A simple method to predict long-term morphological changes

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Abstract

A method is presented to obtain a first estimate of long-term bathymetric changes based on an initial transport field obtained from a 2DH process model. The results are compared with full morphodynamic simulations and measured bottom developments after extension of the harbour moles at IJmuiden, the Netherlands.

Introduction

Over the past decade, process-based morphodynamic models based on depth-averaged two-dimensional equations for wave action, flow, sediment transport and bed level change have been developed at several institutes and have now become generally available for application in practical model studies (for a review see De Vriend et al., 1993 ; Nicholson et al., 1993).

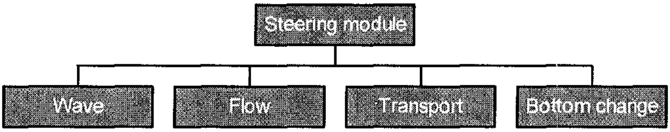
The strength of these models lies within their ability to represent the various processes simultaneously, and to evaluate the changes in these processes due to human interference in the form of structures, nourishments or dredging. The outcome of the model is often not very accurate and expertise is needed to calibrate it for a given situation. Even then, absolute predictions are often difficult to make, but a comparison of simulations with and without various scenarios of interference usually yields useful and objective results, based on which an overall advice can be given.

A major problem still lies in the fact that the time-scale of interest in many cases is in the order of decades, whereas the simulation period that can be feasibly covered is usually not much longer than some years. In this paper a simple method will be presented which reduces the computational effort by an order of magnitude, while maintaining an acceptable accuracy. This clears the way for simulations over periods in the order of decades. The simple method will be compared with the full morphodynamic method, and both will be tested against measured bathymetric changes after constructionof a large extension of the harbour of IJmuiden in the Netherlands.

'Standard' morphodynamic method

The 'standard' morphodynamic method applied by various institutes (e.g. de Vriend et al. (1993), Nicholson et al., 1997) involves a coupled simulation of waves, currents, transport and bottom changes. The Delft3D-MOR system, developed by WL | Delft Hydraulics, is one of the systems designed to apply this method in consulting practice. The details are outlined in Roelvink and Van Banning (1994) and Roelvink et al. (1994). Here we present the main features.

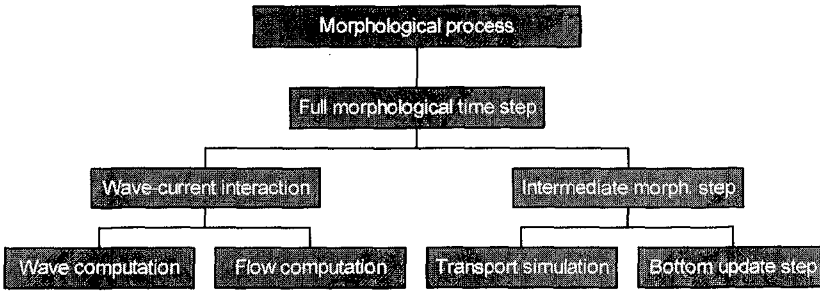
Figure 1 Delft3D model structure



The model structure consists of a steering module and four computational modules, as outlined in Figure 1. The steering module calls the computational modules in any prescribed order, and arranges the time-progress of each module. It allows iterations between modules. The computational modules are:

- Wave module based on HISWA (Holthuijsen et al, 1989). Refraction and dissipation of directionally spread random waves. Several computations through a tidal cycle in one call.
- Flow module solves non-steady, 2DH or 3D shallow water equations on a curvilinear finite difference grid, using ADI scheme. Wave effects on flow through bottom friction and driving terms.
- Transport module solves quasi-3D advection-diffusion equation for sediment. Equilibrium concentrations in this study based on Bijker with wave effects. Recently added cross-shore transport terms using Bailard approach.
- Bottom update module solves sediment balance using explicit scheme of Lax-Wendroff type, with automatic timestep.

Figure 2 Process tree



A simulation in Delft3D-MOR is built up like a hierarchical tree structure, a so-called process tree. In Figure 2 a typical tree is given. A morphological process is built up from morphological time steps, which consist of a simulation of wave-current interaction over a tidal cycle, followed by a number of intermediate steps where transport is computed and averaged over a tidal cycle, and the bottom is updated. The transport and bottom computations are repeated a number of times using "continuity correction" (see below), until bottom changes are so large that a full hydrodynamics computation is required.

Sediment balance

The sediment balance equation reads:

$$\frac{\partial z}{\partial t_{mor}} - \frac{\partial S_x}{\partial x} + \frac{\partial Sy}{\partial y} = 0 \tag{1}$$

Here, z is the bed level (positive downward), S_x and S_y the components of the tide-averaged sediment transport vector, and t_{mor} the time; the subscript refers to the fact that the time scale of bottom changes is generally much larger than the tidal period.

Continuity Correction

The sediment transport field is generally a function of the velocity field $\vec{u}$ and the orbital velocity u_{orb}:

$$\vec{S} = f(\vec{u}, u_{orb}) \tag{2}$$

When the bathymetry changes, the flow field and orbital velocity change, and have to be recomputed. The "continuity correction" is a frequently applied method to adjust the flow field after small changes in the bathymetry. The flow pattern is assumed not to vary for small bottom changes:

$$\vec{q} \neq f(t_{mor}) \tag{3}$$

where $\vec{q} = h\vec{u}$ is the flow rate vector and h is the water depth. The same goes for wave pattern: wave height, period and direction are kept constant, and only the orbital velocity is adapted for the local water depth:

$$H_{rms} \neq f(t_{mor}) \tag{4}$$

$$T_p \neq f(t_{mor}) \tag{5}$$

Since $\vec{u} = \vec{q} / h$ and $u_{orb} = f(H_{rms}, T_p, h)$, adaptation of the sediment transport field is now simply a matter of adjusting the velocity and orbital velocity and recomputing the sediment transport using eq. (2).

In case of a tidal flow situation, a number of velocity and wave fields based on the original bathymetry are stored, and when the depth changes, the adapted transport field is computed for a number of time points in the tidal cycle and subsequently averaged. This averaged transport field is then used in the sediment balance (1).

The method still requires full transport computations through tidal cycle, which can be time-consuming when suspended-load transport is to be accounted for. The morphological time step is often dominated by some shallow points, which are usually not of interest. This means that typically after some 10-20 continuity correction steps, the full hydrodynamic model has to be run on the updated bathymetry.

Rapid Assessment of Morphology (Delft3D-RAM)

In practical consultancy projects there is often a need to interpret the outcome of initial transport computations without having to resort to full morphodynamic simulations. One way of doing this is looking at initial sedimentation/erosion rates, but this method is flawed in many respects. Initial disturbances of the bathymetry lead to a very scattered pattern, and, as De Vriend et al. (1993) point out, sedimentation/erosion patterns tend to migrate in the direction of transport, a behaviour which is not represented in the initial sedimentation/erosion patterns.

What we propose in this paper is a simple method which overcomes these disadvantages. In the previous section, we have seen that under the assumptions used in the "continuity correction", the tide-averaged transport rates are a function of flow and wave patterns which do not vary on the morphological time-scale, and the local depth, which does vary on this time-scale. In other words: given a certain set of currents and waves, the transport at a given location is only a function of the water depth.

If we can now approximate this function by some simple expression with coefficients which vary from place to place, we end up with a very simple set of two equations: the sediment balance (1) which expresses bottom change in terms of sediment transport gradients, and :

$$\vec{S} = \frac{\vec{S}_{t=0}}{\left|\vec{S}_{t=0}\right|} f(z) \tag{6}$$

This equation describes the reaction of sediment transport to bottom changes. The form of the function f(z) can be estimated by considering that transport usually is proportional to the velocity to some power *b*:

$$\left|\vec{S}\right| \propto |u|^b \propto \left(\frac{|\vec{q}|}{h}\right)^b \propto |\vec{q}|^b h^{-b} \tag{7}$$

Since a similar relationship with the orbital velocity can be assumed, a suitable function is:

$$\left|\vec{S}\right| = A(x,y)h^{-b(x,y)} \tag{8}$$

where the water depth h is taken as $h=z+HW$, and HW is the high water level, which ensures that water depth is always positive.

As a further simplification b can be assumed constant throughout the field. In this case, the value of A in each point can be derived directly from the local water depth and the initial transport rate, which may be computed using a sophisticated transport model.

The combination of equations (1) and (8) can be solved using the same bottom update scheme as in the full morphodynamic model and requires very little computational effort (in the order of minutes on a PC).

In De Vriend et al. (1993), a steady-state version of this concept, aiming at a direct estimate of the equilibrium bathymetry, was presented for the case of a schematised river outflow. In this case, the solution is governed by the upstream boundary condition. In real life, such a condition cannot be found; by using a time-dependent approach as given here and choosing weak boundary conditions far from the area of interest, this problem is avoided.

Applications

RAM is applicable where the flow- and wave patterns are restricted by the geometry, so small bottom changes do not change the overall pattern. This is typically the case near river outflows, around harbour moles and near river training works. In these cases the behaviour simulated by RAM is similar to that using a full morphodynamic model. At the beginning of a simulation, the RAM simulation matches the full solution exactly: the simplified transport equation is made to fit the full model and the bottom update scheme is the same. As time progresses, the two models will deviate as the flow *pattern* starts to react to the bottom changes.

Test case: IJmuiden harbour

The harbour moles of IJmuiden, the sea port of Amsterdam (see Figure 3), were extended by approx. 2500 m in the period of 1962-1968. A large scour hole has since developed near the tip of the longest, southern harbour mole, and the coast line has accreted more than 500 m since then, especially on the southern side. Further away from the harbour, the coast has suffered erosion.

Regular surveys of the area have been performed and dredging data collected routinely, apart from the yearly sounding of coastal profiles which takes place along the whole of the Dutch coast. In the framework of this study, these data have been compiled, digitised where necessary and tailored for model validation. Data have been collected over a period of 28 years; in this paper we focus on the first 8 years of this period, from 1968 to 1976. Directional wave data are available from stations in approx. 20 m water depth.

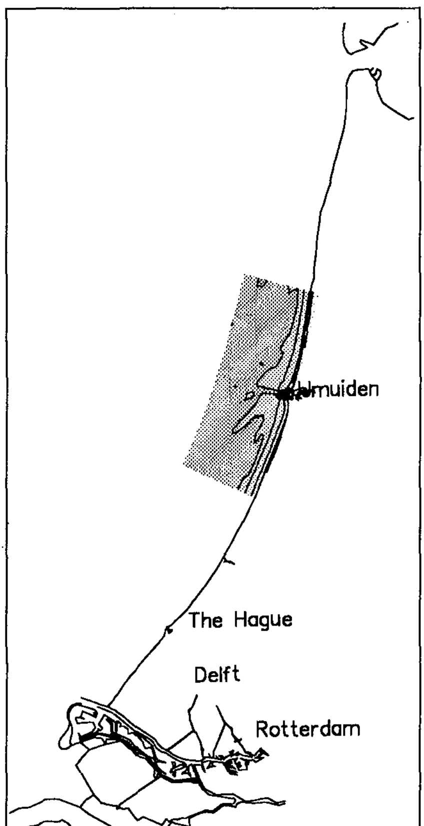


Figure 3. Location map

The full data set and details of simulations are described in Boutmy (1998).

The tidal motion in the area is well documented and several operational models exist which can be used to generate boundary conditions for a detailed model of the vicinity of the harbour.

In Figure 3 the detailed model area is shown. A curvilinear grid was constructed with a good resolution near the harbour entrance and near the coast, but gradually coarsening towards the model boundaries, which were put some 10-15 km from the harbour. A single representative tide was chosen with an amplitude of 1.1 times the average amplitude. Simulations were carried out without waves, with waves perpendicular to the coast, and with two wave conditions representing south-westerly (245^0 N) and north-westerly (335^0 N) wave directions. This coarse schematisation was (for the time being) thought to be good enough to represent most of the important processes in this comparative study, and allows an insight into the importance of:

- tide only
- waves acting as stirring agent for sediment
- wave-driven currents and
- other wave-induced processes.

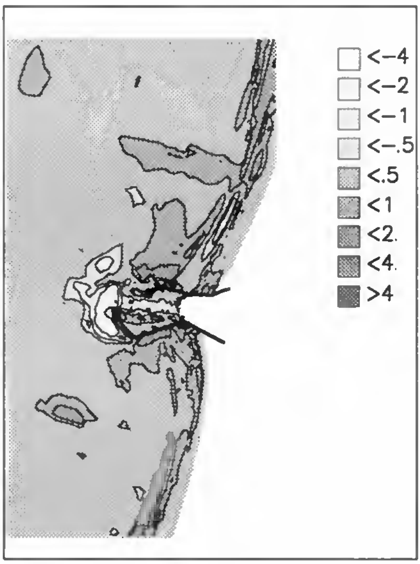


Figure 4. Measured bottom change 1968-1973

Tide only

In Figure 4, the measured sedimentation and erosion is shown for the period 1968-1973. Clearly a scour hole develops in front of the southern harbour mole. The coast southward of the moles accretes strongly, as does the foreshore to the north of the moles. In Figure 5, the same period is simulated with the full morphological model, but taking into account only the tidal flow. Due to contraction around the moles, a scour hole develops; the eroded sand is deposited on either side of the harbour, in deep water. Near the coast and in other areas, nothing happens at all.

In Figure 6, the results are shown for a simulation with RAM based on the first computed transport field. As could be expected for this situation where RAM is clearly applicable, the results are quite similar to the full model. Both runs simulate the development of the scour hole reasonably well.

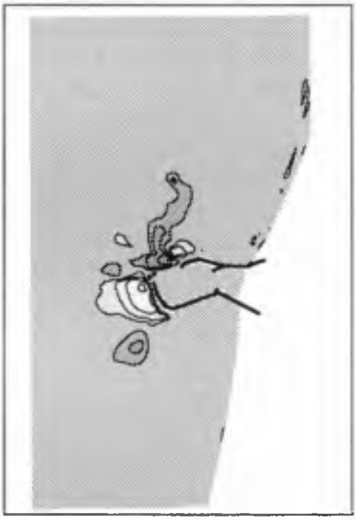


Figure 5. MOR computation '68-'73

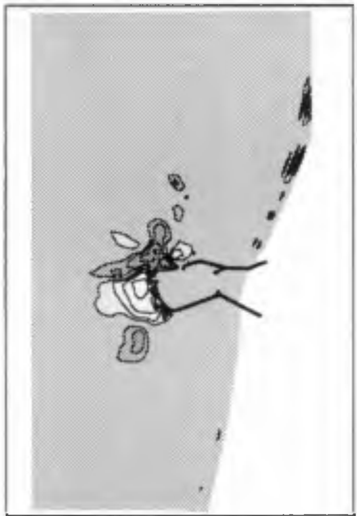


Figure 6. RAM computation '68-'73

Tide plus wave stirring

In the next simulations, waves incident perpendicular to the coast have been introduced in the sediment transport module. The effect of the waves is merely to stir up the sediment which is transported by the tidal current. A representative significant wave height of 1.68 m was derived from the available wave data.

The first simulation with standard settings revealed a rather surprising result (Figure 7): there was a small scour hole some distance from the southern mole, but the dominant feature is the accretion at the entrance. The area near the coast is now eroded, which can be attributed to the large eddies downstream of the moles which transport sand towards the harbour mole and outwards; there, the stirring by waves decreases and the sediment is dropped. This also explains the reduced scour hole in this simulation.

One way to reduce the somewhat exaggerated effect of waves on the stirring of sediment is to reduce the wave-related roughness applied in the Bijker formulation from 5 cm (standard run, Figure 7) to 1 cm. The results are shown in Figure 8. The development of the scour hole and the accretion areas near the harbour is much more

Figure 7. MOR with wave stirring, '68-'73, roughness 5 cm..

in line with the measurements, and the scour hole develops to much greater depth. The interesting conclusion here is, that *decreasing* the transport rates (by reducing the roughness) has the effect of *increasing* the scour.

In Figure 9, the results are shown for RAM, based on the same initial transport field as in Figure 8. The agreement is still quite good, albeit that the changes in RAM are sharper, since it lacks the smoothing effects of a free water surface and spatial lag in the suspended transport.

In none of these simulations the accretion of the shoreline is represented.

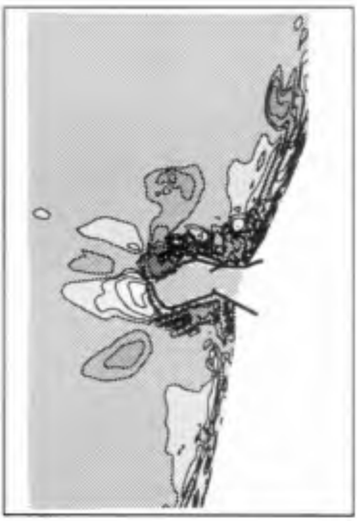


Figure 8. MOR with wave stirring

Figure 9. RAM with wave stirring

1968-1973, roughness 1 cm

The results so far show that for a case where the flow pattern is severly restricted by the geometry, the RAM model is able to reproduce the pattern of sedimentation and erosion over a number of years with reasonable accuracy. The computational cost of the RAM simulation is in the order of minutes on a PC. Obviously, the outcome is very much determined by the quality of the initial sediment transport field provided by the Delft3D process model.

The nearshore area is dominated by wave-driven currents and cross-shore transport phenomena: the longshore current will deposit sand near both sides of the moles, which will be redistributed across the profile. As a result of this, the coastline moves in seaward direction, while the coastal profiles keep more or less the same shape.

In the final set of simulations, we will review the effect of processes not yet introduced in RAM, in order to see how much further a full process modelling approach will take us.

Tide plus waves

In the final scenarios the simulations were run with alternating wave directions; since we are only interested in the long-term evolution, the wave direction is switched each half year of simulation. Figure 10 shows a detail of the initial tide-averaged sediment transport field for southwesterly wave conditions.

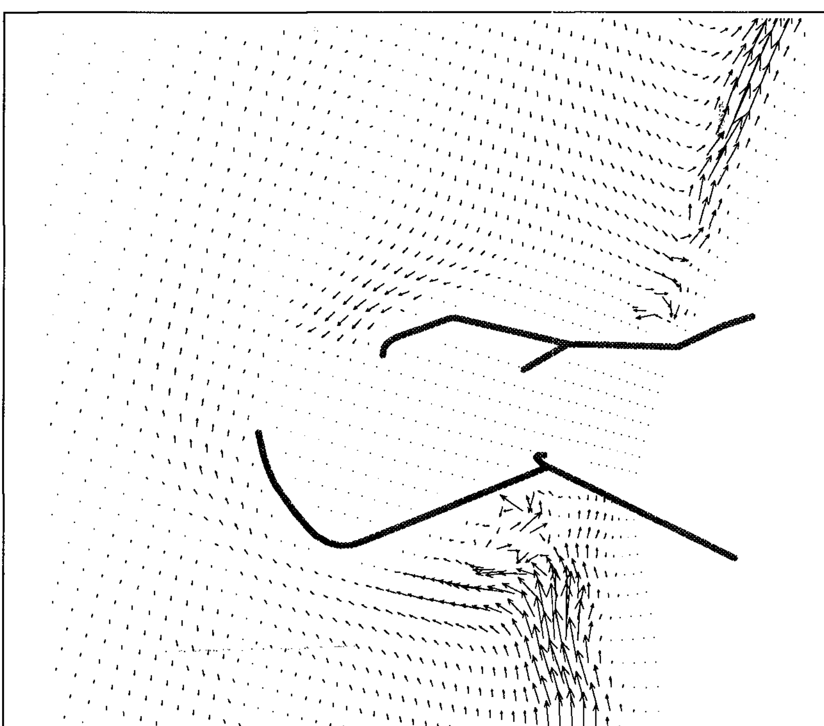


Figure 10. Initial transport field, SW waves.

The northward longshore current is stopped and diverted seaward near the southern mole. At the tip of this mole we see an area with accelerating transports, responsible for the scour hole in that region. Near the tip of the northern mole, the eddy during northward tidal flow and the contraction of the southward ebb current combine to generate a southward nett transport in the direction of the harbour entrance, responsible for considerable accretion. North of the northern breakwater, the longshore current is first directed towards the harbour, due to shielding of the southern waves, but further northward the full transport capacity is restored.

These simulations have been carried out over a somewhat longer period, from 1968-1976. The measured depth changes are shown in Figure 11. In Figure 12, the simulated development is shown. There is now clearly accretion of the coast due to the effect of the longshore current. The developments near the tip of the breakwaters are quite similar to the simulations without wave-driven currents, so that we may conclude that the two systems can be looked ate seperately, at least for the first decade.

The accretion near the southern breakwater takes place about one kilometre from the coast; therefore the coastline itself does not move seaward at all.

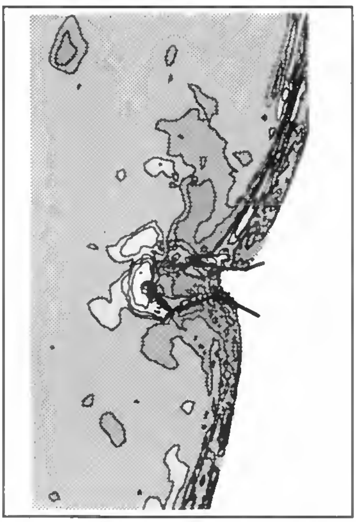


Figure 11. Measured depth changes

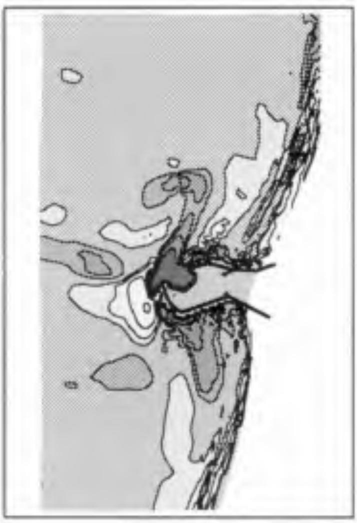


Figure 12. MOR with wave-driven currents

1968-1976, roughness 1 cm

This is due to the fact that in these simulations redistribution of sand across the profile by cross-shore transport is not taken into account. In a final simulation, this effect was investigated.

Figure 13. Depth changes '68-'76, simulation including cross-shore transport and dredging.

The Bailard formula (Bailard, 1981) was used to account for the effect of bed slope and wave asymmetry. The contributions of these terms to transport were simply added to the total transport during each morphological step. Calibration coefficients were applied to both terms in order to make the model produce reasonable equilibrium profiles and adaptation time scales. The results for a first test run are shown in Figure 13. Also in this run, a realistic dredging scenario was applied in the simulation, to avoid a build-up of sediment in the harbour entrance. The results appear to be more realistic, and show a clear accretion at the beach. The present settings of the cross-shore transport model are not ideal yet, and lead to profiles wich are somewhat too steep; this explains the erosion of the foreshore in areas outside the direct influence of the harbour.

Finally, the measured 1976 bathymetry is compared with the last simulation in Fig 14 and 15, respectively. This shows that the cross-shore transport module generates too steep profiles; on the other hand, it has the effect of shifting the coastal profiles in seaward direction in a more or less uniform way; this has important benefits in longer-term simulations. The overall shape of the coastal evolution is qualitatively in line with the observed shape.

All simulations shown so far underestimate the depth of the scour hole which develops in front of the harbour. A likely explanation for this is the lack of large-scale 2D turbulence generated near the breakwaters in the model. This is a point of further study at the moment.

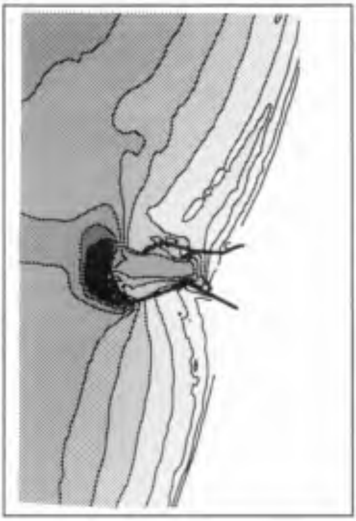


Figure 14. Measured 1976 bathymetry

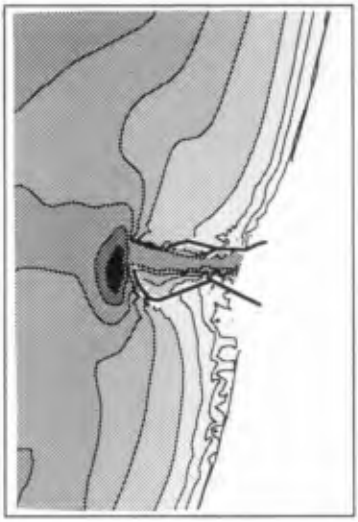


Figure 15 Computed 1976 bathymetry

Conclusions and recommendations

A method has been presented to estimate long-term bathymetric changes based on a single initial transport field. The results over a 5-year period show good agreement between the full morphodynamic MOR model and the simplified RAM approach.

For the present test case, the developments around the harbour entrance can be seen as separated from the coast, and can be modelled well using the RAM approach. This approach means a significant improvement over initial sedimentation/erosion models.

The quality of the initial transport field dominates the outcome; inaccurate modelling of the transport due to combined currents and waves can lead to completely wrong morphological developments. The large-scale 2D turbulence generated near the tips of the breakwaters is likely to be important and must be incorporated in the model.

The simulations with the full model taking into account more wave-related processes show much better predictions in the nearshore area. The processes active in this area cannot be represented in the RAM module for the moment. Further work should be done on implementing these processes in a simplified way.

Acknowledgements

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