in an idealised estuary (Hibma et al., 2003)

The combination of data analysis, numerical models and a stability analysis for a pair of ebb- and flood-channels with dredging and deposition (Wang and Winterwerp, 2001) has led to the so-called cell-concept of how the Western Scheldt functions as a sediment sharing system (Fig. 8). At present, this concept forms the basis of a number of large exploratory studies on how to sustainably manage this estuary.

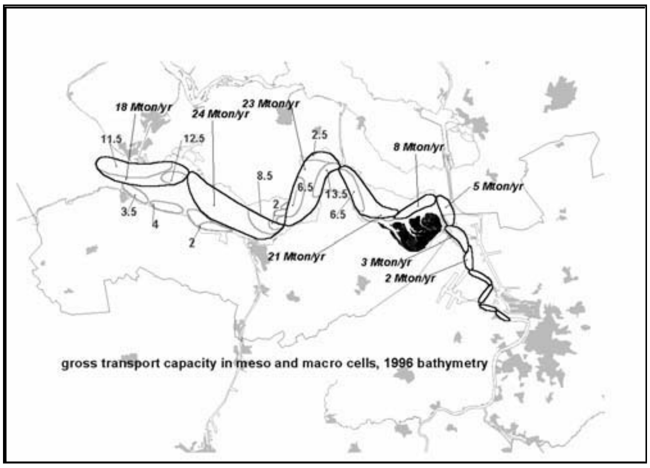

Fig. 8 Cell concept of the Western Scheldt; the sediment circulation within each cells is a multiple of the exchange between cells (Winterwerp, et al., 2001)

Another example of mutual validation of research methods concerns numerical modelling and behaviour analysis. Linear perturbation analyses of bar formation in shallow well-mixed estuaries with a sandy bed (e.g., Seminara and Tubino, 2001) reveal preferent modes of unstable bed waves. Since the analysis is linear, it only applies to small-amplitude waves, which leaves us with the open question how much it tells about finite-amplitude bedforms. On the other hand, the equations solved are closely similar to the ones in the numerical simulation model, so the latter should be able to reproduce the initial formation of unstable bed modes. Hibma, et al. (2003b) show that this is the case, indeed, in the initial stages of their model simulation for an idealised straight estuary with dimensions like those of the Western Scheldt. As the amplitudes of the bedforms increase, however, non-linear interactions take over and give rise to an essential change of pattern and a shift in dominant length scale.

WESTERN SCHELDT VERSUS WADDEN SEA

An example of mutual validation of numerical models and experience from observations concerns the channel-shoal pattern in short and elongated tidal basins. Van Veen (1950), after studying maps and other information on estuaries and coastal lagoons of different shape, came to the conclusion that in elongated estuaries (length comparable to the tidal wave length) the channel system has the shape of a willow branch, with the main branch formed by a continuous meandering ebb-channel and the sprouts formed by short flood-channels (Fig. 9). The channel system in a short basin, however, is much more like an apple tree, i.e. multiply branched (Fig. 10).

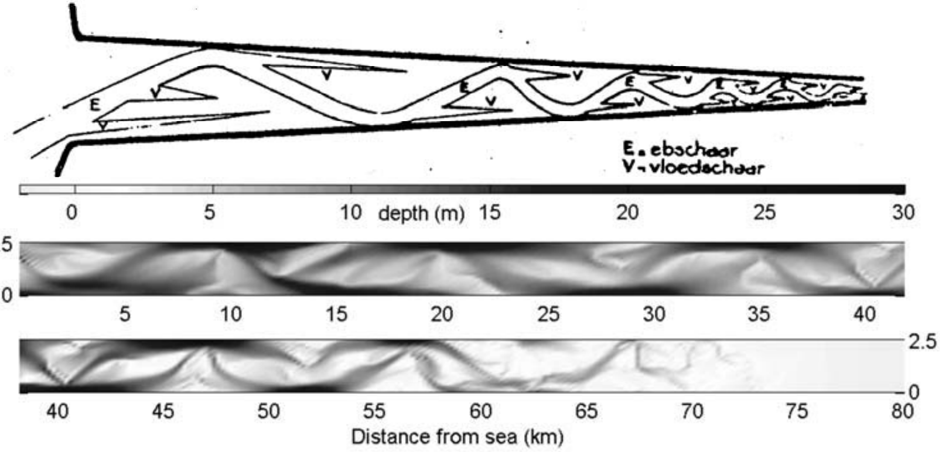

Fig. 9 Channel patterns in an elongated estuary; top: as drawn by Van Veen (1950); bottom: as computed with a Delft3D morpholigical model (Hibma, et al., 2003)

Numerical models of the formation of channel-shoal patterns yield the same picture. The bottom panel of Fig. 9 shows a typical result of a 2-D depth-averaged morphodynamic model of an elongated estuary of constant width and driven by a harmonic M2-tide (Hibma, et al., 2003). The willow-tree structure is visible, especially in the seaward part.

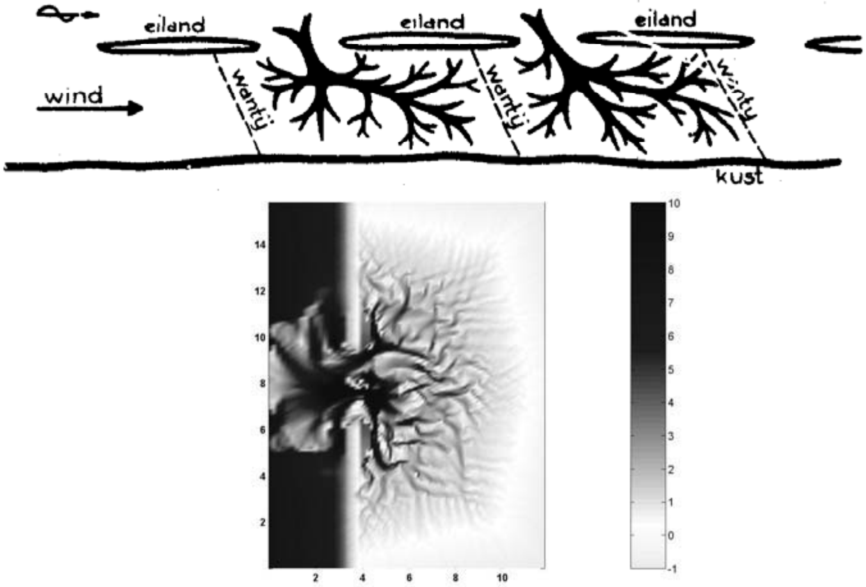

Fig. 10 Channel pattern in a short tidal basin; top: as drawn by Van Veen (1950); bottom: as computed with a Delft-3D morphological (Marciano, 2003, pers.comm.)

The bottom panel of Fig. 10 shows a result of a similar model for a short basin of similar dimensions as the basins in the Wadden Sea. Although the channel pattern still doesn't match the observed pattern (too many ebb-channels), the apple-tree structure is visible. Also the fractal structure turns out to agree well with the results from an analysis of the channel patterns in a number of Wadden Sea basins (Cleveringa and Oost, 1999).

CONCLUSION

The main conclusion to be drawn from these examples is that there is added value in the combination of research methods when analysing or predicting the morphological behaviour of sandy estuaries and coastal lagoons. Different methods provide partly overlapping, partly different information. The overlap can be used for mutual validation of the methods, the differences for further analysis, uncertainty reduction, etc. Since the methodology is generic, these findings also apply to other situations than the ones shown here.

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