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First Results of a Long Term Morphodynamic Process Based Model

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ABSTRACT

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Long-term morphological and basin filling modelling studies traditionally comprehend simulations carried out by conceptual, geometric, behaviour-oriented or, more recently, dynamic abstracted diffusion models. The increase of computational capability and the development of new mathematical approaches, allowed the use of more complex models. This will enable, in the near future, a shift from the synthesis to the reductionist paradigm. In this new approach, numerical algorithms are used to solve explicitly the physical equations of the relevant processes, coupled with empirical and semi-empirical equations for the unresolved phenomena, that will create the possibility of working with a wide range of time and space scales. In this work, the first results of a long-term morphodynamic evolution obtained with a process based model are presented. The used model is the MOHID modelling system, which simulates explicitly the hydrodynamic, sand transport and the bottom's dynamics. For that purpose a schematic bathymetry was constructed representing a coastal zone with 50 km in length and 1 km in width. The model considers a tidal input at open boundary, while the freshwater input is neglected. The results of 2000 years simulations were compared with other approaches of morphodynamic's modelling. The use of a process based model requires a considerable computational effort, so in order to reduce that, an extrapolation scheme is proposed and tested against standard runs. The results obtained show a decrease in the computational load to one third, maintaining the data consistency.

ADITIONAL INDEX WORDS: *Morphodynamic Modelling, MOHID, Extrapolation Scheme*

INTRODUTION

The first attempts for a quantitative description and simulation of basin filling in geological times started in the late 60´s of the last century (eg. SCHWARZACHER, 1966; BRIGGS and POLLACK, 1967). An excellent synthesis of basin quantitative models can be found in ALLEN and ALLEN (1990).

Most of the models presently used to study fluvial basin filling are of the "diffusion type" (FLEMMINGS and JORDAN, 1989). It must be noted that these models do not assume that the sediment transport is performed by a physical diffusive process. Instead, they are synthetic models based on mass conservation: If one considers 1D mass transport of sediment along a river basin, the mass conservation equation can be written as:

$$\sigma + \frac{\partial \eta}{\partial t} = \frac{-1}{C_0}\frac{\partial q_s}{\partial x} \qquad (1)$$

Where σ is the subsidence rate (m/s), η the elevation of the sediment surface over a datum level (m), t is time (s), C_0 is the volume sediment concentration in the deposit (m^3/m^3), q_s is the mean sediment flux per unit width of the basin (m^2/s) and x is the downstream distance along the axis of the basin (m).

This has the mathematical form of a diffusion equation. The physical meaning however is of a mass equation; the diffusion coefficient embodies the parameterization of the sediment flux q_s.

It can be shown that the diffusion equation can be obtained from the momentum equation only for very stringent special situations (PAOLA *et al.*, 1992). One problematic assumption for geophysical simulations is that the dimensionless (or Shields) stress τ^* must be constant. With τ^*defined as:

$$\tau^* = \frac{\tau_0}{\rho g(s-1)D} \qquad (2)$$

Where τ_0 is the bottom shear stress (Pa), ρ is the fluid density (Kg/m^3), s the sediment specific gravity (-) and D the median grain size (m). This is obviously difficult to accomplish in real situations. Other very stringent assumption for the applicability of the diffusion equation in real situations is that boundary conditions, such as sediment supply and river flow, must be constant. The simulation of time dependent processes, such as the impact of climate change, is thus difficult to accomplish with such models.

Models like these can be termed synthetic, because they assume the dynamic of complex systems occur in many time and space scales and that the dynamics of each scale can be more or less independent of the dynamics of lower scales. The implication is that higher level dynamics is controlled by only a few important processes and the small scale processes do not need to be included. In opposition to this is the reductionist viewpoint that states that there is no objective reason to discard lower scales. In this viewpoint the system is broken down into its fundamental components and processes and the model is build up by selecting the important processes regardless of its time and space scale. This viewpoint was only possible to pursue in the recent years due to improvement in system knowledge and computer power.

In this article this last approach is pursued. A process-based hydrodynamic, sediment transport and morphodynamic model, solving explicitly the mass and momentum conservation equations is used to perform river basin evolution simulations, traditionally studied with synthetic models Even thought the assumptions are different, the results obtained are compared with similar simulations of synthetic models and with what can be called "intermediate models". As the simulations were performed with a thousand years time scale, it takes a great computational effort. In order to reduce that, it was tested an interpolation scheme in is validity but also in its computational efficiency.

The next section presents a brief description of the model used and the simulations layout. The results are then presented and discussed.

METHODS

The MOHID Water Modelling System (www.mohid.com) was the chosen model to perform the simulations. It is being developed for the last 30 years in the IST (Technical University of Lisbon, Portugal), and its code is open accessed. It has originally been created for short time studies (days to years), being used for the first time in a geologic timescale. It is a modular system that includes, among others, models for hydrodynamics, sediment transport and sediment bed evolution. The system architecture is object oriented (MIRANDA *et al.*, 2000). The velocity fields are computed in the hydrodynamic module, using a 3D formulation with hydrostatic and Boussinesq approximations (MARTINS *et al.*, 1998). The equations are solved using the finite volume method with an ADI (Alternate Direction Implicit) discretization. The resulting equations are obtained by integration of the Navier Stokes equations over the cells:

$$\frac{\partial}{\partial t}\int_v \vec{v}dV = -\oint_A \vec{v}(\vec{v}\cdot\vec{n})dA + \oint_A \upsilon_T \frac{\partial(\vec{v})}{\partial n}dA - g\oint_A(\eta - z)\cdot\vec{n}_{xy}dA - g\oint_A\left(\int_z^{\eta}\frac{\rho-\rho_0}{\rho_0}dz\right)\cdot\vec{n}_{xy}dA - \oint_A p_{atm}\vec{n}_{xy}dA + \int_V 2\vec{\Omega}\cdot\vec{v}dV \quad (3)$$

Where $\vec{v}$ is the velocity vector, V the cell volume, n the normal to the cell and Ω the Earth rotation. The horizontal grid is the orthogonal Arakawa C type staggered grid. In the vertical direction, a generic vertical geometry is implemented (MARTINS *et al.*, 2001). At the open boundaries, both imposed values and radiative conditions can be set (COELHO *et al.*, 2002). In tidal flats, a moving boundary condition is implemented, enabling the drying and flooding of cells as a function of the water level. The bottom stress is implemented implicitly using a quadratic law.

The transport of properties (including suspended sediments) uses an advection-diffusion equation with the same formulation used for momentum. The bed evolution is computed solving the mass balance equation:

$$(1-n)\frac{\partial n}{\partial t} + div\vec{q}_s = \frac{\theta_s}{\rho_s} \quad (4)$$

Where n is the sediment porosity (-), Θ_s is the sediment flux between the water column and the bed (Kg/(m^2 s)) and ρ_s is the dry sediment density (Kg/m^3). The sediment fluxes are computed using the MEYER-PETER and MULLER (1948) formulation for the bed load and the ACKERS-WHITE (1973) formulation for the suspended load.

The MOHID results were obtained computing explicitly the hydrodynamics, the sediment transport and bed evolution processes. In a present day PC it takes approximately 7 minutes to simulate each year. The computational time is thus a relevant issue in this type of models. Several extrapolation options were investigated to allow longer and more elaborate simulation, saving computational power. It was tested a first and a second order extrapolation. For the first order, in each cell it was computed the depth at time t_3 using the depths at times t_1 and t_2 with the following equation:

$$\eta^{t3} = \eta^{t1} + (t_3 - t_1)\frac{\eta^{t2} - \eta^{t1}}{t_2 - t_1} \quad (5)$$

The same was done for the second order extrapolation, using:

$$\eta^{t4} = \eta^{t1} + (t_4 - t_1)\frac{\eta^{t2} - \eta^{t1}}{t_2 - t_1} + (t_4 - t_1)(t_4 - t_2)\frac{\frac{\eta^{t3} - \eta^{t2}}{t_3 - t_2} - \frac{\eta^{t2} - \eta^{t1}}{t_2 - t_1}}{t_3 - t_1} \quad (6)$$

The scheme consists in a sequence of successive runs followed by the linear extrapolation considered, of the depth evolution during a certain time period. The cases considered were:

a) Run100_Int50_1: 100 years simulation followed by a 50 years first order extrapolation;

b) Run100_Int100_1: 100 years simulation followed by a 100 years first order extrapolation;

c) Run100_Int200_1: 100 years simulation followed by a 200 years first order extrapolation;

d) Run50_Int100_1: 100 years simulation followed by a 200 years first order extrapolation;

e) Run200_Int100_1: 100 years simulation followed by a 200 years first order extrapolation;

f) Run100_Int50_2: 100 years simulation followed by a 50 years second order extrapolation.

Since the extrapolation time is negligible compared with the simulation time, the above schemes produce computational savings of 1/3, 1/2, 2/3, 2/3, 1/3 and 1/3, respectively.

To facilitate the analysis of the different cases, several parameters were used, such as the water volume (WV), total eroded volume (TEV) and total eroded volume relative difference (TEVRD).

$$WV = \sum(depth)_{along\_the\_profile} \quad (7)$$

$$TEV = \sum(depth_{simulated\_batim} - prof_{initial\_batim})_{along\_the\_profile} \quad (8)$$

$$TEVRD = Abs\left(\frac{TEV_{run\_continuous} - TEV_{run\_interpolated}}{TEV_{run\_continuous}}\right)\cdot 100 \quad (9)$$

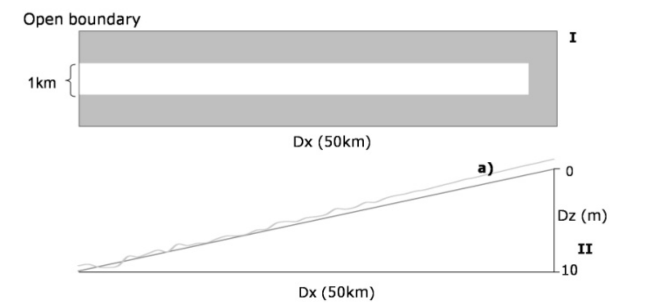

Figure 1. Schematic representation of the initial bathymetry used in simulations. I – horizontal view; II – vertical view, profile a) represents a 5% random perturbation over a linear batimetry.

Simulation Layout

A schematic bathymetry of an estuary was constructed with 50 (1 Km x 1 Km) cells, covering an area with 50 km length and 1 km width (Figure 1). The initial bed depth was imposed with a linear variation from 0 m at the head of the estuary to 10 m at the mouth. A 5% random perturbation over that linear profile was set to promote initial transport. The tide was imposed at the bathymetry's open boundary, forced only by a M_2 tide with constant amplitude of 1.75 m. No river flow or sediment flux was considered. Noncohesive sediments with d_{35}, d_{50} and d_{90} values of 250, 200 and 100 μm respectively were used. At the open boundary, the 10 m depth is held constant over time. The sediment concentration at the open boundary during ebb is equal to the interior concentration adjacent to the boundary. During flood, the concentration of sediment entering the system is obtained from a first order relaxation equation to a fixed exterior value with an infinitely large decay time. The period considered for the simulations of the evolution model and for the extrapolation scheme was 2000 years.

RESULTS

In Figure 2 it is represented the evolution of the bed profiles during 2000 years, called as continuous run. It is possible to observe a clear equilibrium tendency, achieved after the first 1000 years of simulations.

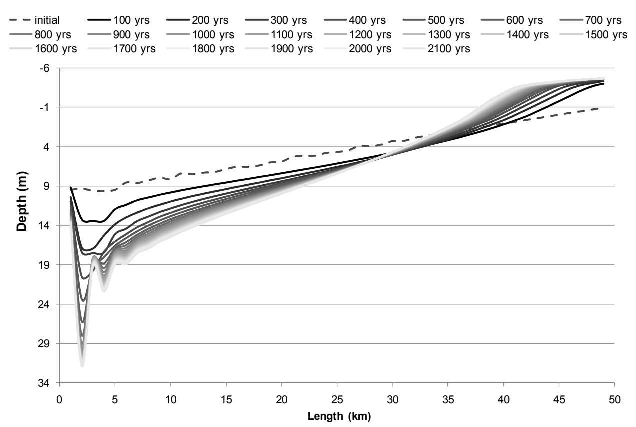

Figure 2. Bathymetry evolution obtained by the continuous run, derived by an initial linear bathymetry with a 5% of perturbation

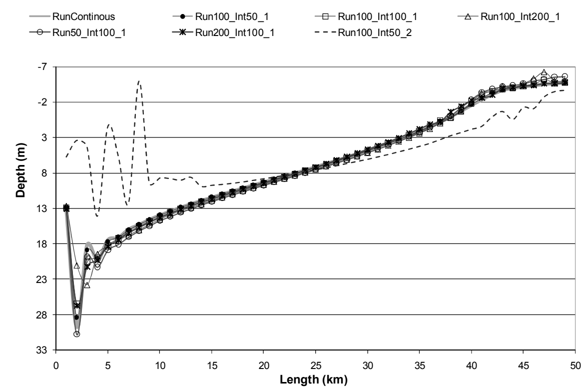

Figure 3. Equilibrium profile after 900 years obtained with MOHID, running continuously and using different extrapolation schemes

The Figure 4 shows the comparison of the different approaches for the reduction of computational effort. It can be seen that the bed profile obtained with the second order extrapolation clearly differs from the general patterns of the results obtained with the continuous run and first order interpolation. That means that the bed evolution can´t be correctly explained by a second order extrapolation. So, in the next step of the evaluation of the different cases of the extrapolation scheme, it was neglected the Run100_Int50_2. Each of the remaining cases originates a different bed profiles evolutions. To help the correlation between them and to determine which have more similarities with the continuous run, several parameters were used. The results along time for the Total Eroded Volume (TEV) are presented in Figure 4. Figure 5 and 6 show respectively, the values obtained for the Water Volume (WV) and for the Relative Error of Total Eroded Volume (RETEV). It's easily observable that for the two first parameters the several schemes of extrapolation have the same behaviour. From the results of the RETEV, it is evident that the Run50_Int100_1 highlights from the others approaches, revealing a major distantiation from the trend of the continuous run. Besides that, all the values tend to decrease with time.

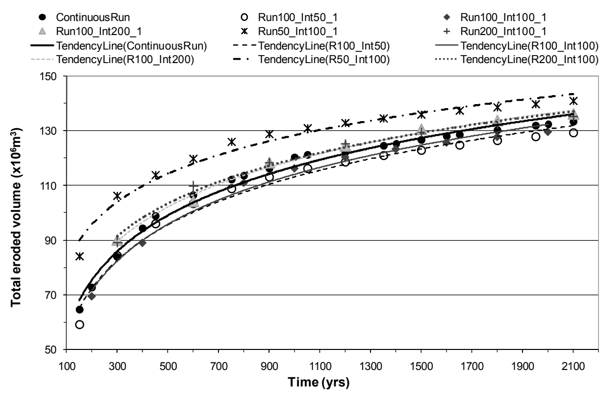

Figure 4. Total Eroded Volume values for the several cases considered in the extrapolation scheme

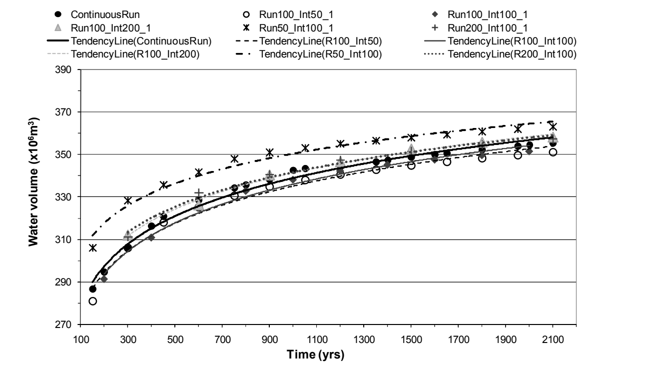

Figure 5. Water Volume values for the several cases considered in the extrapolation scheme

DISCUSSION

The SCHUTTELAARS and SWART (2000) equilibrium model predict a unique equilibrium profile as long as the basin length is maintained constant and a single frequency tide is imposed. When overtides are imposed at the border, multiple equilibrium profiles arise. In the MOHID simulations a pure M_2 tide was imposed at the border, but due to nonlinearity of the advection and bottom stress terms, internal overtides are produced inside the system. Furthermore, due to sedimentation at the head of the estuary, the active basin length is reduced during the simulations.

The morphodynamic model obtained shows a very high depth in the first cells near the boundary, followed by a rapid restoration to levels close to the equilibrium profile. This rapid deepening in MOHID is believed to be caused by the effect of the boundary, a similar behaviour is reported by HIBMA et al. (2003); the best solution for these boundary problems is to extend the boundary to include at least the ebb delta.

The extrapolation experiments resumed in figure **Erro! Marcador não definido.** show that second order extrapolation gave rise to very intense instabilities in the results. From the first order schemes tested it can be seen that globally all represent the original continuous simulation with a high degree of precision along all the length of the basin.

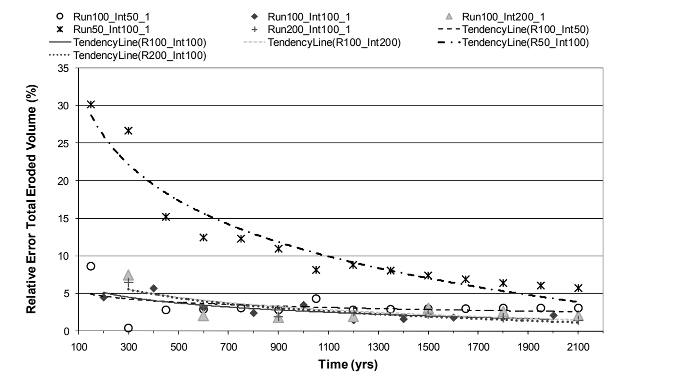

Figure 6. Relative Error of Total Eroded Volume values for the several cases considered in the extrapolation scheme.

When we look for values of the parameters that try to correlate the several approaches with the trend of the continuous run and for the computational time that they permit to save, the best results are showed by Run100_Int200_1. This extrapolation scheme allows achieving a gain of 2/3 of the computational time spent during the standard runs.

CONCLUSIONS

A process-based morphodynamic model was used to simulate the evolution of the sediment bed of a conceptual 1D embayment for periods in the order of a thousand years. It was shown that a nontrivial equilibrium profile is reached despite the inclusion of nonlinear terms and variable basin length. The model results were compared with both an idealized and an intermediate model. The results show similar trends for most of the basin. The differences, more visible near the mouth and the head of the embayment, were discussed. Finally, several extrapolation schemes were tested to accelerate the simulations. It was shown that second order extrapolations produce severe instability of the solution. From the first order arrangements tested, the simulation of 100 years followed by interpolation of 200 years shows the best results. It´s possible to say that the morphodynamic extrapolation scheme is able to reduce computational load to 1/3 of the total time, with small losses of accuracy, maintaining the data consistency.

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