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Coastal Morph Dynamics and Long-term Morphological Modeling: A Review

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Abstract: In this study, different methods of long-term morphological modeling are briefly reviewed. These methods include input reduction, schematization of flow perturbation induced by bed changes and increase of the morphological time step. In the discussion of schematization, methods like tide-averaging, continuity correction, RAM, online or morphological factor and MORFAC, are presented. In the next discussion, the morphological time step, four methods namely straightforward extrapolation, time-centered extrapolation, lengthening of the tide and extrapolation of sediment transport as a function of bed evolution are discussed. As a conclusion it can be postulated that RAM method and time-centered extrapolation are best methods among the rest.

Keywords: Bed change, estuary, extrapolation, input reduction, tide, wave

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 (De Vriend, 2003). Estuaries and river basins have complex patterns and processes because of their interaction with tidal changes of seas and oceans. Interactions between an estuary and its adjacent open coast often have significant effects on the evolution of the up- and down-drift coastline and geomorphology of the estuary itself (Jing *et al*., 2013). Over a considerable period of time, such interactions can change the estuary's capacity and influence sediment transport pathways, as well as regional equilibrium state, as shown by many recent studies (Pontee and Cooper, 2005). Detailed analysis and prediction of morphological changes in these areas require advanced and process based models. These models have been subjected to significant developments in the last decades. The technique to couple the short-term function of hydrodynamics and sediment transport with long-term changes of morphology is the key to simulate long-term morphological evolutions.

Long-term simulation of morphological evolutions using real time models will end up into hugely time consuming calculations and therefore it is practically impossible. In this study some applicable techniques are present in order to reduce the calculation efforts in tidal current models.

Three methods can be employed so that the long-term modeling process gets optimized (Latteux, 1995):

- **Input reduction:** The number of incidents affecting the model must be decreased as much as possible. In fact, small part of each phenomenon must be chosen to represent it properly, instead of modeling the whole process in details.
- Schematization of flow perturbation induced by bed changes
- **Increase of the effective morphological time step:** The first two methods are to reduce the cost of hydrodynamic calculations of current and third step is to reduce the cost of morphological calculations. From long-term morphological modeling point of view, a simplified approach is considered to be a good way for estuary-coastal regions (Roelvink and Reniers, 2012).

MATERIALS AND METHODS

Input reduction: Contrary to other hydrodynamic phenomena (wind, wave ...), the tide is a certain phenomenon and therefore it can be predicted and analyzed accurately. Therefore, input reduction for tide data is possible and easy to achieve and no uncertainty will be introduced to the procedure. Yet, unsteady currents in a tidal cycle, increases the calculation efforts. Thus, it is necessary to find a way to represent a full tidal cycle (for example a Saros which is equal to

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18.6 years and period of tidal currents is based on rotation of earth, moon and sun) by using a few single tides. Selection of the representatives and their corresponding weighing factors must be in such a way that their cumulative effect be close enough to the real case. In this procedure below considerations must be considered:

- According to the nonlinearity of the process, the average effect of the input data is different from the effect of the average input data.
- The chronological order of the incidents might be highly effective on the outputs. Especially when the system has small morphodynamic inertia due to the time.
- On-way and long-term effect of a single phenomenon must be considered even if it is negligible compared to the other short-term parameters.

Generally in input reduction method it can be said that (Dano *et al*., 1998):

- Where the topography is fairly simple, a single tide represent the tidal current, which must be chosen according to the measurements on the flow and sedimentation.
- If the topography is complex and it leads to unusual and complicated flow fields, the tidal cycle can be represented by a few numbers tidal classes. The weighing factor of these classes must be chosen carefully, so that the modeling output in measured points is accurate enough.

Schematization of flow perturbation induced by bed changes: Modeling river mouth (i.e., where river flows into the sea) is complicated because the current, sediment transport and bed level change are not separate from each other and influence each other. This interaction obliges the flow calculations to be revised in each time step and after applying bed level changes. Though the hydrodynamical and morphological processes are in mutual interaction, the bed level change rates are usually very little and therefore, repetitive calculations can be avoided by choosing different time steps for hydrodynamical and morphological calculations. In this approach, after running sub-program for hydrodynamic and finding flow pattern, morphological calculation runs each, say 100, time steps. Then, the bed level changes according to the results and then the hydrodynamical calculations run again. Different strategies might be taken to reduce the error which all of them have similar theory:

- The effect of the bed level change on flow perturbations can be neglected over short time steps (as long as bed level change is fairly small).

The flow with new topography can be matched by mass conservation equation. In this method, it's been assumed that water level stays constant and the flow pattern will not change by the bed level change. Then, a new velocity field is computed based on the new depths. Also, this method is based on the assumption that flow direction is more sensible to the flow velocity than to the bed topography.

- Perturbations and flow alterations caused by the bed level changes must be detected. It is assumed that water level is constant in this method too. It is also hypothesized that these perturbations are weak enough and can be computed from Poison's equation by linearization of shallow water equation (De Vriend *et al*., 1993b).

There are other complex methods which are more accurate. It should be noted that the purpose of this procedure is to reduce the calculation effort by changing time steps of hydrodynamic and morphodynamic. Yet, using complex methods questions this purpose.

In the next sections, a few methods for long-term modeling of morphology will be presented. First, Tide-averaging method is reviewed which is based on the Continuity Correction method. Then, RAM method is explained which is the extension of continuity correction method. Next, the improved type of Tide-averaging method which is called online method, is discussed. Finally, the MORFAC method is introduced as a useful method to achieve longer time-scales of morphological changes.

Tide-averaging approach: This method is based on the fact that morphological changes take place on larger time-scales than the hydrodynamical ones. Therefore, morphological changes can be neglected over a single tidal cycle and bed level can be assumed to be constant.

The diagram of the tide-averaging approach is shown in Fig. 1. Starting from a given bathymetry, the interaction of wave and current is solved over a tidal cycle, using an iterative approach. The resulted flow and wave fields are then fed into a transport model, which calculates bed load and suspended load transport. The averaged result is applied to compute bed changes. The new bathymetry is fed back into the transport model employing the continuity correction or full hydrodynamic module (Hauguel, 1978).

Continuity correction: Generally the transport field is a function of the flow field and the orbital velocity. Any change in bathymetry, will cause change in the flow field and orbital velocity and therefore it will obliges recalculation of these values. The continuity correction is a frequently applied method to compute changes in flow field and orbital velocity by taking flow pattern constant for slight changes in the bathymetry.

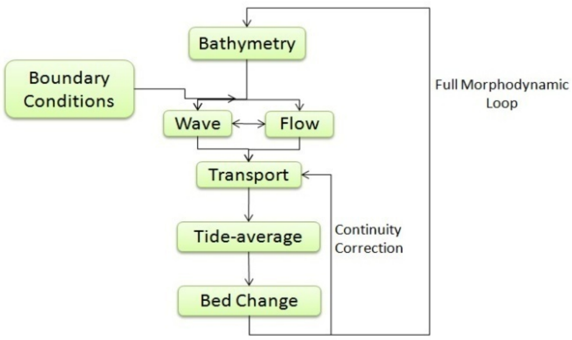

Fig. 1: Flow diagram of tide-averaging morphodynamic model setup (Hauguel, 1978)

In a tidal flow situation, the 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.

It is still necessary in this method to compute the sediment transport through the whole tidal cycle, which can be time-consuming when suspended-load transport, needs to be accounted for. Grid cells in the shallow regions of the flow introduce considerable error into the process and therefore typically after 5-20 continuity correction steps, the full hydrodynamic model has to be run based on the updated bathymetry (Hauguel, 1978).

The main deficiency to this method is the assumption that the flow rate and pattern stays constant in a time step. For example, according to this method, any decrease in the depth of a shallow region in the flow field, would cause increase in the velocity. However this is not true in the reality, as the discharge will be directed to the deeper part instead, because of higher friction effects.

Some examples of application of this method are presented in Latteux (1995) on a migrating tidal inlet after a beach and in Lesser (2004) on the impact of a long dam near a tidal inlet.

RAM approach: In consultancy projects there is often a demand to interpret the output of the initial transport computations without full morphodynamic simulations. A solution is to check the initial sedimentation/erosion rates, but this method is flawed in many respects. Initial disturbances of the bathymetry lead to a very disordered pattern and, as De Vriend *et al*. (1993a) have pointed out, sediment/erosion patterns tend to migrate in the direction of the transport. However, the initial sedimentation/erosion patterns do not represent this behavior.

The RAM approach is a simple solution that overcomes these disadvantages. This method is tested in Roelvink (2006, 1994). If we assume that for small bed level changes the overall flow and wave patterns do not change (an assumption in the 'continuity correction' method), the tide-averaged transport rates would be a function of flow and wave patterns which are constant on the morphological time-scale, while the local depth 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 one approximates the relationship of water depth and the sediment transport using an equation with spatially variable coefficient, two equations will be resulted: the sediment balance and the sediment transport vector.

The sediment balance (1), which describes bottom changes in terms of sediment transport gradients:

$$\frac{\partial z_b}{\partial t} + \frac{\partial S_x}{\partial x} + \frac{\partial S_y}{\partial y} = 0 \qquad (1)$$

where,

z_b = The bed level

S_x, S_y = The sediment transport components and the sediment tranpost vector:

$$\left|\vec{S}\right| = A(x,y)h^{-b(x,y)} \qquad (2)$$

where, the water depth h is taken as $h = HW - z_b$ and HW is the high water level, which ensures that water depth is always positive. As a further simplification, b is assumed to be constant throughout the field. In this case, the value of A in the horizontal plane can be calculated directly from the local water depth and the initial transport rate, which may be computed using any transport model.

The combination of Eq. (1) and (2) 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 dynamic flows, as in estuaries and outer deltas, the RAM method may still study well enough to be applied as a quick updating scheme. As soon as bottom changes become too large, a full simulation of the hydrodynamics and sediment transport is carried out for a number of input conditions. A weighted average sediment transport field is then determined, which is the basis for the next RAM computation over, say, a year of morphological time. The updated bathymetry is then fed back into the detailed hydrodynamic and transport model. An important point is that the costly computations to update wave, flow and transport fields can be carried out in parallel, using different processors. The simplified updating scheme and the parallel computation for various input conditions together may lead to a reduction in simulation time in the order of a factor of 20. The flow diagram of this scheme is depicted in Fig. 2 (Hauguel, 1978).

Some examples of this approach are represented in Dano *et al*. (1998) for the development of a scour hole in front of an extended harbor on the Dutch coast and Roelvink *et al*. (2001) for the evolution of two estuary mouths in the southwest of the Netherlands, over a period of 40 years.

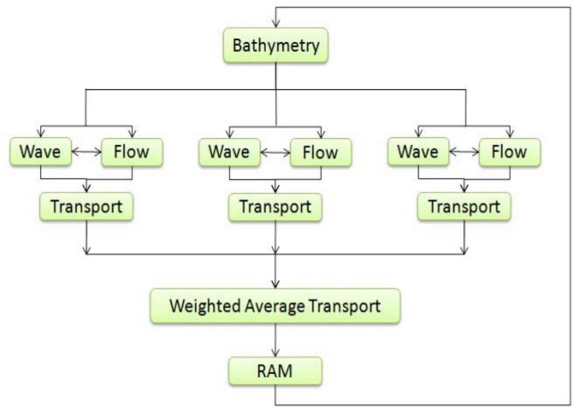

Fig. 2: Flow diagram of RAM approach (Hauguel, 1978)

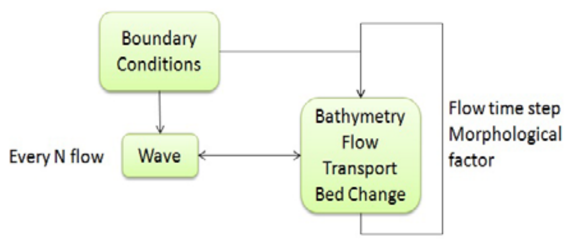

Fig. 3: Flow diagram of 'online' morphodynamic model setup (Hauguel, 1978)

Online approach with morphological factor: The methods above have in common that the morphology is updated relatively infrequently compared to the number of flow time steps per tidal cycle (typically with less than one minute time steps) and the number of sediment transport time steps per cycle (typically more than 20).

The online method is a completely different approach to run the flow, sediment transport and bed changes all in the same small time steps. In order to take into the consideration the difference in time scales between the flow and morphology, a simple solution can be used, namely the 'morphological factor' (Lesser, 2004, Fig. 3). Lesser (2004) presented the key features of formulations used to model both suspended and bed load transport of non-cohesive sediment and describes the implemented morphological scheme. This factor, n, simply increases the depth change rates by a constant factor, so that after a simulation over one tidal cycle, the morphological is indeed modeled over n cycles. This is similar to the concept of the 'elongated tide' proposed by Latteux (1995), who applied it, in combination with continuity correction. The results obviously have to be evaluated after a whole number of tidal cycles.

An important difference with the previous methods is that the bed evolution is computed in much smaller time steps, even if relatively large values of n are used. An advantage of the ' online' method is that short-term processes are coupled at flow time-steps level, which makes it easy to include various interaction between flow, sediment and morphology. This will also make it unnecessary to store large amounts of data between the processes. Moreover, the treatment of drying and wetting areas become more straightforward, because in these areas it is a great advantage to take small morphodynamic time steps. In comparison with the 'elongated tide' method proposed by Latteux (1995), the advantage is that no continuity correction is required and therefore processes in shallow water would be more accurate (Hauguel, 1978).

MORFAC approach: Using traditional morphodynamic up scaling techniques such as the 'continuity correction' method, it was only possible to numerically simulate coastal evolution up to a couple of years. The introduction of the morphological acceleration factor (MORFAC) concept to coastal morphodynamic modeling by Lesser (2004) and Roelvink (2006) removes this limitation. Using the MORFAC approach enables numerical simulation of coastal morphological evolution due to waves and currents is possible at time scales of decades (Steijn *et al*., 1998) and for uniform forces such as a tidal ones, it is possible even for centuries (Tonnon, 2007).

The MORFAC approach is different from traditional way of thinking and essentially multiplies the bed levels computed after each hydrodynamic time steps by a factor (MORFAC) to enables much faster computation. The significantly upscaled new bathymetry is then used in the next hydrodynamic step (Fig. 4) (Van der Wegen, 2008).

Increase of the effective morphological time step: As mentioned before, simulating every detail of all tides for a long-term morphological process would need an enormously large number of time steps. In order to reduce the number of morphological time steps, four very pragmatic methods have been developed and tested, in such a way as to simulate the effect of repetitive identical tides by detailed computation only on a few of them. These four methods are described briefly here.

Straightforward extrapolation: In this method, a threshold is assumed for the bed level changes to be considered effective on the flow. The results of computed bed changes on a first tide, with a fixed bed, is then extrapolated for a number of N tides such that the maximum evolution over these N tides is below the given threshold. This method is very simple and cheap; however, as it is not centered in time (bed changes over N tides are computed from the first one); it leads rapidly to instability for high magnitudes of N. Because of the type of extrapolation in this method, it cannot reproduce he propagation of bed forms.

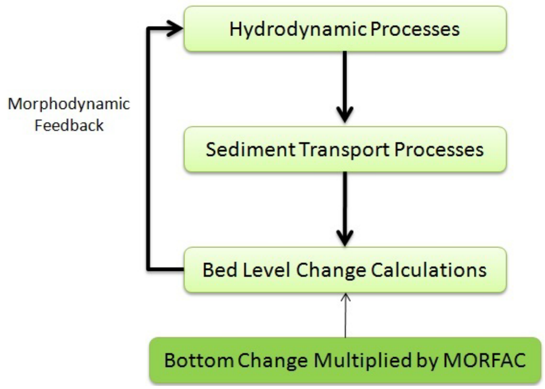

Fig. 4: Flow diagram of MORFAC approach (Van der Wegen, 2008)

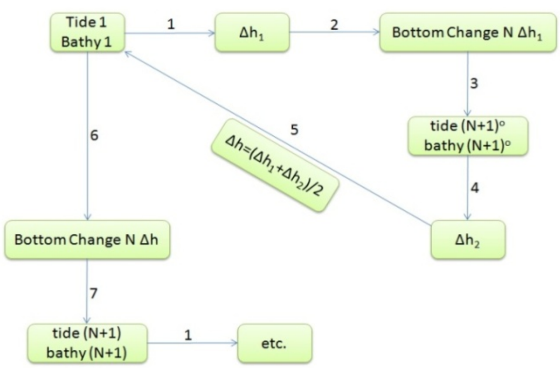

Fig. 5: Time-centered extrapolation principle

Time-centered extrapolation: The idea is still based on the extrapolation; however in this method the reference tide is no longer the first one, but it is more or less the one in the middle. In a first trial, the straightforward extrapolation method is used to derive an initial guess of the bed changes over N tides. Then sediment transport is computed over the tide N+1 after considering the effect of the bed evolution in the first extrapolation. The average of the bed changes computed in the first trial over the first tide and afterwards over the tide N+1 is taken as the bed change value. This method looks like the first one, but is more accurate and less unstable. But, just as for the first method, it does not allow the propagation of bed forms (Fig. 5).

Lengthening of the tide: In this method N successive tides are simulated by a single one, extended N times. So after computation of hydrodynamics at the proper time scale, a longer time step can be used in morphological simulation, as the hydrodynamics varies much more slowly. At each long time step the bed evolution is no longer negligible (Fig. 6).

Compared to the extrapolation methods, this method has the advantage of allowing bed form propagation. Yet, the main drawback of the method is that the chronology of the various tidal current phase is no longer ensured.

Expansion of sediment transport as a function of bed evolution: This method is based on the assumption that neither flow lines, nor free surface are disturbed by the bed changes, as long as these changes are small compared to the water depth. Thus, the flow rate is assumed to be the same during the first tide and the tide N+1:

$$\vec{q}(x, y, t + NT) = \vec{q}(x, y,)t \tag{3}$$

where,

q = The flow discharge by unit width
x and y = The coordinates in the horizontal plane
t = The time
T = The tide period

Then:

$$\vec{V}(x, y, t + NT) = \frac{\vec{q}(x,y,t+NT)}{\vec{h}(x,y,t+NT)}$$

$$= \frac{\vec{q}(x,y,t)}{\vec{h}(x,y,t)-[\vec{\xi_b}(x,y,t+NT)-\vec{\xi_b}(x,y,t)]} \tag{4}$$

where,

V = The flow velocity
h = The water depth
ξ_b = The bed evolution

The sediment discharge q_s can be expressed as:

$$\overrightarrow{q_x}(x, y, t + NT) = \overrightarrow{q_s}(V(x, y, t + NT), h(x, y, t + NY)) = \overrightarrow{q_s}(\vec{q}(x, y, t), h(x, y, t + NT)) \tag{5}$$

Expanding this expression to the first order as a function of water depth and using:

$$h(x, y, t + NT) - h(x, y, t) = -[\overrightarrow{\xi_b}(x, y, t + NT - \xi b x, y, t] \tag{6}$$

$$\overrightarrow{q_s}(x, y, t + NT) = \overrightarrow{q_s}(x, y, t) - [\overrightarrow{\xi_b}(x, y, t + NT) - \overrightarrow{\xi_b}(x, y, t)] \frac{\partial \overrightarrow{q_b}}{\partial h}(x, y, t) + \vec{0}({\xi_b}^2) \tag{7}$$

So the sediment discharge q_s is obtained as a function of bed evolution ξ_b. By further mathematical manipulation and using Eq. (8) (P is the porosity of bed materials), one can write the Eq. (9):

$$\frac{1}{(1-P)} \int_0^T \frac{\partial \overrightarrow{q_s}}{\partial h} dt = \vec{\Gamma}(x, y, T) \tag{8}$$

$$\xi_b(x, y, (1 + N)T) - \xi_b(x, y, NT) = \xi_b(x, y, T) + div[\xi_b(x, y, NT)\vec{\Gamma}(x, y, T) \tag{9}$$

In this expression the last term is a correcting term taking into account the bed changes on the N previous tides. Then the bed changes on the whole tide N+1 can

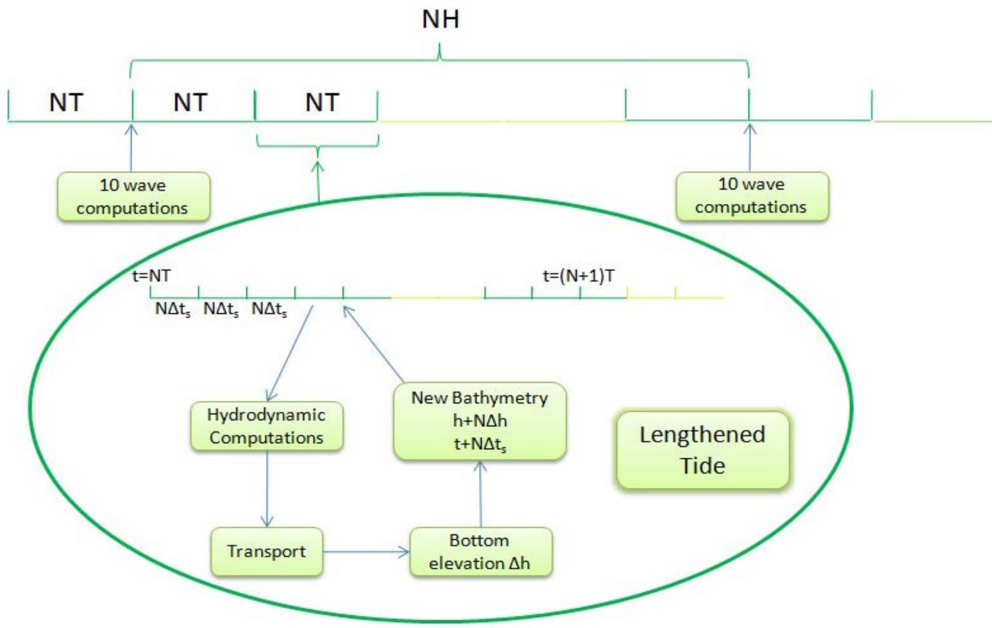

Fig. 6: Lengthening of the tide principle

be directly evaluated from the changes on the preceding one and from terms which are computed on the first one. Afterwards, the morphological time step becomes the tidal period T.

RESULTS AND DISCUSSION

Conclusion: Long-term modeling of morphology is just at the beginning of its development, especially in cases which deals with river mouths interacting with sea. The key element in long-term morphological analysis and prediction, is reduction in input, model, output and measured data.

Input reduction is in fact a procedure to choose series of data to represent all of data which this procedure for areas with simple and complicated topography is discussed.

Updated approaches to compute morphological evolutions approved in past years, has been explained. Applying these approaches in highly tidal active regions, may help to include human activities and climate change in the predictions. The 'tide averaging' and the 'continuity correction' methods are basic methods but despite the fact that they are highly time consuming, they are being used widely. Introducing the 'RAM' approach was an important improvement in acceleration of modeling and results of applied scenarios show the validity of this method. Other methods like 'Online' and 'MORFAC' are also new methods that have been successful. The relative efficiency of the methods is determined by three factors: the numerical stability, the accuracy and the ability to cope with variable input conditions (wind, waves, discharges, etc) (Roelvink, 2006). As a conclusion it can be said that the 'RAM' approach is the most reasonable choice for simulation as it can cope with variable input conditions with no restriction (Roelvink, 2006).

Increase in morphological time step was discussed and different methods with their criteria of application were discussed briefly. As an advice the time-centered extrapolation is the most efficient method and has a desirable accuracy.

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