INTERTIDAL FORM ANALYSIS

Method Indicator		
Bottom-Up	Hybrid	Top-Down
		YES

Summary of key issues

Issue	**Description**
Description	• The concept of balance between eroding forces and strength of bed material to resist erosion; or • The concept of net balance between erosion and deposition of sediment.
Temporal Applicability	Short to medium-term (Tidal to decadal).
Spatial Applicability	Intertidal profile from HAT to LAT, where profiles are selected in a shore-normal orientation.
Links with Other Tools	Historical Trend Analysis (HTA) provides information on the profile changes that have taken place.
Data Sources	• Topographic and bathymetric profile datasets (as HTA); • Tidal forcing over the period of interest; • Wave forcing over the period of interest; • Allowance for sea level rise; • Suspended sediment concentration at offshore boundary; • Sea bed resistance to erosion. Wave and tide forcing may be determined from measurements or synthesized, e.g. using astronomical prediction of tides.
Necessary Software Tools / Skills	• Understanding of intertidal morphology and flow and sediment processes; • Access to reports and papers describing the methods used; • Access to existing software codes from developers of the methods; • Geomorphological interpretation of output.
Typical Analyses	• As a conceptual model for understanding the sensitivity of intertidal profile form to tidal current and wave forcing; • As a method of predicting the short to medium-term future response of the intertidal profile to changes in forcing or sediment supply.
Limitations	• Shorelines may be non-uniform alongshore in which case a profile approach is approximate; • Applies only to muddy sediment profiles; • Data inputs may be sparse; • Cannot predict change in channels running through the mudflat.
Example Applications	• The Humber; • The Wash.

Overview of technique

Intertidal zone geomorphology is an important feature within the larger estuarine morphological system, providing the transition between the estuary's subtidal channel and the shoreline with its natural features or man-made coast protection or flood defence works. Several approaches are reviewed here to predict the evolution of the intertidal profile formed in muddy sediments (mudflats). These methods can be used to determine the equilibrium shape of the mudflat given the prevailing environmental conditions. The inputs that are required are:

- Initial intertidal profile from subtidal, e.g. Lowest Astronomical Tide (LAT) to at least Highest Astronomical Tide (HAT);
- Tidal range and shape of tidal curve;
- Wave parameters offshore of the intertidal: height, period and direction;
- Bed sediment properties: erosion threshold; and,
- Boundary sediment concentration.

The methodology for application of the various modelling approaches is presented to enable (i) assessments of the natural behaviour of mudflats under wave and current forcing; (ii) response of mudflats to sea-level rise; and, (iii) the response to engineering works or encroachment.

For sandy shores there is an extensive body of work to describe the cross-shore form (Dean, 1977; Dean, 1987), however, work on cohesive shores is not as extensive. Early work on the form of the intertidal under currents and under waves was done by Friedrichs (1993) and Friedrichs and Aubrey (1996). Whitehouse and Roberts (1999) extended the work to include sediment properties and a sediment concentration term, allowing investigation of a wider range of parameters. Pethick (2002) derived a method to predict the profile evolution under waves, examining the role of sea level rise.

Mudflat typology and classification

Mudflats are a subset of the estuarine system and the EC project INTRMUD produced a descriptive typology and classification of these features in north-west European sites. An initial assessment of a particular site can be made based on simple information collected from site visits. The typology (Dyer, 1998) was based on tidal range (controlling the overall morphological profile); atmospheric exposure; waves; sediment; bedforms; and biology. The approach taken was to start from the basis of the geographical situation, and the external driving parameters which are imposed on the mudflat of tide dominated North-west European mudflats. Factors used in the typology include:

1. Tide range:macro-, meso-, micro-tidal;

2. Wave energy: high, low (qualitative);

3. Sediment supply: surplus or deficit, depending on whether the profile is depositional or erosional;

4. Steepness (slope): flat or steep, threshold at 1:750;

5. Zones: upper, middle, lower depending on lunar tidal range and mudflat profile

6. Sediment density:– soft, intermediate, hard;

7. Bedforms: indicating presence or absence of channels; gullies; slumps; planar; cliffs.

8. Organic content: high taken as organic matter content exceeding 5% determined by loss on ignition;

9. Biology: indicating presence or absence of worms; bivalves; macrophytobenthos; microphytobenthos.

A typology of 12 mudflat types based on these parameters was devised in the form of a matrix. A classification was subsequently produced (Dyer *et al*., 2000) and was based on the readily observable field measurements that formed the basis of the typology. The most important external driving variables were tidal range, followed by exposure to waves and mudflat slope. The next level for the meso- and macrotidal mudflats examined yielded a separation into three groups based on the bed sediment dry density. Floral and faunal assemblages were also analysed and showed that the relationships between sites on the upper mudflat were caused by grain size variation. The relationships for the middle and lower mudflats were not well defined. Further developments were proposed to build on the classification using the typology, e.g. to indicate the presence or otherwise of bedforms and biological assemblages.

If the information is collected in the framework of the Dyer (1998) mudflat typology, then an initial assessment of the mudflat condition can be made. More detailed assessments of the historical behaviour can be made by the analysis of historical charts. Future behaviour will be a function of the system's current state, the system's history and the most likely changes in natural or man-made external conditions, and can be undertaken from analysing modelling data.

The importance of hydraulics and sediment properties

Assessing mudflat response requires the combination of knowledge of the physical principles governing mudflat behaviour with an examination of the local conditions (O'Brien *et al*., 2000; Whitehouse *et al*., 2000a). By considering hydraulic influences, together with gross easily identifiable features of the mudflat morphology and width, the typology gives an indication of what types of smaller scale features are to be expected, such as sediment density, bed forms and biological activity. Not every mudflat will fit all of the listed features in the typology, but for those which fit reasonably well, an idea of behaviour can be gained by comparison with other mudflats of the same type.

Hydraulic influences

Energy sources available to modify mudflat geomorphology include tidal range; magnitude of tidal currents in the estuary, particularly near the mudflat, which may manifest as cross-shore or shore-parallel currents; and tidal asymmetry. Sediment transport balances in flood and ebb dominated systems influence mudflat shape and position in the tidal frame (Pethick, 1992). There also needs to be a consideration of fluvial flow, fresh water discharge, tidal discharge, and mudflat salinity. Exposure to waves from the open sea or to local wave generation requires assessment in conjunction with wind climate (frequency and direction); and the wet area of the estuary at high and low water, in order to identify if there is a big difference in fetch length at different water levels. The potential variation in wave conditions can be estimated from, for example, Yarde *et al*. (1995).

The dominant form of energy acting on the mudflat is one (or a combination) of waves and either cross-shore or shore-parallel currents. Examples of the conditions at three sites in the UK, including suspended sediment concentrations, are summarised in Box 1 (Whitehouse and Roberts, 1999).

Box 1. Summary of conditions experienced by mudflats in three UK estuaries
• Stour: low energy, low suspended sediment concentration (SSC), relatively coarse sediments, dominated by long-shore currents, with waves being more important than cross-shore currents. • Humber: medium energy, medium SSC, fine sediments, dominated by cross-shore currents, with waves being more important than long-shore currents. • Severn: high energy, high SSC, fine sediments, dominated by long-shore currents, although waves are also larger than at the other sites.

Cross-shore currents are proportional to the width of the mudflat and hence are significant on wide intertidal areas but negligible on narrow mudflats. The magnitude of the cross-shore tidal current on the intertidal, below mean sea level, can be approximated for a semi-diurnal sinusoidal tide curve by:

$$u_{\max} = \frac{\pi W}{T_{tide}} \quad (1)$$

where u_{max} is maximum value of current speed, W the mudflat width, and T_{tide} the tidal period (Friedrichs and Aubrey, 1996; Le Hir *et al*., 2000; Roberts *et al*., 2000). Above mean sea level on the upper flat the maximum current occurs at the tidal front and can be predicted by a modified form of Equation 1 (Friedrichs and Aubrey, 1996; Le Hir *et al*., 2000).

Shore-parallel currents are dependent on tidal range and tidal volume; for example, a large tidal volume is associated with a large cross-sectional area. If measurements are available of current speeds in the estuary channel, an approximate guide for extrapolating those to flows over the mudflat is that the current speed is roughly proportional to the square root of the water depth. If we assume a constant shear stress over the intertidal profile, in balance with the water surface slope (Whitehouse *et al*., 2000a) we arrive at the following expression for the variation of flow speed with position on the intertidal:

$$u_z = \sqrt{\frac{h}{\rho C_z}} \quad (2)$$

$$C_z = \left[\frac{\kappa}{\ln\left(z/z_0\right)}\right]^2 \quad (3)$$

The cross-shore profile of current speed u at height z above the bed can be described based on the local water depth h and the drag coefficient C_z with κ the Von Karman constant (0.4) and z_0 the bed roughness length related to the configuration of the sediment boundary. If the water depth at a point on the mudflat is four times smaller than in the estuary channel at a given time, the long-shore current speed on the mudflat will be about half that in the estuary channel. A more accurate assessment can be made from current measurements on the mudflat or from the results of a computational model of the estuary hydrodynamics, e.g. the TRANSVERSE model to determine the tidal currents perpendicular to the cross-shore profile (Uncles *et al*., 2000).

Direct measurements of waves at the mudflat site over a long period are the most useful information. However, hindcasting models, combined with a measured wind climate, provide a good approximation. For example, on a fetch length of about 5km length, the waves reach their fully developed state in around 30-40 minutes depending on wind speed. There will also be differences in the wave exposure in an estuary, with higher wave exposure in the area adjacent to the open boundary with the sea and lower exposure in the inner parts of the estuary (Pethick, 1992). Generally, it has been found that a wave-dominated mudflat tends to be more concave upwards than a mudflat where waves are negligible (Friedrichs and Aubrey, 1996; Lee and Mehta, 1997a). Therefore consideration of the mudflat cross-sectional profile can give a clue to mudflat behaviour. A crude measure can be obtained by looking at the horizontal distance of the mean water line (obtained approximately from spot depths on navigation charts or simple visual observation) from the high water line and from the low water line. A concave upwards mudflat has the mean water line closer to high water than to low water and hence a relatively short period of mudflat exposure on each tide.

Sediment information

Further clues to mudflat behaviour can be gained from sediment type, and the type and abundance of suspended sediment. High concentrations of suspended sediment mean that there is the potential for rapid accretion if conditions allow. Relative stability (i.e. no rapid accretion) means the large sediment supply must be balanced by strong currents and/or waves which maintain suspension. Low suspended sediment concentrations are commonly associated either with low-energy mudflats or mudflats which are resistant to erosion, because of consolidated or relatively coarse sediments. Future behaviour of a mudflat following a change in forcing will depend on sediment supply. Coarse mudflat sediments indicate low sediment supply and/or strong forcing from waves or currents.

Underlying sediments can exert an influence on the profile response. Seasonal sediment deposition can accrete to protect the underlying clay profile from erosion, thus the underlying sediment can only erode when it is exposed. Mitchener and O'Brien (2001) found that when a clay substrate was exposed by erosion of the seasonal (underconsolidated) sediments it was considerably more consolidated than the modern layer but it had an erosion threshold similar to the underconsolidated sediments. This evidence led them to conclude that the surface of the sediment had been weakened since becoming uncovered and hence the surface layer was more susceptible to erosion than might have been expected from its bulk strength.

Modelling approaches

Previous approaches to modelling intertidal form in estuaries due to currents and waves are reviewed below. It is essential to treat the mudflat response in context of the whole estuary, except for certain special cases such as the influence of cross-shore currents and of waves on the profile where long-shore currents are locally less important. These modelling techniques are required to provide details of the intertidal areas that are only treated in a general way by presently available whole estuary morphological approaches.

Friedrichs

Friedrichs (1993) and Friedrichs and Aubrey (1996) predicted the equilibrium profile (hypsometric profile) under tidal dominated conditions. The tidal current induced shear stress led to an upward convexity in the bed profile, more particularly a linear lower portion to the profile with convexity becoming strong above the mean water line. Equilibrium was defined by uniformity of peak bed shear stress over the whole tidal flat with the bed shear stress arising from the rise and fall of the tide across the flat.

For wave dominated conditions, Friedrichs adopted an approach in which the equilibrium profile was defined by the situation where the rate of energy dissipation was uniform over the mudflat; also akin to uniformity of maximum shear stress. He found that the solution led to a concave upwards profile with a 2/3rds power dependence of elevation *h*(*x*) on distance *x* across the intertidal flat:

$$\frac{h_x}{h_0} = \left(1 - x/L\right)^{2/3} \tag{4}$$

In which $x = 0$ at the offshore limit with depth h_0 and $x = L$ at the onshore limit. This is similar to Dean (1991).

Friedrichs (1993) used analytical and geometric arguments to link profile form to the plan shoreline curvature. A profile varying to the 2/3rd power applies to a straight shore. However for an embayed shore, the concave profile form is reduced; strongly embayed shores can become convex. Conversely a lobate/headland shore enhances the degree of concavity. Given that most muddy shores are straight or weakly lobate, profiles should be concave. However, Lee and Mehta (1997b) show that by including the wave-bottom interactions one obtains a more realistic description of the form. The theoretical form was again derived by considering wave energy dissipation over the intertidal but including the influence of the mud rheology.

$$z(y) = f_s \cdot y \cdot e^{-\beta \cdot y} + z_o \cdot e^{4\kappa(y_o - y)} \cdot \left(\frac{y}{y_o}\right)^2 \tag{5}$$

where f_s is the bed slope at y=0, y_o is the distance to the seaward limit of the profile, z_o is the depth at the seaward limit, β is a profile specific coefficient, and κ is the wave attenuation coefficient. The profile shape is thought to provide an indication of stability of the shore, with convex-upward profiles being accretionary and concave profiles being erosional (Kirby, 2002; Mehta and Kirby, 2001). Furthermore, Mehta and Kirby (2001) proposed a profile stability number, $S = 1\text{-}F_s/F_d$, where F_s represents shore stabilising factors and F_d shore destabilising factors. This gives S=0 for shores that are marginally stable and S>0 for eroding shores and S<0 for accretionary shores. Extensive data sets would be required in order to use this approach as a predictive tool.

Whitehouse and Roberts

Whitehouse and Roberts (1999), Roberts *et al*. (2000) and Roberts and Whitehouse (2001) extended the modelling approach for cross-shore current dominated environments. The equilibrium profile, or target profile (Lee and Mehta, 1997b), was defined from the concept that at each point on the profile there is net zero sediment transport integrated over a chosen time period; tide, spring-neap cycle or longer. The balance is determined when the deposition flux integrated in time and space balances the integrated erosion flux in time and space. The mudflat profile is assumed to be uniform alongshore so that the profiles are similar to the hypsometric diagrams for such situations.

Solving for the long term equilibrium profile – cross-shore currents

This section follows the approach presented in Roberts and Whitehouse (2001). The idea of equilibrium is that given sufficient time and constant forcing the morphology will adjust to a stable form, which does not change when viewed over a suitable time scale. This can be defined as

$$\int_{t^-}^{t^+} deposition(x,t)\, dt \;=\; \int_{t^-}^{t^+} erosion(x,t)\, dt \tag{6}$$

for all points *x* on the mudflat, where (t^-, t^+) is the relevant time interval.

To obtain a precise definition, in a situation where the forcing on the mudflat is varying on various time scales, becomes complicated. As a simple first case, Roberts and Whitehouse addressed the situation of a uniform tidal range, i.e. a system where every tide is the same. In this case the time interval in Equation 6 is the tidal period and the definition of equilibrium allows variation of mudflat level during the tide, but no net change over a tidal cycle. Thus periods of erosion must be matched by periods of deposition. The magnitude of these intertidal fluctuations (e.g. Whitehouse and Mitchener, 1998) would be expected to vary according to sediment properties and sediment supply.

To evaluate the expressions in Equation 6 requires knowledge of hydrodynamics and sediment transport rates. The approach taken was to use simple formulations of the water and sediment behaviour, to see which aspects of mudflat form could be shown to arise from the basic elements of the water and sediment dynamics. The hydrodynamics of the flow of tidal currents across the mudflat were represented by solving an equation for the conservation of water volume, with a sinusoidally varying water level imposed at the seaward boundary of the modelled area. As the water level rises and falls, water flows onto the mudflat during the rising tide and off the mudflat during the falling tide. The conservation of momentum equation is ignored, so the water surface is always horizontal. Therefore, any shallow water, inertia and frictional effects and thus any effects of tidal asymmetry on residual sediment transport are not represented by this approach. This is a reasonable approximation as long as the width of the mudflat is small compared with the tidal wavelength, or equivalently, that the Froude number, $Fr = u/\sqrt{(gh)}$, of flow across the mudflat is small, where *u* is the depth-averaged velocity, *g* the acceleration due to gravity and *h* is the water depth. This approximation may break down when the slope of parts of the mudflat becomes very small (i.e. very flat); this can be examined using Equation 1 to derive *u*.

The current speeds are calculated from the volume flux per unit width divided by the local water depth. A sinusoidally varying water level has been applied. The main influences on the current speed are the rate of change of water level, fastest at mid-tide, and the slope of the bed. Shallow bed slopes mean that the water's edge must move quickly as the water level changes and this leads to rapid cross-shore currents. The conservation of water volume is represented by:

$$\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} = 0 \tag{7}$$

where *h* is the water depth, *u* is the depth-averaged velocity and *x* is the cross-shore distance, in this case defined at the landwards end of the profile. Equation 7 is solved with a boundary condition for water depth h_{bnd} at the offshore boundary of the model domain, i.e.:

$$h_{bnd} = 0.5R\cos(2\pi t/T) \tag{8}$$

where *R* is the tidal range and *T* is the tidal period, and:

$$\frac{\partial(h+z_b)}{\partial x}=0 \tag{9}$$

where z_b is the local elevation of the sea bed, i.e. the water surface is forced to be horizontal.

To calculate the sediment transport, a simple approach was taken. The conservation of sediment was expressed as a depth-averaged equation for the advection of suspended sediment, with source and sink terms representing the exchange of sediment between suspension and the bed. The equation was solved with a boundary condition for suspended sediment concentration (SSC) on inflow, representing the external supply of sediment to the mudflat:

$$\frac{\partial(ch)}{\partial t}+\frac{\partial(uch)}{\partial x}=Q_e-Q_d \tag{10}$$

where c is the depth-averaged concentration, Q_e is the flux of material from the bed into suspension by erosion and Q_d is the flux of suspended material depositing on the bed. Q_e and Q_d were calculated using the following characteristic formulations (referenced in Dyer, 1986):

$$Q_e=m_e\left(\frac{\tau}{\tau_e}-1\right) \tag{11}$$

$$Q_d=cw_s\left(1-\frac{\tau}{\tau_d}\right) \tag{12}$$

where m_e is the erosion rate, τ_e is the critical bed shear stress for erosion, w_s is the settling velocity (assumed constant) and τ_d is the critical bed shear stress for deposition. [Note: The use of a threshold for τ_d is convenient as a tuning parameter but its physical meaning has been questioned recently (EstProc Consortium, 2006)].

The usual longitudinal diffusion term was not explicitly included in Equation 10, but the numerical method used to solve the advection equation introduces a certain amount of numerical diffusion. Large concentration gradients can occur in the shallow water, but the numerical method for advection makes use of the unidirectional currents to maintain conservation and non-negativity, with an acceptably small amount of numerical diffusion. The boundary conditions are expressed as:

$$\begin{aligned} c_{bnd} &= c_0, u<0 \\ \left.\frac{\partial c}{\partial x}\right|_{bnd} &= 0, u>0 \end{aligned} \tag{13}$$

where u is positive in the offshore direction. In real estuarine situations, the suspended sediment concentration will normally vary throughout the tidal cycle. However, rather than represent the full complexity of the natural variations, the above schematic approach was taken, to investigate the gross effect of high or low sediment supply.

The bed shear stress was calculated from the depth-averaged velocity, as follows:

$$\tau = \rho c_D u^2 \tag{14}$$

where c_D is a drag coefficient, assigned a constant value in the Roberts and Whitehouse simulations of 0.002.

The profile optimisation was attempted using two approaches, simulated annealing which searches for a global minimum of a function (following the method in Roberts and Whitehouse, 2001), and a morphodynamic approach, in which the variation of current speed with time is calculated from the equation for conservation of water volume. The morphodynamic approach has been selected here following Roberts and Whitehouse (2001). The underlying assumptions are that the tidal variation is sinusoidal, forced at the offshore boundary and that the profile remains monotonic. The morphodynamic approach starts from an initial profile, this could be linear or some measured profile, and solves Equations 6 and 9 over a tidal cycle. With a small number of grid points and the simple equations used it was found quite practical to simulate 100 years of 700 tides per year. A grid of 40 points was used for the simulations, with a grid spacing of 250-300m.

Including the effect of waves

Whitehouse and Roberts (1999) developed the morphodynamic approach to include wave action on the profile, i.e. the situation of waves combined with cross-shore tidal currents, with the assumption that the wave height is small compared with tidal range. The tidal currents contribute to the bed shear stress and act as the mechanism for sediment transport. The model of sediment transport in suspension is the same as for the tidal currents only case, with erosion and deposition rates as a function of bed shear stress (Equations 11 and 12), thus neglecting the more complex aspects of wave-mud interaction. A simple representation of wave behaviour was adopted, as follows. Linear wave theory for small amplitude shallow water waves indicates that the orbital velocity amplitude, u_w is given by:

$$u_w = \frac{H}{2}\left(\frac{g}{h}\right)^{1/2} \tag{15}$$

where H is the wave height, h is the water depth and g is the acceleration due to gravity. Thus the bed shear stress due to such a wave is then given by:

$$\tau_w = \frac{1}{2}\rho\, f_w \frac{gH^2}{4h} \tag{16}$$

where ρ is the density of water and f_w is the wave friction factor. In the schematic model tests a value of $2\text{x}10^{-3}$ for f_w was used. This approximation is used in the numerical model, and is extended somewhat beyond its limits of applicability by using it in intermediate water depths as well as in shallow water (as defined by the ratio of water depth to wave length). In addition, it was assumed that the wave will break when the wave height is approximately 50% of the water depth. Shoreward of this point, the wave height decay is depth limited to a height of less than or equal to 50% of the depth.

The largest stress occurs at the location of wave breaking. Inshore of the breaking point, as the maximum value of wave height is equal to half of the depth the shear stress becomes linearly dependent on the depth and thus decreases towards the shore. The combined effect of waves and currents was treated by linear superposition of the wave and current shear stresses. This is a reasonable approximation to take for the schematic approach adopted but if a more complex approach is needed new methods are available (Soulsby and Clarke, 2004; EstProc Consortium, 2006). The same morphodynamic approach described for the cross-shore current model was used.

The action of waves reduced the convexity of the profile (Figure 1) and with increasing wave height the profile became concave. The highest waves tested produced (unrealistically) large cliffing at the top of the intertidal.

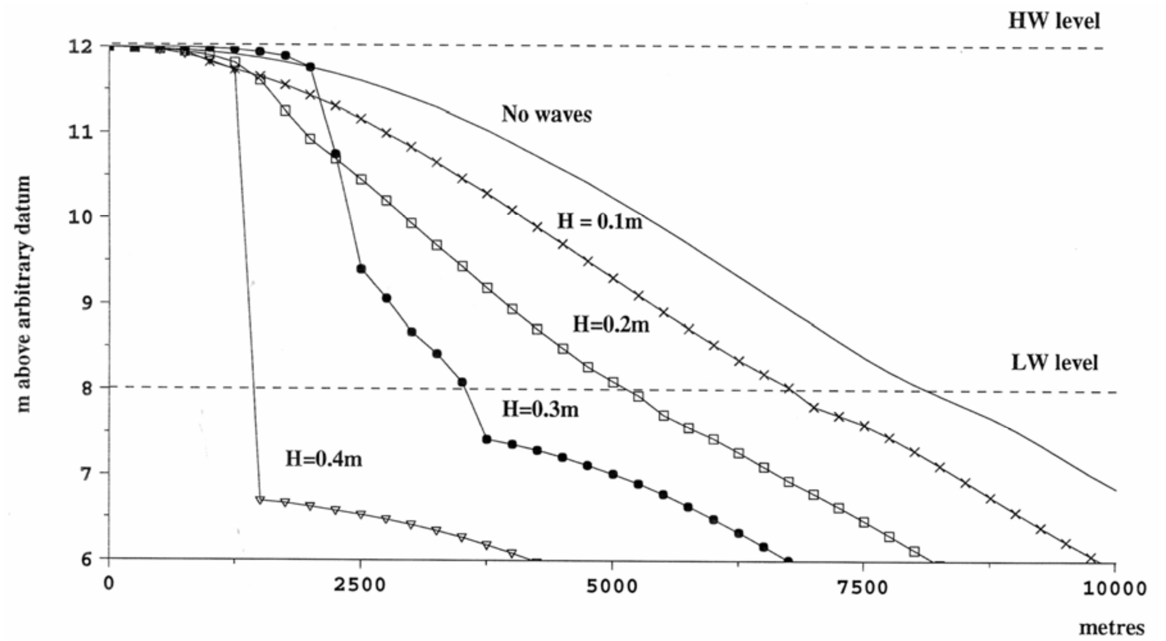

Figure 1. Effect of wave action on the modelled profile (Whitehouse and Roberts, 1999)

One solution to this problem, to introduce a more realistic representation of the occurrence of waves, was proposed by Roberts *et al*. (2000), who examined the comparative response of continuous wave action, wave action varying with tidal level, and intermittent wave action, i.e. waves not occurring on every tide. Extensions included applications with an asymmetric tide and a spring-neap tide (Roberts *et al*., 2000; Roberts and Whitehouse, 2001; Pritchard *et al*., 2002).

Including biology effects on sediment properties

As the modelling approaches include representations of the physical processes of sediment transport it possible e to include the effects of biology on those processes. For example, Wood (2000) used the Biosed model, similar in basis to Whitehouse and Roberts approach, to determine erosion and deposition on a cross-shore current dominated profile including the parameterised effects of biological action on the bed sediments. It is noted that the influence of biological processes on sediments has been further explored and parameterized in recent research (EstProc Consortium, 2006), leading to algorithms that can be implemented directly in morphological models.

Best practice methodology

It is essential to treat the mudflat response in the context of the whole estuary except for certain special cases such as the influence of cross-shore currents and of waves on the profile where long-shore currents are locally less important. These modelling techniques provide details of the intertidal areas that are only treated in a general way by presently available whole estuary morphological approaches, for example the Regime approach or the hybrid model Estmorf (Wang *et al*., 1998).

The following approach to assessing the response of intertidal mudflats to changes in environmental conditions is proposed:

1. Determine the key features present on the intertidal area. If the mudflats examined in the Whitehouse and Roberts, and MUDPACK approaches are analogues of the mudflat to be examined then the results of the model results presented may provide indications as to the response of the mudflat to changes in mean water level, currents, waves, or suspended sediment concentration.

2. Determine how the mudflat is situated within the estuarine system and the prevailing processes relating to sediments, tides, currents, waves (see HTA tools document);

3. The mudflat constraints may be determined by Historical Trend Analysis, regime analysis, rollover, asymmetry relationships, sediment budget analysis, and a review of geological features;

4. If new model results are required and cross-shore currents dominate, then use the Whitehouse and Roberts modelling approach; prescribe the initial profile and sediment characteristics and determine the input forcing time series. Sediment behaviour can be prescribed using the methods in Whitehouse *et al*. (2000b);

5. If waves dominate then drive the model with waves (Whitehouse and Roberts, and MUDPACK approaches); prescribe the offshore wave conditions and transfer them into shallow water across the mudflat using a theoretical approach (Equation 16) or measured information on wave propagation at the site;

6. Wherever possible compare the results of model predictions in hindcast mode with historical data before making forecast predictions; and,

7. Analyse, interpret and present the results, for example within an Expert Geomorphological Framework.

Case studies

The profile model was applied to the Humber Bight Skeffling mudflat (Figures 2 and 3) and a reasonable agreement in profile shape was found (Figure 4) by adjusting the input coefficients to take reasonable physical values (Roberts *et al*., 2000).

Also Whitehouse and Roberts (1999) and Roberts *et al.* (2000) explored the mudflat response to tidal range (Figure 5) and sediment concentration at the boundary (Figure 6). Typically the model results were extracted after 40,000 tidal cycles (i.e. approximately 57 years), as this was found to be similar to that achieved after 80,000 tidal cycles (Roberts *et al*., 2000). The equilibrium shape of the mudflat was found to be independent of the initial mudflat profile.

(Photograph copyright Richard Whitehouse, HR Wallingford)

Figure 2. **The mudflats at Skeffling on the Spurn Bight, Humber Estuary**

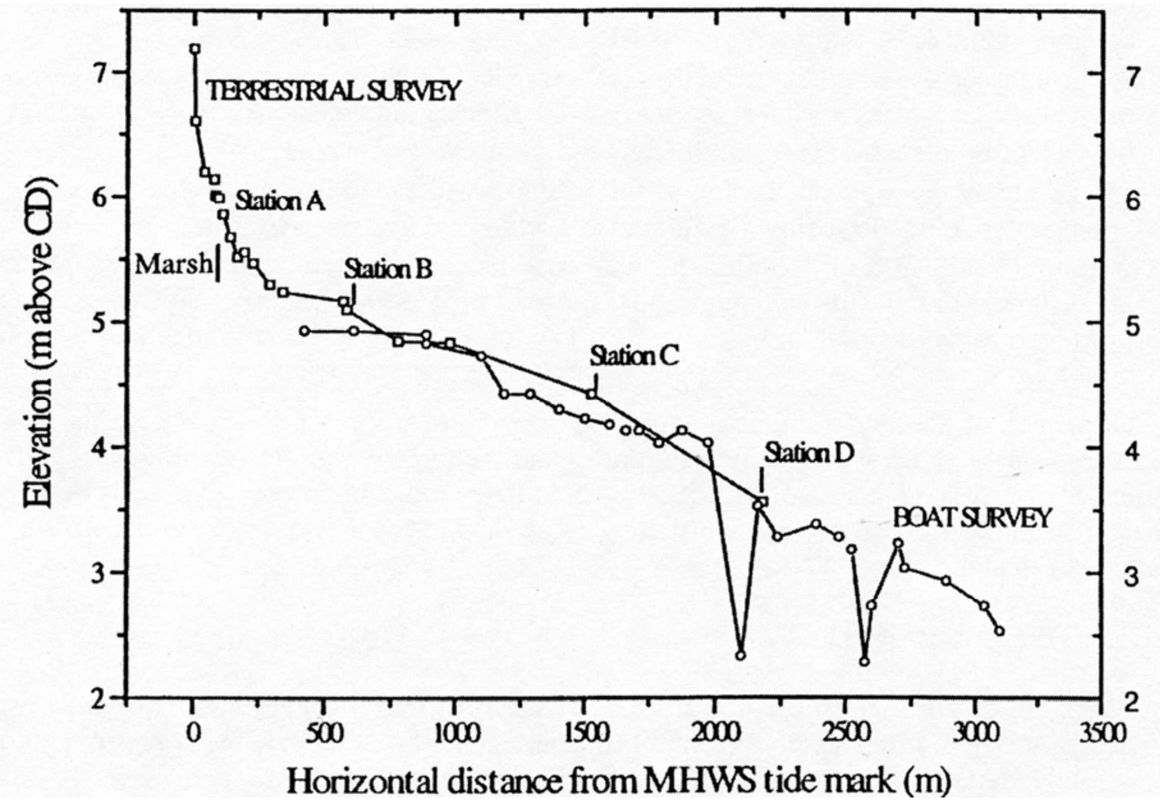

Figure 3. **The Skeffling intertidal profile (Humber Estuary)**

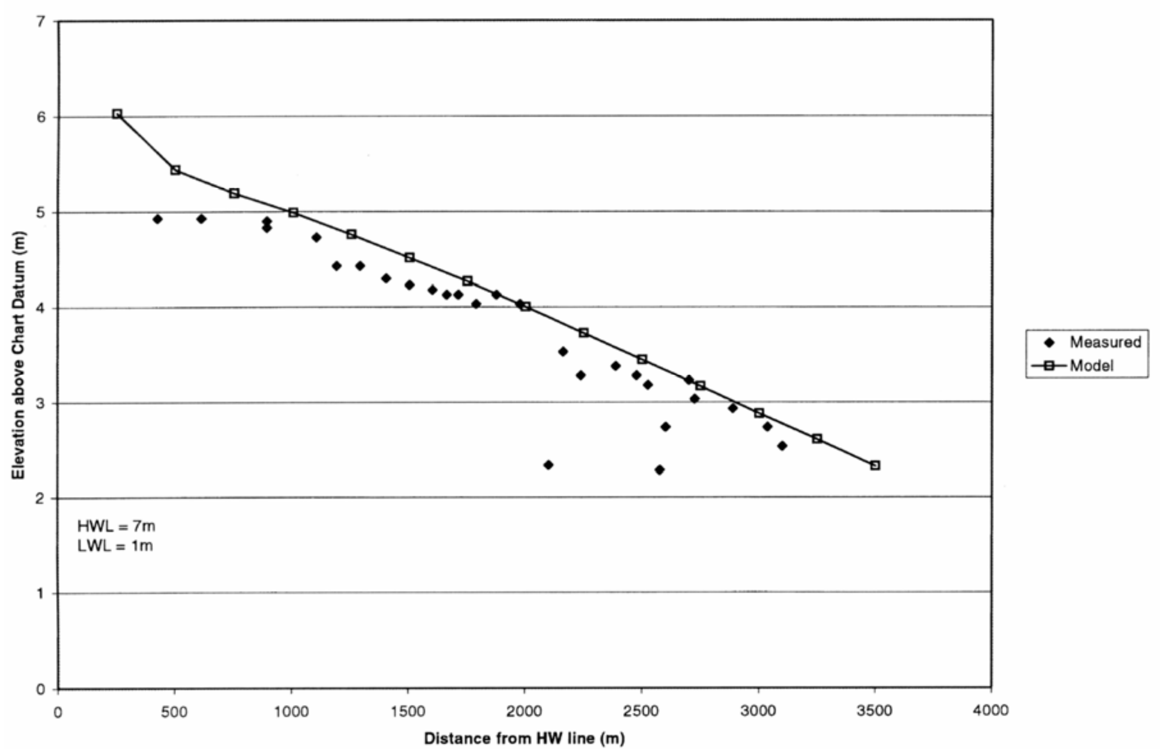

Figure 4. **Comparison between measured and modelled mudflat profile at Skeffling, Humber Estuary (from Roberts *et al*., 2000)**

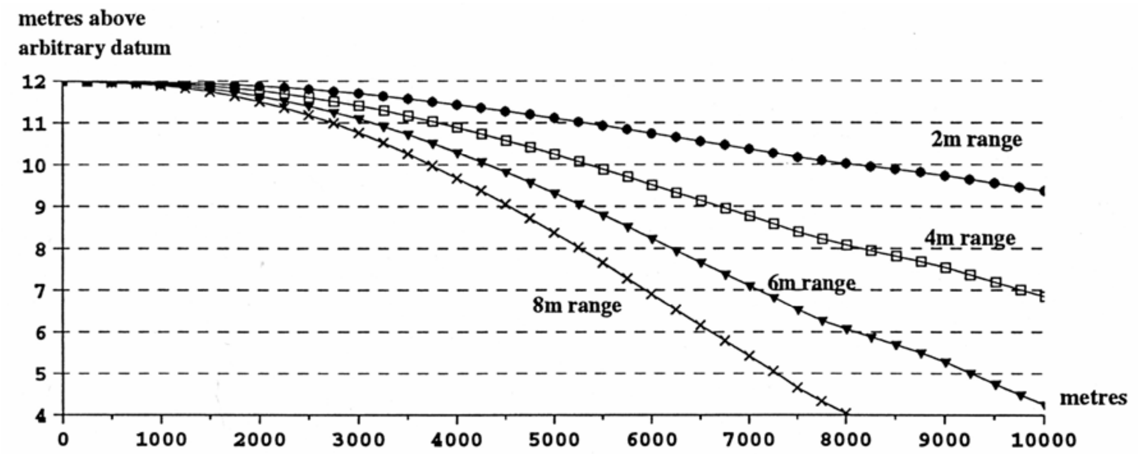

Figure 5. **Variation in modelled intertidal profile with tidal range (Whitehouse and Roberts, 1999)**

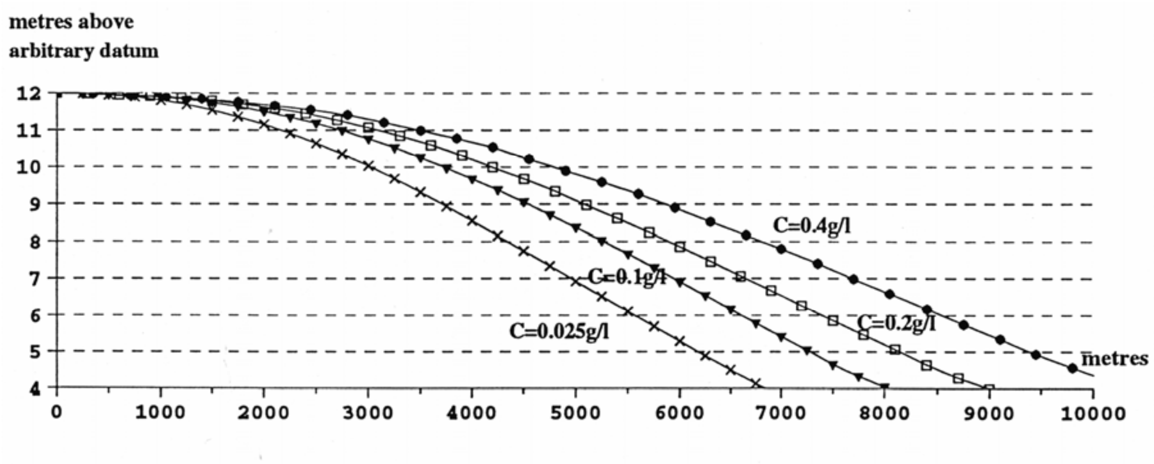

Figure 6. **Variation in modelled intertidal profile with sediment concentration at boundary (Whitehouse and Roberts, 1999)**

MUDPACK model

The MUDPACK model was applied to coastal data analysis and the prediction of long-term intertidal profile evolution modelling in the Wash (Pethick, 2002). This model uses the balance of the forces acting on the mudflat surface; namely the balance between the stresses applied by waves and tidal flows and the resistance to this shear arising from the inherent strength of the sediment at the mudflat surface. The modelling approach is similar to Roberts *et al.* (2000) but the profile was gridded at intervals of 0.05 times the tidal width and the elevation at each grid point adjusted at every time step for the balance between the applied wave-induced bed shear stress and the sediment shear strength. The model is driven with inputs of the initial profile (usually obtained from an intertidal survey along a line normal to the shore), waves, tides, sediment characteristics (shear strength), and the annual rate of sea level rise.

The Weibull statistics of an annual record of wave conditions recorded in deep water over the period of one year were used to derive appropriate duration time series of waves. The wave height decay over the profile was determined from measurements of waves and water levels at three locations on the intertidal. From three locations in the Wash measurements of waves showed wave heights to decay approximately linearly to the shore from locations where the wave height equalled 0.6 to 0.8 the water depth; thus wave breaking was assumed to start further offshore than in the modelling approach of Whitehouse and Roberts (1999).

The erosion is derived from an erosion formula including applied shear stress, threshold shear stress and erosion constant (as Equation 12). The deposition is derived from a function including applied shear stress, threshold shear stress for deposition, suspended concentration and fall velocity (as Equation 13). The sediment strength was defined in the top 100mm of the bed; 5 layers each of 20mm thickness. Shear strength increased with depth in these layers. The model calculates the erosion or deposition every three hours at the pre-defined spatial intervals on the model grid, and the profile was adjusted accordingly. Allowance for SLR is made by adding a linear function of the annual rate at every time step.

Model validation

The model predictions were hindcast over the period 1992 to 1999 and the comparison of the observed and predicted changes are shown for one of the site locations in Figure 7. The predicted profile has similar features to the observed profile but that neither profiles are monotonic (an assumption in the Roberts/Whitehouse approach). The MUDPACK model was optimised for a specific value of boundary suspended sediment concentration.

Model predictions in the long term

The model was then applied in forecast mode over a 50 year prediction horizon to assess intertidal profile change and change to the position of the saltmarsh boundary. Results from one of the sites are shown in Figure 8. The model shows a lowering of the intertidal, as shown in the expanded section in Figure 8, with the effect of SLR resulting in higher elevations after 50 years than those achieved with a static mean sea level.

It is noted that the 50 year model results produce “cliffing” at the inshore and offshore ends of the profile. Mean Sea Level will be near to, or somewhat above, 0m ODN and hence erosion by wave action may be concentrated near to the high (c. 1.8m to 4.5m) and low (c. -0.8m to -2.9m) water stands.

Figure 7. **Hindcast prediction of intertidal response at Wrangle Flats, the Wash, using Mudpack model (Pethick, 2002)**

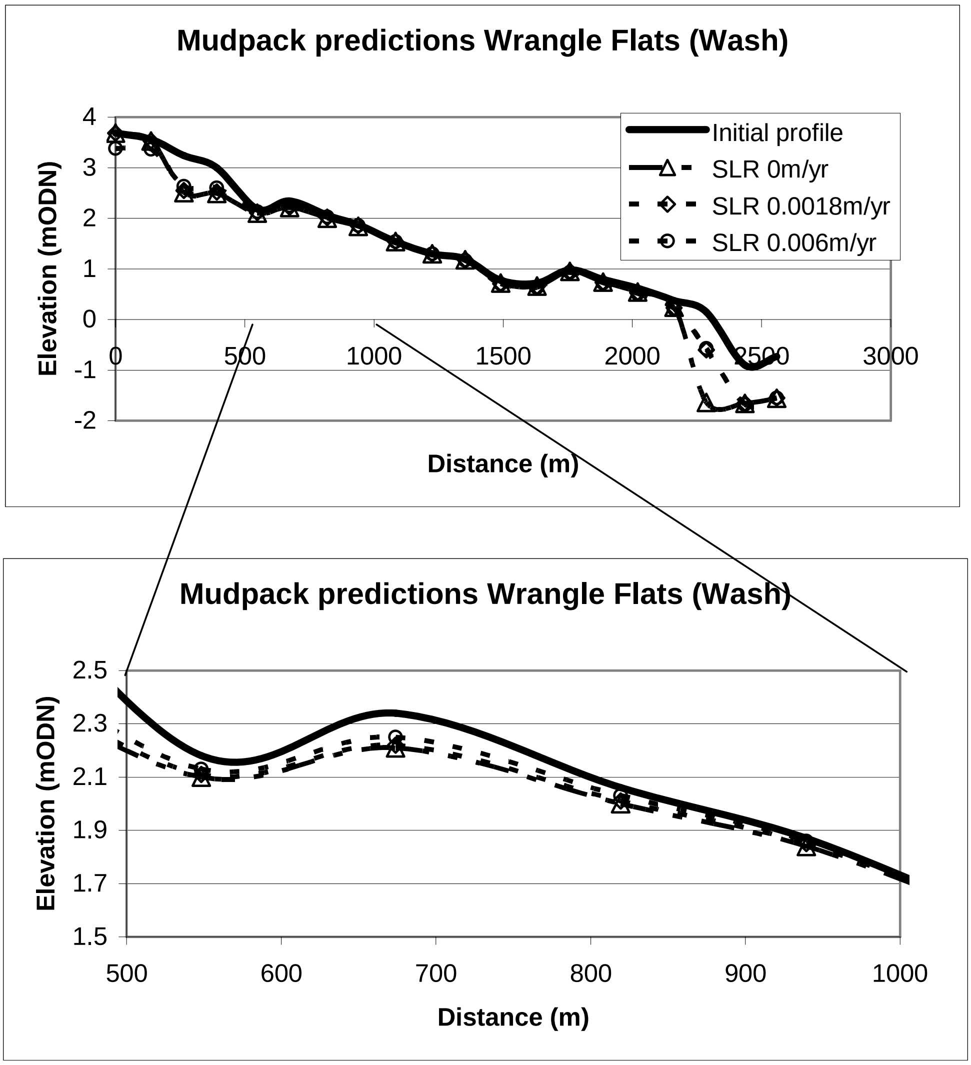

Figure 8. **Predictions of 50 year evolution of the intertidal at Wrangle Flats in the Wash, showing the influence of sea level rise on future morphological response (after Pethick, 2002)**

Practical relevance of the modelling results

The results of these modelling approaches have some relevance for determining realistic mudflat profiles; a basic premise is that convex-upwards mudflat profiles are associated with depositional environments and concave-upwards profiles with erosional environments. Accretionary mudflats are those where there is a net increase in sediment mass on the mudflat over a specified length of time and erosional is where the net mass is reduced over time. This appears to be a reasonably good rule of thumb but there are other factors that need to be considered, one of the most important being the choice of length of time over which any changes are being considered. However, the mudflat level and gradient changes seasonally (O'Brien *et al*., 2000; Yamada and Kobayashi, 2004) and can vary on longer timescales as the flood-ebb dominance of the estuarine system in which it sits varies. This can be over tens of years and might be associated with, for example, the 18.6 year lunar-nodal change in tidal elevations or changes in sediment supply to the estuary or within the estuary. In terms of the mechanism, Pritchard *et al*. (2002) have demonstrated the potential for ebb dominated conditions to lead to an export of sediment from the flat resulting in a lower position in the tidal frame. In reality the mudflat sits within the estuarine system and it will be necessary to determine the sediment budget balance between saltmarsh, intertidal flat and subtidal channel to provide a clear assessment of the sediment supply that is available to the intertidal.

Schematic modelling results suggest that the profile shape is related to the prevailing hydrodynamic conditions and the results of this work lead to the premise that the equilibrium profile for current dominated mudflats is convex and for wave dominated mudflats it is concave. Under moderate wave height and small tidal range the shear stress due to waves dominates and the equilibrium profile will be concave. Where the tidal range is large and waves are moderate then the wave shear stresses probably no longer dominate and the equilibrium profile may be more convex. It can be concluded for certain that a linear profile is not in equilibrium whilst the generally concave upwards profile associated with waves appears to have something in common with the "graded" or "Dean" power law profile produced by waves on sandy coastlines.

The influence of shore planshape is an important factor determining the equilibrium profile shape under both wave and current dominated conditions. A protruding lobate shoreline only slightly increases the concavity of the profile whereas an embayed shoreline greatly decreases the concavity of the shoreline, to the extent that the cross shore profile becomes essentially convex (Friedrichs and Aubrey, 1996).

Conclusions

A range of methods are available with which to predict the cross-sectional form of the intertidal mudflats in estuaries. The methods enable the form of the mudflat exposed to wave and current forcing to be evaluated over a period of tides to a few decades. Much insight can be gained from examination of geomorphological features and the profile shape. An element of quantification can be obtained on how sensitive the profile shape will be in the medium to long term to factors such as wave height, current speed, sea level rise and sediment supply.

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