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A hybrid approach to estuary modelling

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Abstract: A hybrid model incorporating process and system modelling characteristics has been developed and applied to the evolution of a theoretical estuary with a small lake basin, partially enclosed by a barrier with an entrance open to the sea. The one-dimensional model is capable of modelling changes in sedimentation both spatially and temporally and hence, tracks changes in cross-section dimensions along the estuary. The model structure is a series of linked modules to solve the hydrodynamics, the sediment transport equation and a distribution of the sediment to bed and bank. An evolution simulation was conducted for a generic coastal lagoon over an approximate time span of 2000 years with the simplifying assumption of regular sediment supply from the catchment. A further assumption is present for the depositional module in that the distribution is affected by the operation of an attractor state governed by river regime relationships.

Over the 2000 year period the estuary evolved from the lagoonal state to an infilled river dominated form as predicted by the literature. While the timescale and detail of depositional pattern are heavily dependant on the assumptions relating to sediment supply and initial lagoon dimensions, the evolutionary modelling of the estuary has been undertaken essentially via a process model where the hydrodynamics have been extended over a time period not usual in conventional process models. The hybrid structure incorporated in the model has allowed the process component to be extended to a timescale usually only available to system models.

A 100-year event recovery simulation was also undertaken to allow assessment of the event-driven assumption made for the larger simulation. The results proved that there is no requirement to model the low-flow (nominal) periods of time between floods, since the only sedimentation of note was at the entrance. The effects of the entrance morphology on the rest of the system were negligible as the system modelled was fluvially dominated, with a larger tidal prism this may have not been the case.

While the structure of the model allows the investigation of both simulations, the choice of processes and relationships could be modified to suit other applications. Processes not included in these simulations such as wind waves may be incorporated into the process modules while an estuarine rather than river attractor regime may be more appropriate as the system module.

Keywords: *Hybrid model, process, system, evolution, recovery*

1. INTRODUCTION

The evolution of estuaries since the latest sea level change has been dominated by the infilling of drowned valleys and coastal lakes by sediments from catchment erosion and marine sources. The effective management of estuaries requires prediction of the nature and timing of response to management actions.

By compiling fundamental processes numerical modellers have been able to predict morphology change in coastal systems. Initially these models were often unstable and cumbersome to run and had a relatively short simulation time restricting them to only a short-term validity due to the large variation of scales between the fundamental processes and the geomorphic features modelled. With the use of averaging techniques (Roelvink, 2006) and more powerful computers, these models have evolved to enable examination in two and three dimensions over longer timescales.

Alternatively, empirical field measurements of coastal systems have enabled geomorphologists to produce descriptions of estuary evolution paths, such as Figure 1 from Roy (1984). This is a qualitative model, however, regime and attractor relationships have also been constructed from empirical data to for more quantitative models. These system models are able to model estuaries on a much larger scale of evolution than process-based models

These two paradigms have been combined to produce hybrid models (O'Connor, 1990 and Spearman, 1998) allowing advantages from each model design structure. Spearman (1998) looked at long-term changes in both morphology and hydrodynamic regimes that man-made impacts could have on a system.

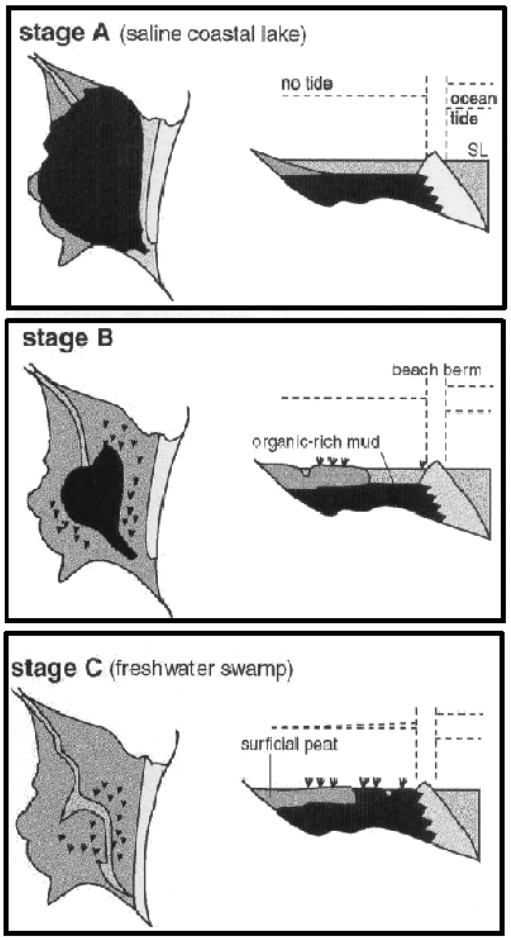


Figure 1: Geomorphic system model of coastal lake evolution from Roy (1984)

The purpose of this paper is to describe the structure of a hybrid model that more closely resembles a process-based rather than system-based model. The advantages such a structure allows are demonstrated in the results from two simulations. The first simulation models the final two stages of Roy's evolution (presented in Figure 1) revealing long-term modelling capabilities while the second simulation examines closely the short-term recovery from a 100-year flood event.

2. MODEL DESCRIPTION

The one-dimensional flow model presented here is capable of modelling changes in sedimentation varying with time and longitudinal position; and hence changes in cross-sectional area. The neglect of three-dimensional processes, in particular meandering and bifurcation, restrict the scope of the model to the later stages of barrier estuary evolution and preclude detailed locality studies.

The model has been written in modules as described in Figure 2. The first few modules combine to form a traditional one-dimensional process model while the linking of the two paradigms is conducted in the deposition module.

2.1. Boundary conditions

The boundary conditions are the same as a process model and are summarised in Table 1. Two are required to solve the hydrodynamic equations, two are required to solve the sediment transport and two conditions are used for the morphology at the upstream end of the system.

Table 1: Boundary conditions (BCs). Note that boundary condition 4 is based on whether sediment is entering or leaving the system.

Module	BC #	Physical Description	Implementation
Hydrodynamic	1	Upstream river flow	Upstream flow, Q
	2	Sea level	Downstream z
Sediment	3	River concentration	Upstream, C
Transport	4a	Downstream transport	Zero concentration gradient
	4b	Ocean concentration	Downstream, C
Deposition	5	Upstream river slope	Regime Slope
	6	Upstream breadth	Constant Breadth

2.2.

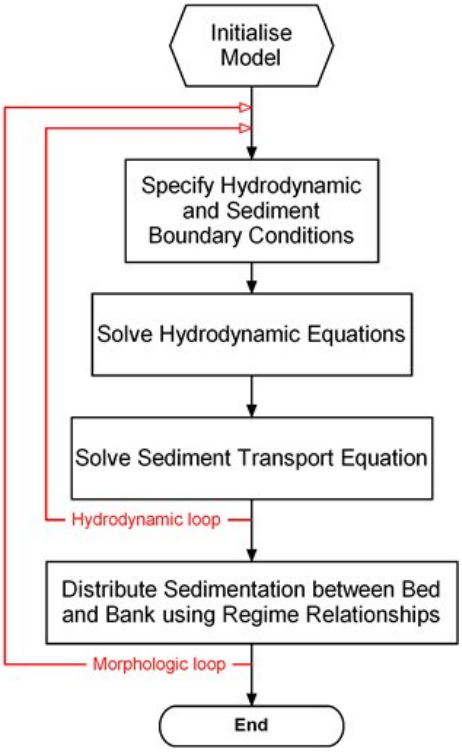


Figure 2: Flowchart of program modules

2.3. Initial Conditions

A plan view of the system at initial conditions can be found in Figure 4 where a river in regime (channel slope, depth and breadth) for a 10 m^3/s bankfull discharge enters a small lagoon. A similar channel downstream of the lagoon then enters the ocean and the slope is constant throughout the whole estuary. The system begins with a "nominal discharge" (3 m^3/s) throughout the system that represents low, non-event flows.

2.4. Hydrodynamics

The hydrodynamics are represented by the one-dimensional St Venant Equations; (1a) & (1b),

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \qquad (1a)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + gA\frac{\partial \zeta}{\partial x} + gAS_f = 0 \qquad (1b)$$

where A is cross-sectional area, Q is volumetric flow rate, S_f is frictional slope and ζ is water surface elevation and each are functions of position, x, and time, t.

These are approximated with finite difference equations that are solved by a MacCormack method (similar to a Lax-Wendroff method) accurate to second order in space and time. The system is always subcritical, so a boundary condition is required at both ends of the domain specifying either Q or A. The variable not specified is found using the method of characteristics. For example, BC 2 from Table 1 gives the water elevation and hence A. The method of characteristics is then used to solve for Q at this boundary.

2.5. Sediment Transport

Now that the hydrodynamics are known, the sedimentation can be found by solving Equation (2) (note that "sedimentation" refers to either deposition or erosion throughout this paper):

$$\frac{\partial(CA)}{\partial t}+\frac{\partial(QC)}{\partial x}-\mu\frac{\partial}{\partial x}\left(A\frac{\partial C}{\partial x}\right)=b(E-\Delta) \quad (2)$$

where E is the entrainment of sediment from the bed or bank (m/s), Δ is the deposition of sediment (m/s), b is the breadth (note that this is not necessarily the regime breadth, B), μ is the dispersion constant (taken as 10 m^2/s for these simulations based on calculations from Fischer et al., 1979) and C is the sediment volume concentration in the water column.

The entrainment and deposition can be defined as

$$E=f(u,\zeta,h) \quad (3a)$$

$$\Delta=\omega C \quad (3b)$$

where h is the water depth, u is the average fluid velocity and ω is the fall velocity of sediment particles (m/s). Any entrainment function from the literature can be implemented into Equation (2) and van Rijn (1984) has generally been recognised as providing a relatively reliable suspended sediment load calculation. However, this method is computationally expensive; consequently a curve fitted approximation reported in Soulsby (1997) has been implemented. A similar relationship for bed load is employed by this model separately from the suspended transport and is also presented in Soulsby (1997).

The change in area of the system is then given by

$$\frac{\partial A}{\partial t}=\frac{b}{1-\rho}\left(E-\Delta+\frac{\partial q_{bed}}{\partial x}\right) \quad (4)$$

where q_{bed} is the bed load.

2.6. Deposition

The previous modules solve the net sedimentation at each cross-section. The deposition module distributes the sedimentation to bed and bank in such a way as to approach the river regime relationships:

$$D=\sqrt[3]{\frac{F_S Q_E}{F_B^2}} \quad (5a)$$

$$B=\sqrt{\frac{F_B Q_E}{F_S}} \quad (5b)$$

where Q_E is the effective discharge, F_B and F_S are constants calculated from sediment particle and bank properties. To distribute the sediment the regime dimensions for the instantaneous flow, Q, are calculated throughout the estuary. This is done using equations (5a) and (5b) with Q substituted for Q_E. The difference between these calculated temporary attractors and the present dimensions are then found (actual – regime). The ratio of the breadth difference to the depth difference is then the ratio in which the sedimentation is distributed to bed and bank.

The above process actually only comes about when both dimensions, depth and breadth, are larger than the regime values in a deposition state or smaller in an eroding state. The system could be in an eroding state even though the breadth and depth are larger than the regime values so that the system would actually evolve away from the regime dimensions. Similarly, one dimension may be approaching regime while the other is moving away from it. When these states occur, a different distribution of morphological change is employed. Alternatively there may be no sedimentation available for evolution either brought about by an area similar to the regime area or no sediment transport.

This algorithm can be summarised as: if sedimentation exists, distribute it to bed and bank to approach the regime based on the instantaneous flow.

3. VALIDATION

No detail on the validation of the model is given here. However, Gould and Hinwood (2009) validated the model on three contrasting time scales: process (hydrodynamic), seasonal (perturbation recovery) and evolution. Conservation checks at the hydrodynamic scale ensure the model is behaving at that level while the seasonal perturbation and evolution simulations were conducted to ensure long-term stability and robustness of the model. The simulations in this paper have been conducted with a spatial step of 25 m and a hydrodynamic time step of 3 s. The morphology was updated every 10 hydrodynamic time steps.

4. EVOLUTION SIMULATION

The evolution simulation described in this paper began with the initial conditions described in Section 2.2 and presented in Figure 4: a generic lagoon. The system then experienced repetitive flooding at both bankfull and what was termed 10-year event levels (every 10 bankfull floods) that were introduced to the system as an upstream discharge boundary condition. These flood events lasted 40 hours and were followed by 80 hours of nominal conditions until the next flood event. The 10-year event was defined as a flood with a maximum discharge of twice bankfull flow and the flood profiles are presented in Figure 3a. In addition, there was a 1% likelihood of a 100-year flood event. This flood had a very different profile, as described by Figure 3b, with 120 hours of duration. Nominal conditions followed the 100-year event for 120 hours.

The elapsed time may be calculated from the number of flood events during the simulation. An underlying assumption for this simulation was that the morphology change between the events was negligible implying that the time being represented between the floods was the time between bankfull floods: 1-1.5 years in temperate regions; this proposition is confirmed in Section 5. Thus with 120 hours representing the evolution between one flood and the next, 90000 simulation hours comes to 750 floods or approximately 1000 years of evolution.

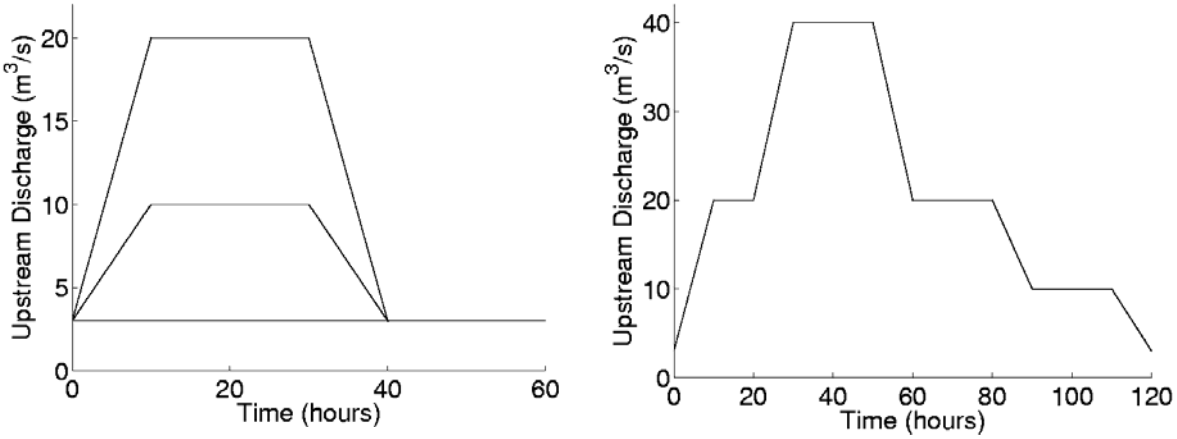
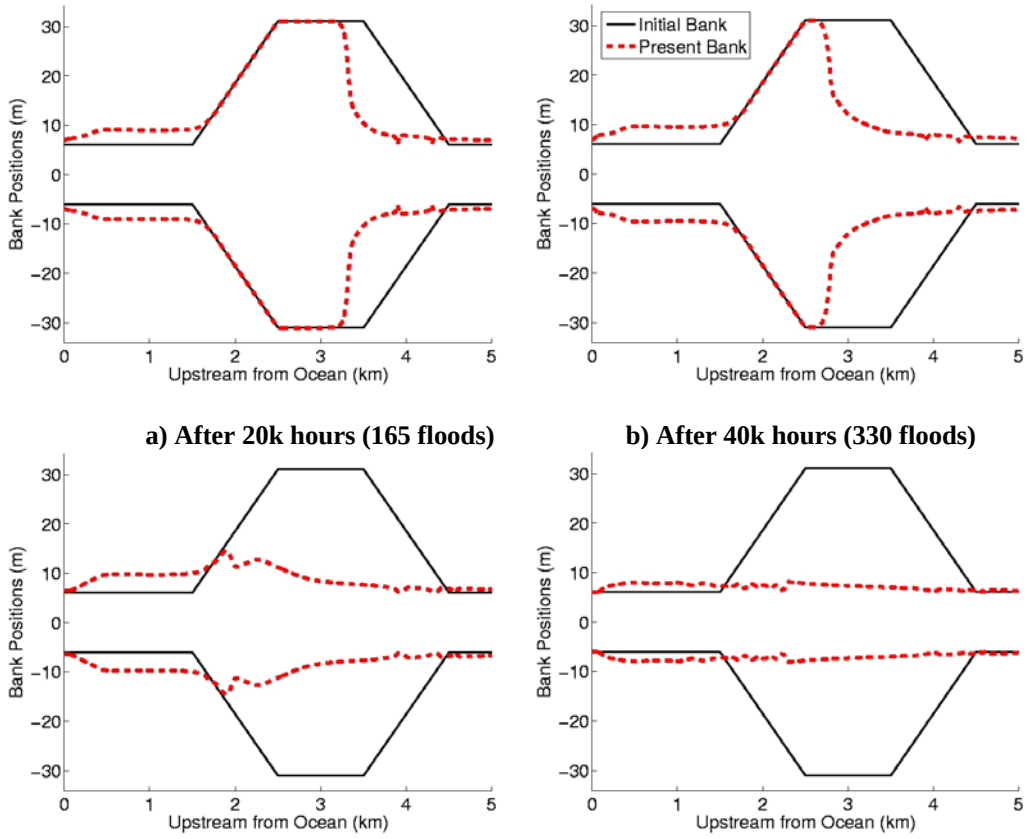


Figure 3: Flood event hydrographs: nominal, bankfull, 10-year and 100-year

The downstream ocean boundary conditions for the simulation maintained a constant tidal amplitude of 0.7 m as well as a constant ocean sediment volume concentration (for when the ocean acted as a sediment source, BC 4b) of 0.00015.

The snapshots in Figure 4 show the gradual evolution of the system towards a tidal river. The lagoon gradually diminishes as successive floods bring sediment from upstream to deposit in the lagoon similar to Roy's description in Figure 1. The larger floods have a bigger impact on the system and speed the evolution (for example if the hundred year events are not included, the system takes an additional 40 floods to evolve even though only four 100-year floods eventuated).



a) After 20k hours (165 floods) **b) After 40k hours (330 floods)**

c) After 90k hours (750 floods) **d) After 170k hours (1400 floods)**

Figure 4: Evolution path results

A constriction is formed during nominal conditions at the entrance that is continually washed away to different extents each flood event. This constriction originates from the ocean sediment and only impacts the system several hundred metres inland from the ocean. This system is not tidally dominated as the river discharge over a tide cycle is of the same order as the tidal discharge. With a tidally dominated system, the penetration of the ocean influence would be much further upstream.

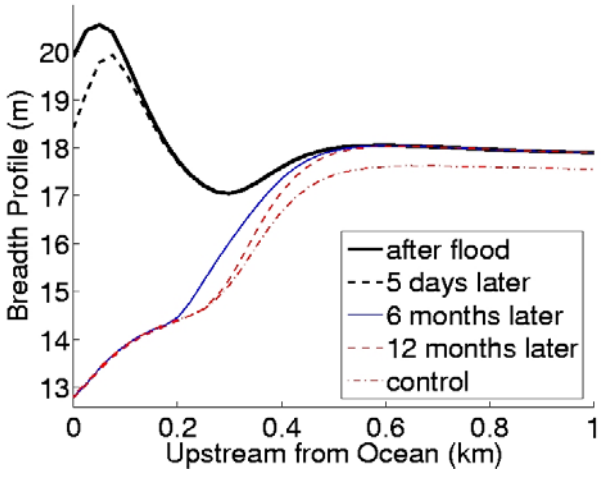


Figure 5: Recovery from 100-year flood event

5. 100-YEAR EVENT RECOVERY SIMULATION

Figure 5 presents a progression of entrance breadth recovery after a 100-year event. The system does not fully recover even twelve months later by which time another flood event could be expected.

The control curve in Figure 5 is the breadth of the channel 12 months after the initial curve if the flood event had not eventuated and this additional time allows the system to recover more fully from a previous bankfull flood event. The smaller breadth at the upstream end (from 0.4-1 km) of the control curve is the same as the initial curve (not shown here). The 100-year event has widened the channel throughout this region. This is a more

permanent feature of the system created by the major event as opposed to the changes immediately at the entrance. The only sediment source available for allowing the channel to diminish in size is from the ocean and the penetration of this source is only a few hundred metres. The other curves in Figure 5 are at various times after the event and the progression is towards the control curve. There is very little other change throughout the rest of the estuary during the 12 months of nominal conditions and this supports the event-driven evolution assumption made for the longer simulation. The only significant change of morphology between floods is limited to the entrance and has little impact on the rest of the estuary. Therefore, there is no requirement to model the nominal conditions between flood events.

6. CONCLUSIONS

The system component in these simulations of the model used the geometric ratio of a river in regime. Other geometric regimes may be more appropriate in modelling other systems including entrance dimensions for tidally dominated systems. Similarly other processes may be important for modelling and included in the process component of the model, for example, wind wave effects.

The key difference between this model and other hybrid models is that the sediment transport is calculated and physically consistent allowing the morphology to evolve over a known time. This structure allows the model to have more in common with process models rather than system models.

The evolution simulation modelled the final stages of a generic lagoon showing similar plans to Figure 1 from Roy (1984). This simulation did assume that the evolution was event-driven and neglected modelling the system when in a nominal state. This assumption was validated by examining the recovery of the system from a flood in a second simulation. The effects of a 100-year flood event were examined over 12 simulated months and very little recovery took place except at the entrance.

The hybrid structure incorporated by the model allowed the detail examination usually only available to process models over an evolution scale of modelling usually only available to system models.

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