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Reproduced from a paper published in:
Rivers, Coastal and Estuarine Morphodynamics
Santa Fe, Argentina, pages 941-946
2009

MORPHOLOGICAL MODELLING OF INTERTIDAL PROFILES IN ESTUARIES WITH STRONG TIDAL CURRENTS

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Abstract

This paper describes a numerical model for predicting the morphology of muddy intertidal cross-shore profiles. The model is an extension of an earlier model by Roberts et al. (2000) which described the equilibrium profile of mud flats in response to cross-shore currents and waves. The extended model also includes long-shore currents and has more detailed handling of hydrodynamic processes, allowing the profile evolution in response to changes in forcing, to be modelled as well as the equilibrium state. The model was applied to successfully reproduce an observed profile from the Severn Estuary and displayed an appropriate degree of variability in response to seasonal wave inputs.

1. Introduction

Muddy intertidal areas are commonly found in estuaries where they provide important wildlife habitat and help to dissipate wave energy, thereby contributing to flood defence. The shape of the intertidal flat is important in determining both the habitat and flood defence value of muddy intertidals.

Kirby (2000) states that high, convex intertidal mud flats, associated with accretion, are desirable for flood defence as the broad high intertidal affectively attenuates waves approaching the shoreline, decreasing the need for artificial defences. Similarly, high convex mudflats profile wider feeding grounds for wading birds. Low concave mudflats, often backed by eroding saltmarsh cliffs have been linked to long term intertidal erosion (Kirby, 2000). These mudflats are less desirable for both flood defence and habitat.

The shape of the intertidal mudflat is affected by tidal range, wave energy and sediment supply. Sediment properties, such as erosion threshold and fall velocity also influence the shape of the intertidal and may be modified by biological activity which may bind sediment together on the bed (biostabilisation) or enhance erosion (bioturbation) (Widdows and Brinsley, 2002).

Early work on the form of the intertidal under currents and under waves was done by Friedrichs (1993) and Friedrichs and Aubrey (1996). Roberts et al. (2000) extended the work to include sediment properties and a sediment concentration term. This method for currents and waves allowed investigation of a wider range of parameters; the work was extended by Pritchard et al (2002) and Pritchard and Hogg (2003). Waeles et al (2004) also developed a cross-shore profile morphological model which has since been used by Le Hir et al (2007) to explore how biology affects the long-term evolution of intertidal profiles.

Friedrichs and Aubrey (1996) developed an analytical model describing the hypsometry (distribution of area with elevation) of intertidal areas and assumed the hypsometry was in equilibrium if the maximum bottom shear stress was spatially uniform across the intertidal area. Concave profiles were correlated with small tidal ranges, high wave activity and erosion. Convex profiles correlated with large tidal ranges, low wave activity and accretion. The shape of the shoreline also influences the hypsometry of an intertidal area, with embayed shorelines enhancing convexity and lobate shorelines favouring concavity.

Roberts et al. (2000) used a simple numerical model to predict the equilibrium profile of intertidal mudflats in response to different tidal ranges, wave conditions and sediment supplies. Larger tidal ranges gave steeper tidal flats, but had little effect on the overall flat width. Waves tended to make the upper part of the intertidal profile steeper and higher sediment concentration gave wider flats with shallower slopes. The model results were found to be consistent with those predicted by Friedrichs and Aubrey (1996).

Pritchard et al. (2002) extended the Roberts et al. (2000) model to be very accurate in shallow water. This allowed the effect of tidal asymmetry to be evaluated , and the model tended to result in steeper profiles. Flood dominant profiles tended to accrete and prograde, whilst ebb dominant profiles exported sediment and retreated landwards. Spring-neap cycles were also modelled by Pritchard et al. (2002) and gave similar profiles but with less accretion in the upper intertidal due to shorter inundation times. Pritchard and Hogg (2003) used the model to investigate sediment transport processes including settling lag.

Recently Le Hir et al (2007) used a similar morphological model developed by Waeles et al (2004) to examine the long term effect of microphytobenthos and saltmarsh vegetation on morphology. The sediment-binding effect of the former was found to be minimised by seasonal wave action. The inclusion of saltmarsh in the model, whilst allowing significant accretion of the upper flat, did not include the erosion of the saltmarsh cliff by wave action, which is usually a key process for saltmarsh retreat.

These methods are applicable where the cross-shore currents and waves dominate (e.g. Skeffling Bight, Humber Estuary) but are not applicable to the case where the long-shore tidal current is strong (e.g. Wentlooge Levels, Severn Estuary) (Table 1). This paper describes extensions to the Roberts et al (2000) model to include long-shore currents and an updated handling of hydrodynamic processes to convert to bed shear stress; the driver for sediment transport in the model. The extended model has been applied to a profile from the Wentlooge Levels in the Severn Estuary where long shore currents are strong and cannot be ignored.

Table 1 Short description of two UK estuaries with contrasting wave and current regimes

Skeffling Bight, Humber Estuary	Medium energy Medium suspended sediment concentrations Fine sediments Dominated by cross-shore currents, with waves being more important than long-shore currents.
Wentlooge Levels, Severn Estuary	High energy High suspended sediment concentrations Fine sediments Long-shore currents dominate over cross-shore currents, although waves are also important

2. MODEL DESCRIPTION

2.1 Model concept

The Intertidal Profile Model is based on the mathematical model described by Roberts et al (2000) exploring the effects of tidal currents and waves on the shape of intertidal mudflats. The Roberts et al model predicted the equilibrium profile of a mudflat in response to different tidal ranges, sediment concentrations and wave conditions. These processes were represented in highly parameterised, simplified form.

The equilibrium morphology was defined as "the state where no net sediment transport occurs, when considered over a suitably long period" (Roberts et al., 2000). Mudflat profiles vary on a range of timescales (semi-diurnal, lunar and seasonal timescales) but appear to be approximately stable over long periods.

The new model has been extended to predict the evolution towards a new equilibrium state following changes in forcing. In addition, the hydrodynamic forcing inputs to the model have been developed to be more physically realistic, including the use of spring-neap tidal cycles, the inclusion of longshore currents and a more detailed handling of waves. Predictions are typically made over periods of years to decades

2.2. Model Equations

The intertidal profile is described by bed elevations at fixed cross shore intervals (nodes) (Figure 1). Cross shore currents are driven by changes in the water level at the offshore boundary. Changes in water level imposed at the off shore boundary force water onto/off of the intertidal flat and generate currents determined by the volume flux across each node, divided by the water depth.

Cross shore tidal currents are represented with simplified hydrodynamics, taking only conservation of mass into account and ignoring conservation of momentum:

$$\frac{\delta h}{\delta t} + \frac{\delta(uh)}{\delta x} = 0 \qquad (1)$$

where h is water depth, u is the depth average velocity and x is the cross shore distance. Roberts et al. (2000) reviewed the impact of this simplification and found that the mudflat profiles predicted were qualitatively similar to those predicted using the shallow water model of Brenon and Le Hir (1999) which includes conservation of momentum.

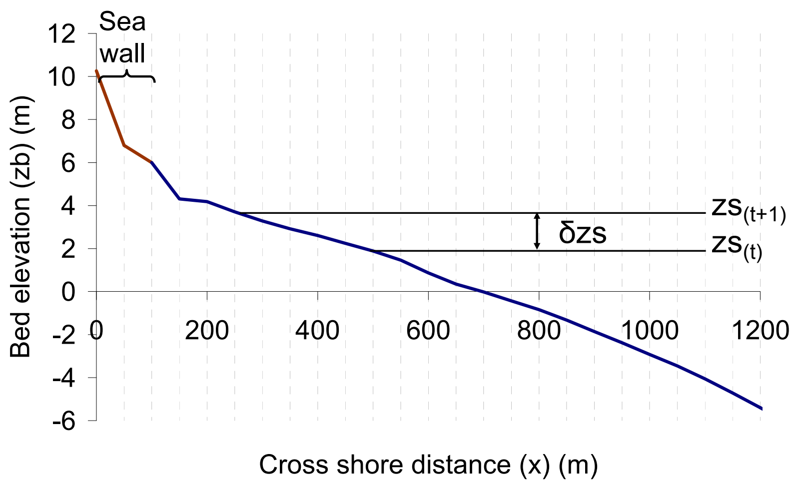

Figure 1 Schematic of the intertidal profile model. Changes in water level (zs) drive cross shore currents based on conservation of mass

Sediment transport in the model is described by an advection equation with source and sink terms for erosion and deposition:

$$\frac{\delta(ch)}{\delta t}+\frac{\delta(uch)}{\delta x}=Q_e-Q_d \tag{2}$$

where c is the depth averaged concentration and Q_e is the erosion flux and Q_d is the deposition flux.

Only the cross -shore currents transport sediment, with waves and long-shore currents creating additional shear stress at the bed but not carrying any sediment. This means there is an inherent assumption of stretches of similar tidal flat where the long shore gradient in net long shore sediment flux is minimal. This assumption must be remembered when selecting profiles for modelling. The seaward boundary is assigned a sediment concentration which is proportional to the tidal range.

Erosion occurs when the predicted shear stress from currents and waves exceeds the erosion shear stress. Deposition is assumed to occur at all shear stresses and is allowed to occur simultaneously with erosion, as proposed by Winterwerp (2007). The erosion flux is calculated using the Partheniades formulation and the deposition flux calculated using the produce of the settling velocity and suspended sediment concentration:

$$Q_e = m_e\left(\frac{\tau_b}{\tau_e}-1\right) \text{ (positive bed flux)} \tag{3}$$

$$Q_d = cw_s \quad \text{(negative bedflux)} \tag{4}$$

where m_e is an erosion rate constant, τ_e is the critical bed shear stress for erosion and w_s is the settling velocity. τ_b is the bed shear stress calculated from combined cross-shore and long-shore currents (τ_c) and waves (τ_w).

$$\tau_b = \tau_c + \tau_w \tag{5}$$

$$\tau_c = \rho C_D(u^2 + u_{\ln g}{}^2) \tag{6}$$

$$\tau_w = \frac{1}{2}\rho f_w u_p{}^2 \tag{7}$$

where ρ is the water density (assumed to be 1026 kg/m^3), u is the cross shore current velocity, u_{lng} is the longshore current velocity, C_D is the drag coefficient (z_0 is the bed roughness length) (Equation 8), u_p is the peak wave orbital velocity (Equation 9) (Soulsby, 2006) and f_w is the wave friction factor (Equation 10).

$$C_D = \left(\frac{0.4}{\log(h/z_0)-1}\right)^2 \tag{8}$$

$$U_p = \sqrt{2}\cdot\left(\frac{H_s}{4}\right)\left(\frac{g}{h}\right)^{1/2} \exp\left\{-\left[\frac{3.65}{T_z}\left(\frac{h}{g}\right)^{1/2}\right]^{21}\right\}$$

(9)

$$f_w = BR_w{}^{-N} \tag{10}$$

where H_s is the significant wave height, g is acceleration due to gravity (9.81 m/s^2), h is water depth, T_z is the zero crossing period of the wave (T_p=1.28T_z), R_w is the wave Reynolds number (U_pA/ν, $A=U_wT_p/2\pi$, ν is kinematic viscosity (1.36x10^{-6} m^2/s) and B and N are coefficients for smooth turbulent flow (B=0.0521 and N=0.187) (Soulsby, 1997). Smooth turbulent friction factors are used because combined waves and currents make laminar friction in appropriate (Soulsby and Clarke, 2004).

2.3. Boundary conditions and constraints

The sediment concentration at the seaward boundary (c_{bnd}) in the intertidal profile model varies over a spring neap cycle so that it is larger on spring tides and smaller on neaps. In this case c_{bnd} was allowed to vary through a spring neap cycle as follows:

$$c_{bnd} = c_{bnd\_in} \cdot \left(\frac{range}{springrange} \right)^3 \qquad (11)$$

A spring tide range of 11.2 m and a neap tide range of 5.6m were used in the simulations with a repeating 28 tide cycle. Sea-level rise can be included in the model providing the initial profile extends landwards of high water. The cumulative amount of sea-level rise is added to the water level so that water levels progressively move up the slope. As sea-level rises new nodes can become wet. These nodes do not have long shore currents from the flow model and therefore new long shore currents are estimated using a Chezy relationship and an assumption that the free surface along-shore gradient is independent of local morphological change.

The model includes the role of resistant material underlying modern sediment layers in controlling erosion. A profile with different erosion properties (higher shear stress for erosion, different sediment density) can be specified below the modern sediment surface. If this layer is exposed, erosion is limited by the greater resistance of the sediment. Alternatively, if the constraint is rocky, erosion of this layer can be prevented entirely.

3. Model Application

The model was applied to model the equilibrium profile of a mudflat at the Wentlooge Levels in the Severn Estuary. This site was chosen because the variability of the profile has been studied seasonal, spring-neap and tidal timescales (O'Brien et al., 2000).

The mudflat is located on the north shore of the Severn Estuary and has a macrotidal regime with strong tidal currents, high turbidity and exposure to short period wind waves. The tidal currents are flood dominant, with peak velocities occurring on flood tides. Peak long shore current velocities of 1 m/s have been measured (O'Brien et al, 2000). Suspended sediment concentrations vary between 300-400 mg/l on spring tides and less than 100 mg/l on neaps.

The intertidal profile model was driven using water levels and long-shore currents taken from flow model results over a spring –neap cycle and a two year time series of hindcast wave data to investigate seasonal variability in the profile in response to wave conditions. The sediment parameters used are shown in Table 2.

Table 2 Sediment property parameters used for Wentlooge

Parameter	Value
Critical shear stress for erosion (τ_e)	0.18 N/m^2
Settling velocity (w_s)	0.001 m/s
Erosion rate constant (m_e)	0.0001 kg/m^2/s
Bed roughness length (z_0)	0.0002 m
Bed sediment dry density	500 kg/m^3
Boundary concentration (C_{bnd})	350 mg/l (spring tides)

4. Results

With long-shore currents included the intertidal profile model successfully reproduced the observed mudflat profile of the study site (Figure 2). Without long-shore currents, the modelled profile shoaled rapidly and the intertidal area expanded into subtidal regions of the profile. This is unrealistic for this site and emphasises the importance of long-shore currents in shaping the profile.

The role of wave action was mainly confined to the upper flat while the tidal currents dominated the lower flat.

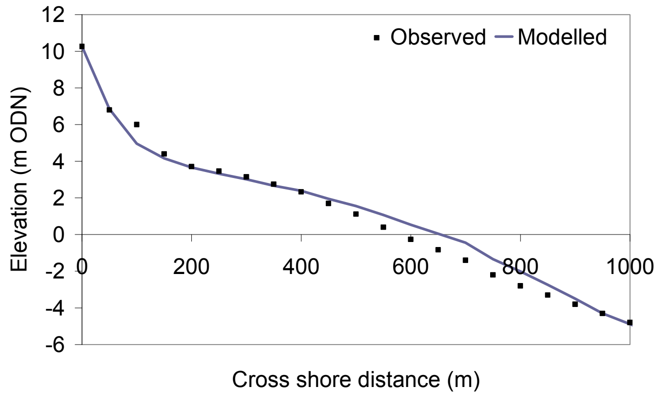

Figure 2 Comparison of observed and modelled profiles

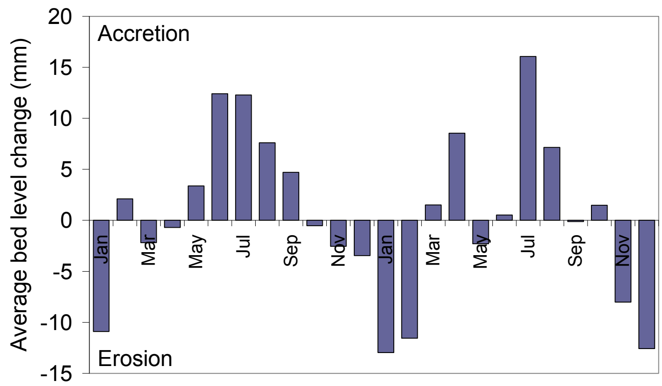

Figure 3 Monthly variations in average bed level

Variations in the profile were observed in response to temporal changes in wave conditions. The average elevation change between months is shown in figure 3. There is a general trend for accretion during the summer months and erosion in winter. Averaged over the whole profile (cross-shore distances 0 m to 800 m on figure 2), the predicted changes in any one month are up to 15 mm in magnitude. The predicted total change between summer and winter bed levels was up to 100 mm in magnitude and was greatest slightly below mean tide level (cross-shore distance of 650 m on figure 2).

O'Brien et al. (2000) report seasonal variability of bed levels to be in the order of 100 mm, with maximum variations of 240 mm between summer and winter profiles occurring at approximately mean tide level. This suggests that the predicted and observed seasonal variations in bed level are of a similar order of magnitude, although the range is smaller in the model predictions. In addition, the areas where the highest variability is observed are located at similar cross-shore locations in the model and observations.

5. Discussion

The extended cross-shore model has been applied to a site with strong long-shore currents and was shown to successfully reproduce the main features of the observed profile. Without the inclusion of long-shore currents the model predicted rapid accretion, particularly of the subtidal regions of the profile, making it impossible to represent the observed mudflat accurately. The development of the intertidal profile model to include long-shore currents significantly extends its potential utility by expanding the locations at which the model may be suitable. Initial testing with a limited selection of sites – of which one is presented in the current paper

– has given promising results, but further testing is needed to prove the robustness of the model.

The use of a wave time series allowed the sensitivity of the model to changes in forcing to be assessed. The model generally predicted accretion in the summer and erosion in the winter, although there were differences between locations along the profile. The range of seasonal variability in predicted bed level was up to 100 mm. This is smaller than the range observed by O'Brien et al. (2000), but is of an appropriate order of magnitude. The measured profile variations included responses to seasonal and inter-annual changes in tides as well as waves, whilst the model repeats the same spring-neap tidal cycle throughout. This means that any variability caused by tidal events is not captured in the model, in this case.

The intertidal profile model has been shown to respond to changes in forcing over seasonal time scales. These relatively short term changes in forcing can be viewed as inducing small variations in morphology around the equilibrium profile. The model could also be used to investigate changes in the mudflat response to changes in tidal levels, currents, waves and sediment supply that might result from engineering works in an estuary. In addition, if appropriate long-term trends in forcing can be identified, the model could also be used to simulate long-term trends in mudflat development. Larger scale changes in boundary conditions and forcing parameters, including sea level rise, will over a long period of time cause changes to the mudflat profile that can be evaluated with the model.

6. Conclusions

The paper has described the extension of an existing cross-shore mudflat profile model to include the action of tidal currents running perpendicular to the profile. The model predicts sediment transport due to waves and currents and the bed levels are updated to evolve the cross-shore profile in time. The average shape of the mudflat profile in the macro-tidal Severn Estuary at Petersone Wentlooge has been successfully predicted using input data for the tidal currents and water levels associated with spring-neap tidal variations and a two year time series of hindcast wave conditions. The model also has provided plausible results for the seasonal variation in erosion and accretion at the site. Applications of the model over longer periods of time is now anticipated including a more representative simulation of changes in tidal range, velocities and associated concentrations. The sensitivity to phasing of tides and waves, and the influence of long-term sea level rise, will need to be explored in these longer term simulations.

7. Acknowledgements

The extension of the morphodynamic model was carried out as part of the company research programme of HR Wallingford.

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