A One-Dimensional Tidal River Morphological Model

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Keywords: estuary; hydrodynamics; morphology; sediment transport; numerical mode.

EXTENDED ABSTRACT

Fundamental process models may be compiled to form a comprehensive system that can predict morphological changes in a river or estuary from catchment inputs. In the case of tidal river morphology, regime theory, hydrodynamics, entrainment and deposition rates along with other processes must be amalgamated. The system to be discussed is a one-dimensional tidal river morphology model containing all of these components to provide the upstream segment of a morphology model to simulate the evolution of temperate estuarine channels as found in south eastern Australia.

The compilation of these processes has been calibrated for certain known equilibrium states that can be observed from current river systems. These include hydrodynamic equilibrium (uniform flow) and morphological equilibrium (no net scouring or deposition). In the course of applying these calibrations to the model, a number of issues related to the boundary conditions have emerged and are discussed once the workings of the model have been described.

The upstream boundary is a river that is in equilibrium, hydrodynamically, morphologically and geometrically. By the time the river has reached close to the tidal limit, it has achieved uniform flow (hydrodynamic equilibrium). The concentration of sediment within the flow is such that the deposition rate is equivalent to the entrainment rate (morphological equilibrium). The geometrical dimensions of the channel follow regime theory as the only influences inland are fluvial.

The equilibrium concentration must be defined in the upstream boundary condition for the suspended sediment load. This places a constraint on the entrainment function that can be used by the model.

The downstream boundary condition is a coastal lagoon although the mechanism to describe this is kept relatively simple. The water level of the lagoon is calculated from the ocean-level and flow into the lagoon from the tidal river to provide a hydrodynamic boundary condition while the bed elevation is updated from the sediment loads entering the lagoon to provide the morphological condition.

To validate the suggested boundary conditions, two tests were given to the model. The first test was to apply a perturbation to the bed elevation half way down the tidal channel and record recovery times for different flows. The second test was to run the program for some time, with initial conditions well away from equilibrium and observe the evolution of the bed and sediment loads. The tests show that the system behaves appropriately when compared to observations and experience.

So a process model has been produced and preliminary validation has provided optimism for the model to achieve goals in long term evolutionary modelling.

1. INTRODUCTION

A process based numerical model of an estuary is being developed to study the long term evolution of estuarine morphology in the estuaries of south-eastern Australia. The component of the model discussed is a one-dimensional channel receiving inflow of water and sediment upstream and driven by tidal waterlevel variations at the downstream boundary.

When modelling the evolution of systems governed by small timescale processes, similar difficulties will arise. These are as simple as rounding errors that can build up over many time steps, through to complicated issues such as procedures for approximating long term parameters as constants over short times. This study examines the form of the boundary conditions as the first step in a sensitivity analysis of a model produced to view the morphological evolution of a tidal channel. The model is governed by the small timescale processes of hydrodynamics, entrainment, deposition and sediment transport, while the boundary conditions are governed by larger timescale processes such as the river regime equations for the geometry of the channel. The goal of the model is to look at the sensitivity of the system when the inputs at the boundaries have been moved away from equilibrium values to enable understanding of the system's capacity to recover.

The response to changed conditions is important for tidal river and estuary modelling as extreme changes in morphology occur at transitions from one quasi-equilibrium state to another (e.g. at the end of a flood suspended sediment is deposited). By modelling the entrainment and deposition as a function of the hydrodynamics, the sensitivity of the system can be observed and transition phases modelled. The sensitivity tests in this paper are the beginnings of analysing these important features.

A point that will also be discussed in some detail is the importance of compatible boundary conditions with model equilibrium. This is especially so for tidal channels and estuaries, where the boundary conditions play a dominant role in the formation of their morphology.

The river leading into the lagoon in Figure 1 is referred to as a tidal river. While the model can cope with ocean tides, none are examined in this paper. The term tidal river, however, will still be used throughout this paper, although to be more accurate it is just a river entering a lagoon.

Sections 2-5 briefly describe the model and its boundary conditions. Preliminary model sensitivity tests are then presented and the conclusions of the paper then summarised.

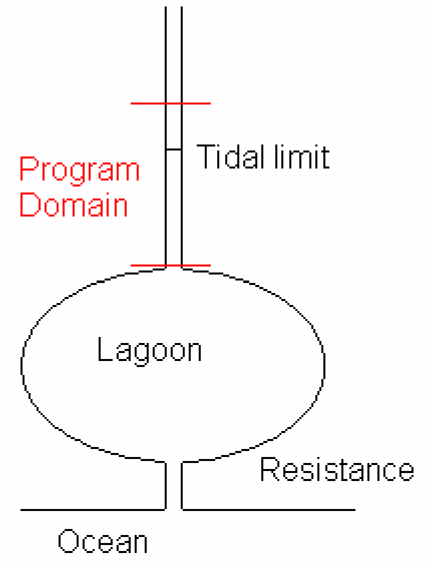


Figure 1. The domain of program with both the upper and lower boundaries clearly indicated.

2. MODEL DESCRIPTION

This is a process model which means that the processes that govern the change in morphology are modelled. It begins by solving the fluid flow which allows the erosion and deposition to be calculated, along with the sediment transport. The difficulty in modelling this way comes about due to the time scale of the processes is much smaller than the effects that are to be observed. In this case, the hydrodynamics are changing much more quickly than bed levels. This model is still under construction and it is hoped the evolution of the bed morphology can be observed over extremely long time periods. It is hoped that by looking at simplistic problems, a better understanding of the attractors of the system can be understood. Many of the quasi-equilibriums come from the boundary conditions, so most of the discussion will revolve around choosing the most suitable for this application.

To simplify the model the flow has been treated as one-dimensional. This reduces computation time and simplifies the boundary conditions. This also increases the robustness of the model although a disadvantage is that more of the physical processes have had to be parameterized than a three-dimensional flow.

The flowchart given in Figure 2 reveals that the general plan of the model is similar to other process models produced by Mason (2001) and Wang and Louters (1995). Initially the channel forming flow is computed using regime theory (Blench, 1957). The regime theory of rivers presumes that given sufficient time a river flowing in its own alluvium reaches an equilibrium state where the energy dissipation exactly balances the gravitational potential gradient and the sediment pickup and deposition are equal. These largely empirical formulae are applied to determine the bank-full flow, and hence the principal channel cross sectional dimensions, as the initial conditions for a model simulation. A sequence of flows and downstream waterlevels is then chosen for a given simulation, using the equations described below.

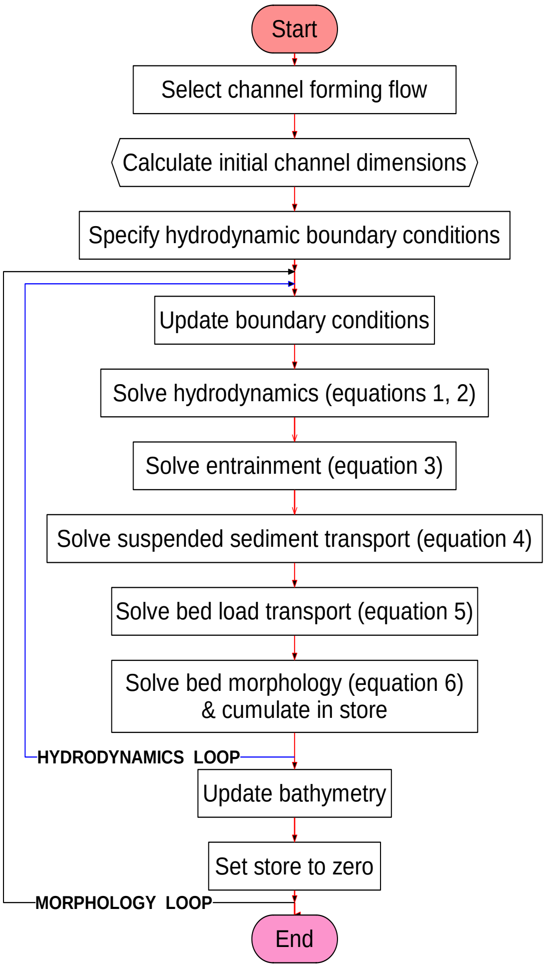


Figure 2. Flow chart of model plan

Note that the morphology is not updated as regularly as the hydrodynamics. For the tests done in this paper, 20 hydrodynamic loops were completed for every update of morphology. This is adequate since the morphology changes at a much slower rate than the hydrodynamics.

The following subsections describe how the hydrodynamics, sediment transport and bed morphology equations are solved. The equations solved in this model are similar in structure to those used in the work of van Leeuwan and Schuttelaars (2000) on tidal inlets. Specifically, two hydrodynamic equations, a suspended sediment equation and a morphology equation. In addition to van Leeuwan and Schuttelaars, this model calculates the bedload.

2.1. Hydrodynamics

The equations solved by the model are one-dimensional continuity and momentum (St Venant). The equations are solved for the variables of flow and area (as suggested by Fenton, 1982) using a semi-implicit scheme including a predictor step for the non-linear components of the equations.

$$\frac{\partial \zeta}{\partial t}+\frac{\partial}{\partial x}\left((\zeta-h)u\right)=0 \qquad (1)$$

$$\frac{\partial u}{\partial t}+u\left(\frac{\partial u}{\partial x}\right)=-g\frac{\partial \zeta}{\partial x}-\frac{ru}{(\zeta-h)} \qquad (2)$$

Where ζ is the water elevation, h is the bed elevation, u is the velocity and r is a linear resistance coefficient. Note that these equations have been written in terms of ζ and u rather than flow and area for clarity.

2.2. Suspended sediment transport

Equation (3) is solved for depth-integrated concentration of the fluid. It includes advection and dispersive terms as well as the processes entrainment and deposition. The entrainment is calculated as a function of the mean velocity while the deposition is proportional to the concentration. Process based entrainment formulae are available in van Rijn (1984c) but are inappropriate for this model.

$$\frac{\partial C}{\partial t}+\frac{\partial}{\partial x}\left(uC-\mu\frac{\partial C}{\partial x}\right)=E-D \qquad (3)$$

Where C is the depth integrated concentration, E is the entrainment and D is the deposition.

$$q_{sus}\approx 1.6258\times 10^{-6}\left(Q^2-Q_c{}^2\right)^{1.1} \qquad (4a)$$

$$E = \frac{q_{sus} \times B}{Q} \quad (4b)$$

Where q_{sus} is the van Rijn predicted equilibrium suspended load (m^2/s), Q is the flowrate, Q_c is the critical flowrate for incipient motion and B is the channel width.

2.3. Bed load transport

As stated earlier, the sediment transport has been split into suspended load and bed load. The bed load has been taken directly from van Rijn (1984a) and so does not include the inherent lag that the system has to reach the equilibrium as the hydrodynamics are changed. However, as the bed load makes up only a small part of the sediment load this inaccuracy is considered insignificant.

$$qbed = f(d_{50}, hydro) \quad (5)$$

Where d_{50} is the median diameter and *hydro* are hydrodynamic parameters like water depth and velocity.

2.4. Morphological equation

Equation (4) updates the bed to include changes from; erosion, deposition and bed load every morphological time step. A way to visualize the morphological changes is to look at the sediment transport gradients. This will be done in one of the tests described below.

$$\frac{\partial h}{\partial t}(1-p) = D - E + \frac{\partial q_{bed}}{\partial x} \quad (6)$$

Where p is porosity of the sediment.

3. BOUNDARY CONDITIONS

The tidal river does not have static boundaries over long periods of time. The lagoon water level will rise and fall and the bed level will gradually rise with deposition. The deposition zone will move upstream until even the river section is affected and thus the upstream bed boundary is also dynamic. The river depth will remain independent of the model on the boundary, but the bed will rise, forcing the water level to do the same. This means that both bed elevation and water level cannot be known independent of the model at the upper boundary. The only parameter worth considering as a reference for the model (over long periods of time) is the mean sea-level. While this value will also be changing with ENSO and climate change, at least the level can be predicted independent of all model parameters. All other boundary conditions are dependant in some way on the domain of the model.

3.1. Hydrodynamic boundary conditions

River: uniform flow is assumed here which allows the water level to be known on the boundary by Equation (7). This in turn allows the cross-sectional area of the boundary to be found. The flow of the river is also known from the input.

$$\frac{\partial \zeta}{\partial x} = S \quad (7)$$

Where S is the slope of the riverbed found by the regime equations.

Ocean: at the lower end of the model is a coastal lagoon that is connected to the ocean. The water level of the coastal lagoon is the boundary condition for the hydrodynamics at this end of the model. The level of the lagoon is calculated by specifying a resistance between the ocean level and lagoon level and recording the flow into the lagoon from the tidal river. Again, from this water level, the area can be calculated for the program to use at the final point of the river (see Figure 1).

3.2. Concentration boundary conditions

River: the concentration at the river boundary is calculated from curves fitted to van Rijn's (1984b) suspended load calculation. The upstream boundary condition for concentration is the parameter that constrains the entrainment function.

Ocean: the ocean boundary is described by assuming that the concentration becomes constant ($C_x = 0$).

3.3. Bed boundary conditions

River: since this boundary is assumed segregated from the tide, the conditions for the last two points are assumed to be just as the river was. Thus, the bed slope is the slope obtained from the regime equations allowing the bed elevation at the boundary to be defined as Equation (7).

Ocean: the bed boundary at the ocean end assumes that the lagoon fills uniformly with sediment from the river. This is a crude approximation to an estuary, as some sediment will be washed out to sea and some deposited on the flood plain, while wind waves will modify the deposition.

3.4. Consequences of boundary conditions

The upstream boundary is taken as a river in equilibrium no matter what the flow which allows van Rijn's suspended sediment load method to be used to calculate the concentration for the boundary condition. This causes a problem maintaining continuity from the boundary through to the domain of the program since van Rijn's suspended load is not used throughout the models domain. In Figure 3, the system contains zones of uniform flow, thus the concentration profile will be constant in these areas. This means the deposition term, which is dependent on the concentration, is also constant and specified. The entrainment term must match the deposition term since the system is in equilibrium so effectively, the boundary equilibrium concentrations constrain the entrainment function at uniform flows. So the entrainment function is going to have a similar form to whatever method is used to calculate the equilibrium concentration.

The disadvantage this has to the model is that the entrainment function cannot be entirely process based and must have a form that satisfies the equilibrium concentrations. This problem will arise whenever different schemes are used for the boundary and within the model. So when running long term boundary conditions, the domain of the model must approach them for the system to maintain continuity.

4. RESULTS

Two tests were conducted to begin to validate the choice of these boundary conditions. Test A and Test B are described below. For a more complete validation, the following steps are being completed.

4.1. Internal consistency checks

These checks include global water and sediment mass conservation balance and a global energy check.

4.2. Tests of consistency at equilibria

An example of this check would be to ensure that uniform flow exists in regime conditions. Another would be that no net scouring or deposition takes place while system is in uniform flow. These have also been achieved.

4.3. Sensitivity tests

By introducing perturbations of the initial and boundary conditions, similar to Test B, the response of the system can be viewed and compared to experience or observations.

4.4. Simulation

This final step allows a direct comparison of an actual case to observe how well the model performs.

The following test cases are part of step 4.3 in validating the model. Once several more of these have been completed to satisfaction, the model will be applied to a case study for step 4.4.

4.5. Test A

The purpose of this test was to show that a perturbation in the bed height of a river section is smoothed out by the disturbance to the sediment loads. As shown in Figure 3, one point along the bed was raised to be 0.1m higher than it would be if the bed was smooth.

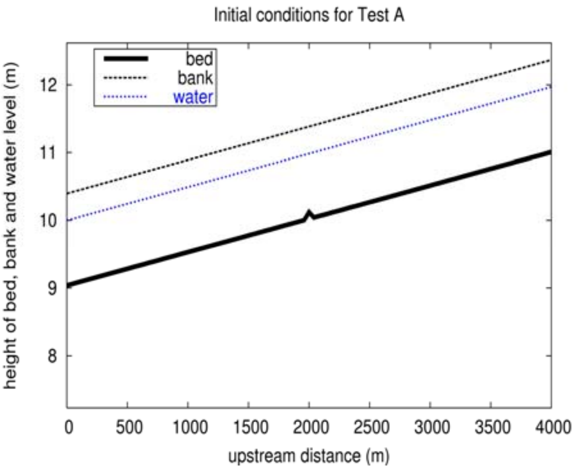


Figure 3. The initial conditions of Test A. The ocean boundary conditions are to the left which is also the direction of flow.

The system was not said to have recovered until all bed elevation values were within one centimetre of the smooth bed. The results are shown in Figure 4. As expected, at higher flowrates, and therefore higher sediment loads, the disturbance was eradicated more quickly. At flowrates below 4 m^3/s, the system could not recover. These cases were run for 5000 hours, but disturbances could not be reduced to less than 1.2 centimetres.

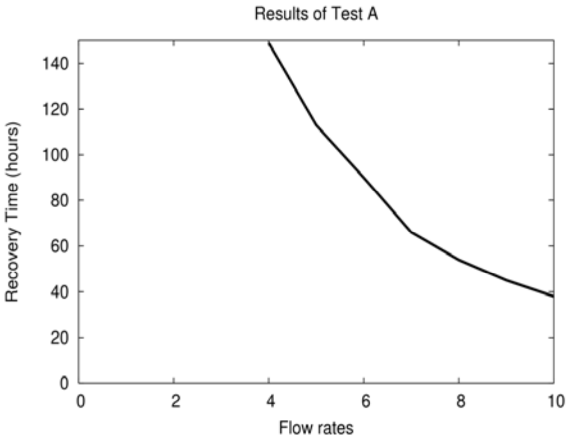


Figure 4. The recovery time reduces with higher flows due to the higher sediment loads

4.6. Test B

This test was devised to see how the sediment loads, and then the bathymetry, evolved. Figures 5 and 6 reveal that as the depth increases closer to the ocean, the entrainment term decreases (shown by the fall of the sediment load in Figure 5) allowing deposition to occur. The lagoon also fills with sediment. Note that a small lagoon was used to allow the bed to rise at a faster rate, and all sediment is assumed to be deposited on the lagoon bed.

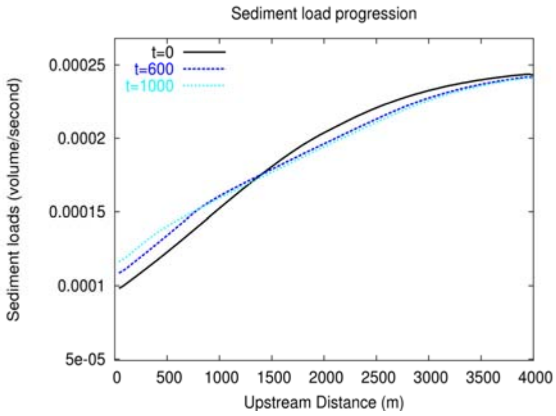
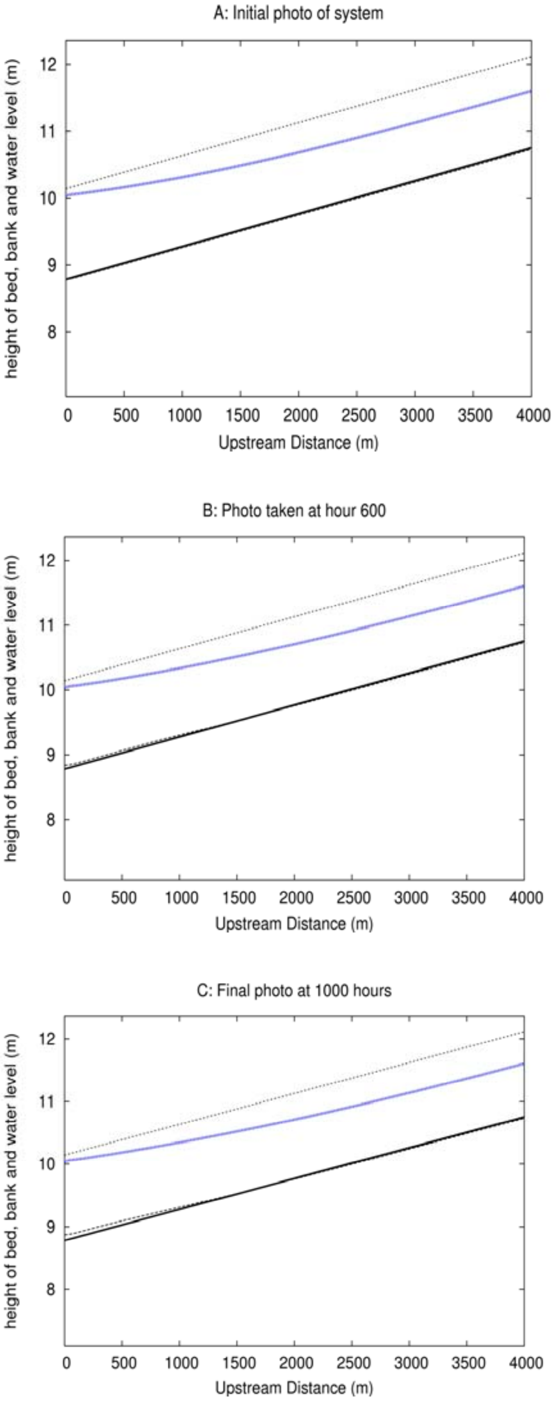


Figure 5. Because the flow is to the left, a positive gradient will result in deposition. Notice that the total load flattens with time indicating that the rate of deposition is decreasing with time.

This test was devised to see how the sediment loads, and then the bathymetry, evolved. Figures 5 and 6 reveal that as the depth increases closer to the ocean, the entrainment term decreases (shown by the fall of the sediment load in Figure 5) allowing deposition to occur. The lagoon is also filling with sediment although this is a little artificial since it is assumed that no sediment is lost (all sediment is deposited on lagoon bed) and windwaves are not taken into account.



Figures 6a,b,c. The change in morphology of the system over 1000 hours of runtime. The thick black line is the initial bed elevation while the thin black lines are bank and current bed level. The blue is the water level.

Again the results are as expected, matching well with experience. While these results are trivial in that they have not found anything new, they do allow certain optimism in the models capability in predicting morphological changes over longer periods of time using the boundary conditions discussed in the paper.

5. CONCLUSIONS

A one-dimensional model of a tidal channel terminating into a simple lagoon has been developed based on solving hydrodynamic and sediment transport equations.

With the structure of the equations used in this model, a constraint is imposed upon the domain by the upstream sediment load (upper concentration boundary condition). When the model is behaving like a river in equilibrium, a regular occurrence in the upper regions of the domain, the entrainment function must produce the same load as found upstream. Since van Rijn's suspended load method was used for this boundary condition, the entrainment function will require a similar structure to van Rijn's equation.

In terms of the results of the test cases, both tests returned expected results validating the use of these boundary conditions. Obviously these are preliminary and will need to be expanded before the model can be run with confidence over much longer times.

6. ACKNOWLEDGEMENT

This work is supported in part by the ARC Linkage Grant LP0347365 Geo-Hydrodynamic Modelling and Estuarine Evolution.

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