Development of Estuary Morphological Models

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Abstract

The accuracy of process-based models decreases through the sequence *water levels and currents* to *sediment transports* and in turn to *evolving morphology.* Especially, the validity of longer-term (decadal) simulations is uncertain. The aim here is to develop, apply and compare models capable of indicating likely estuarine morphologies 50 years hence. From these should come estimates of associated changes in flood risks under various management and climate change scenarios.

"Bottom-Up" process-based models, combined with Lagrangian particle-tracking, have been considered for accuracy and sensitivities to formulation and forcing conditions. A *SHELL Application Framework* aims to facilitate "Hybrid" coupling of 1-D hydrodynamic models and top-down (T-D) "regime" and physical constraints on estuary form. An *ASMITA-type model* (Stive et al. 1998) models sediment inputs and transports between aggregated estuarine elements (flats, channels, delta) to predict adaptation capacity to sea-level rise. An *'Inverse' hybrid model* uses a diffusion-type T-D model equation to retrieve time-averaged "forcing" of recent morphological change as a basis for prediction. An *Analytical Emulator is based on* 1-D dynamical equations with simplifying assumptions.

The various models have been applied to eight estuaries to give an 'ensemble' of predictions for 2050 morphologies for intercomparison.

1. Introduction

Interest in estuaries and associated flood risks, sediment regimes and morphology is raised by concentrated local populations around many estuaries and strong economic dependence on their use. Estuaries support or are affected by many human activities. Estuarine environments face increasing rates of change: raised temperature, changing freshwater run-off and sea level, likely increases in flooding events. Outcomes depend on hydrodynamics and on sediments, which underlie morphology (and affect the ecosystem and water quality). However, the sediment regime is challenging to predict.

Methods are needed to predict changes in estuary functioning and so improve ability to manage estuaries sustainably. Management to minimise flood risk and threats to habitats needs to be informed by accurate, reliable tools. However, well-validated tools (models) to predict estuarine behaviour have been lacking, especially for long-term morphological changes. The UK Defra/EA Estuaries Research Programme (ERP) was formulated to develop techniques to predict large scale, long term morphological changes and the resulting sediment related impacts in estuaries (including water quality aspects) and assess their consequences for estuarine management (HRW, 1996; Pye, 2000; EMPHASYS consortium, 2000).

"Bottom-Up" (B-U) process-based models are mathematical (probably numerical), spatially-resolving and predictive (probably time-stepping); they use dynamical equations for hydrodynamics, sediment transport and evolution of the bed. Thus B-U models represent our basic understanding of the dynamics underlying morphology. However, their ability and stability for long-term predictions is doubtful. Whilst B-U numerical models can accurately reproduce water levels and currents in estuaries, simulation of sediment transports is more problematic. Moreover, errors accumulate in the evolving morphology; the validity of longer-term (decadal) simulations is uncertain. Net sedimentation depends on subtle and complex interactions, e.g. (i) bed roughness changes within tides, (ii) spring-neap variation in salt wedges, (iii) seasonal sediment supply and river flow, (iv) episodic events and (v) underlying bed structure.

"*Top-Down*" (T-D) approaches are generally derived either (i) from analysing observed long-term morphological evolution or (ii) from some whole-estuary regime concept such as volume, energetics, entropy etc. Examples are trend analysis; form characterisation; regime relationships; translation or "rollover" with rising sea level; accommodation space; sediment budgeting; tidal asymmetry; equilibrium along-axis profile. Such approaches may be stable for long-term predictions but some are limited to their basis in data; the extent of valid extrapolation may be uncertain; they may lack a time-scale for evolution.

"Hybrid" approaches combine T-D and B-U elements. Typically, an equilibrium state (T-D concept) constrains the form of evolution and is approached with rates given by B-U models. An inverse method uses bathymetries to infer "forcing" of bed evolution in a BU-based diffusion-type equation.

French et al (2002) provided a vision for ERP Phase 2 including (i) improved data, (ii) enhanced hybrid models, (iii) process studies and (iv) enhanced T-D models. Here we address primarily (ii) with Hybrid (50y) mophological prediction models (combining advantages of T-D and B-U approaches), with links to aspects (i), (iii), (iv). We describe BU and Hybrid model developments (section 2) and the eight estuaries to which they have been applied (section 3). Results of scenario runs are given in section 4 with a discussion in section 5 and conclusions (section 6).

2. Models

The different models and types are listed in Table 1 (along with the estuaries to which they were applied).

Model	***Type***	***Reference***	***Thames***	***Black-water***	***Humber***	***Mersey***	***Dee***	***Ribble***	***S'ton Water***	***Tamar***
Emulator	Hybrid	Prandle (2006)	Y	Y	Y	Y	Y	Y	Y	Y
TE2100	Trend	HRW (2006b)	Y							
Regime-Shell	T-D	Wright & Townend (2006)	Y	Y	Y	Y			Y	
"2.5D"	B-U	Lane & Prandle (2006)				Y	Y	Y		
ASMITA-type	Hybrid	Rossington and Spearman (2007)	Y							
Sandtrack	Hybrid	Soulsby *et al* (2007)	Y							
Realignment	process	Spearman (2007)		Tollesbury						
Inverse	Hybrid				Y					
Estuary properties (from Future-Coast database)										
Spring tidal range (m)			5.3	4.6	6.0	8.9	7.6	7.9	4.0	4.7
Mean river flow (m^3/s)			66	3.8	234	67.1	31.2	33.3	18.1	27
Length (km)			100	21.2	144.7	45.6	37.0	28.4	20.2	34.1
HW Area (km^2 in Emulator)			193	46.1	618	194	99	119	38.6	37.7
Intertidal Area (km^2)			52	27.8	455	118	43	107	13.8	18
Marsh Area (km^2)			2.1	11.0	14.2	8.5	21	22	3.6	3.6

TABLE 1. Models and estuaries of application

The *Analytical Emulator* (Prandle, 2006) is largely based on one-dimensional equations of axial momentum and continuity. It assumes that tidal amplitudes are uniform along the estuary, and provides an expression for estuarine depth in terms of time-averaged river flow and channel side slope. Estuary length and side slope are assumed constant. The assumed uniform side slope involves a compromise between correct volumes or areas at HW, LW or intertidal. Then morphology (depth and width) respond only to changes of river flow among the scenario changes. However, imposed sea level rise gives new values for estuary volume and area. A minimum in-filling time (of the increased volume) is estimated from flushing time and mean SPM concentration (Prandle, 2004); mean SPM concentrations were assumed constant for the various sea level rise scenarios but increase with tidal range. Further details on the Analytical Emulator analysis are provided by Manning (2007a).

Historical Trend Analysis derived 2030 bathymetry for the Thames by extrapolating the 1970-2000 trend. However, this approach does not properly represent changes in channel position, the outcome of dredging, managed navigation channels or works. Hence modifications were applied for more realism: no subtidal erosion of more than 2m was allowed; subtidal accretion was not allowed above 0 mOD.

The *Regime-Shell* model (Wright & Townend, 2006) allows application of a "regime" relationship with a 1D hydrodynamic model (ISIS or Mike11). The regime relationship is empirical, generated from baseline flow model results; it characterises the estuary morphology as a power-law relation, between cross-sectional area and maximum discharge during the tidal cycle. This characteristic relationship is assumed to describe the equilibrium state of the estuary. Then some condition is altered, e.g. changed water levels, engineering works (Figure 1). The hydrodynamic model runs the altered simulation and regime relationships are reapplied to update the cross-section (taking account of constraints of the Holocene surface, solid geology or structures). Here, sea-level rise was applied in 5-year increments (evolution of the estuary is not modelled in time with sea level rise). Physical constraints tend to prevent some sections from widening; such sections then tend to deepen and inter-tidal area is lost.

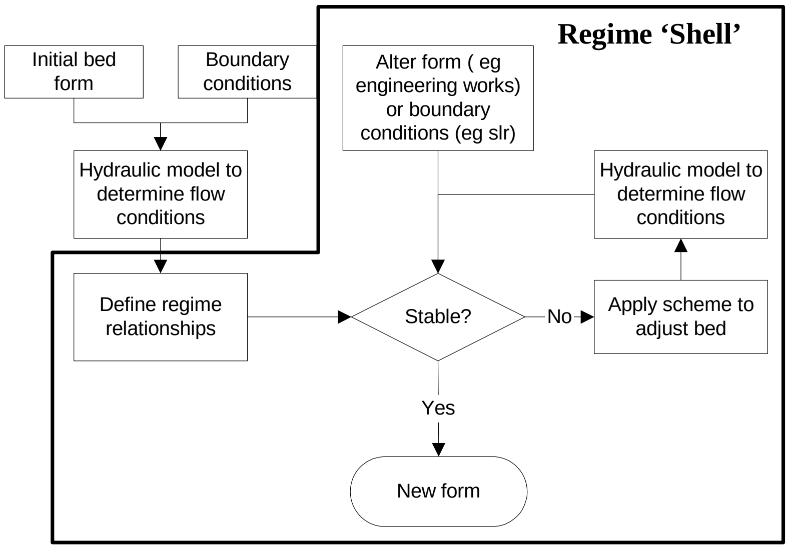

FIGURE 1. Regime-Shell scheme

The *"2.5-D"* model integrates the 2-D shallow-water equations, stepping forward in time, on a finite-difference grid. Vertical structure is derived from the 2-D model pressure gradient and assumed viscosity. Sediment movement is tracked concurrently as particles moving with the flow (plus random vertical steps and settling velocity); erosion at the bed is proportional to stress from the flow; suspended sediment is supplied at the estuary mouth according to the flow there. Bathymetry is fixed during the model run.

ASMITA is a behaviour-based model describing morphological interaction between a tidal basin and its adjacent coastal environment (Stive *et al*., 1998). It schematises a tidal inlet as aggregated morphological elements: intertidal area, channels and ebb-tidal delta. ASMITA assumes that, under constant hydrodynamic forcing, each element tends towards a morphological equilibrium, definable as a function of hydrodynamic forcing and basin properties. The morphological elements interact through sediment exchange, which evolves the whole system morphology as well as the individual elements. Sea-level rise creates accommodation space in the estuary which can then be a sink for available sediment. ASMITA predicts changes in the volume of channel and intertidal-flat elements. A development here is to also predict changes in surface areas, notably intertidal. However, in the application to the Thames, changes in intertidal area were calculated by assuming proportionality with intertidal volume.

The *SandTrack* model (Soulsby *et al* , 2007) has Lagrangian particle-tracking of sand-grains including bedload, suspended load, incipient motion and burial processes. "Tagged" grains of sand are tracked; each represents many billions of similar grains. Runs typically cover a few weeks to a few decades, predicting where the tagged grains go to. SandTrack has been extended (to *Morpho-SandTrack*) by associating a volume of sediment with each tagged grain, depositing it on the bed diffusively as a "lens" with defined maximum thickness and extent; the lenses sum to give the morphodynamic development of the estuary. This process is iterated with re-calculated hydrodynamics. SandTrack gives the *source* of deposited sediment (on tidal flats, salt-marshes) as well as its thickness. The model was applied to the Thames, using one-year update intervals.

The *Realignment* model (Spearman, 2007) predicts local changes in morphodynamics resulting from managed realignment. It builds on the approach of di Silvio (1989, 1990) and others for lagoons. A shell script controls application of a flow model, wave model, derived equilibrium concentrations and time-averaged dispersion characteristics, and time-averaged sediment transport. Sediment transport is modelled using the approximation by Galapatti & Vreugdenhil (1985), sediment erosion $E = w(C_E - C)$ [w is settling velocity, C_E and C are equilibrium and actual concentration]. The model sequence is: (a) set up initial bathymetry, (b) calculate time-average wave heights and periods everywhere, (c) use TELEMAC-2D flow model for flow conditions in set-back field, (d) derive time-average fields of diffusion coefficients and C_E, (e) run a time-averaged sediment transport model using "d" and updating bathymetry, (f) extrapolate predicted change in bathymetry over a longer time, (g) go to "b". Time-averaged transport "e" is modelled as a diffusive process. C_E is chosen on the basis that, in equilibrium, deposition during slack water equals erosion during the rest of the tide. The model was applied to Tollesbury Creek in the Blackwater estuary.

The *Inverse model* uses a 2-D diffusion-type morphological equation with source:

$$\partial h/\partial t = K(\partial^2 h/\partial x^2 + \partial^2 h/\partial y^2) + \text{source} \qquad (2.1).$$

Bathymetry at two times allows "inversion" for the interim time-average source. For bathymetry data at frequent intervals (relative to changes in the estuary and intervention regime), Principal Component analysis of the source identifies trends in bathymetric change. The model was applied to the Humber. Here, the first Component contains almost 92% of the source function, and indicates its near-constancy through time. Prediction uses equation (2.1) with this time-average first Component to represent the future source.

3. Estuaries

Altogether models were run for eight estuaries as shown in Table 1: Thames, Blackwater, Humber, Mersey, Dee, Ribble, Southampton Water, Tamar. In terms of area, the Humber is the largest; there is a middle group comprising the Thames, Mersey, Dee and Ribble; the Blackwater, Southampton Water and Tamar form of group of "smaller" estuaries (but still tens of km^2 and so sizeable by UK standards; the Ribble would also be "smaller" if judged by area at low water).

Data for these and other UK estuaries are in the FutureCoast data-base which has been augmented (Manning, 2007b):
- more detailed freshwater flows (seasonal statistics) from CEH archives for 65 E- and W-coast estuaries
- saline intrusion lengths for most estuaries from literature review and Marine Nature Conservancy Review
- estuary depths and tidal amplitudes for most estuaries.
- more detail for the estuaries considered here.

The expanded data are to be archived with the British Oceanographic Data Centre (BODC).

The *Thames* estuary in south-east England has a length of 100 km and varies up to a width of 3 km at Southend; relatively long and narrow for its area. Fresh water input is from a total catchment area 10,000 km^2 via the Thames (mean flow 66 m^3/s) and some much smaller rivers and channels. Tides are large (mean spring tidal range is 5.3 m at the seaward end) and amplified further as they propagate up the estuary. The outer estuary has large intertidal areas; the inner estuary channel is heavily modified by human activities. The Thames Estuary 2100 (TE2100) study has shown trends over the last century: loss of intertidal volume (40%-50%) and intertidal area (15%-25%) above London Bridge; gain in subtidal volume (15%-25%) and subtidal area (6-12%) above London Bridge; gain in Barking-to-Southend intertidal volume (10%) and intertidal area (12%); loss of Barking-to-Southend subtidal volume (2%) and subtidal area (6%). Thus both sectors of subtidal channel deepened; however, in the upper estuary it widened, reducing intertidal area, whereas in the lower estuary it narrowed in favour of intertidal area.

The *Blackwater* estuary is relatively small (length 21 km), and river inflow (Blackwater and Chelmer) is particularly low, from a catchment area ~ 800 km^2. However, salt-marsh occupies a large proportion of the total estuary area. Tidal range is 4.6 m at the mouth. Whilst this estuary has not been the focus for major studies in recent times, a number of managed realignment projects have been undertaken, notably the Tollesbury managed realignment about which there is considerable information.

The *Humber* estuary in north-east England is the largest of the eight studied here, with length 81 km (plus additional channel length in the Don and Trent, to a total 145 km) and mean width 3 km. Fresh-water input is from a total catchment area 23690 km^2 via the Ouse, Don and Trent (mean flows exceeding 120, 16, 95 m^3/s respectively). Tides are large (up to 6.6 m at the seaward end) and amplified further as they propagate up the estuary. The Humber has areas of salt-marsh, and a complex (almost braided) channel system in its lower reaches. There has been much research. For background see EA (1999, 2000).

The *Mersey* is comparable with the Thames in area and fresh-water input, but shorter and broader. The *Dee* and *Ribble* have about half the area and fresh-water input of the Mersey. All have very large tidal range and significant areas of salt-marsh; the Ribble subtidal area is relatively small. Bathymetry has been gridded from EA Lidar/echo sounder surveys (Mersey, 2002; Dee, 2003, Ribble, 2004). Fine sediment of mean diameter 22 μm (settling velocity $w_s = 0.0005$ m s^{-1}) was assumed for model runs (where used).

Southampton Water has a length 19 km with Itchen and Hamble sub-estuaries (length 7, 8.6 km respectively). Mean width is about 2 km sea-ward of the Itchen. Tidal range at the mouth, 3.75 m, is moderate by UK standards (large by world standards); intertidal area is relatively small. A "double high water" results as arrivals via the two sides of the Isle of Wight are separated by non-linear steepening. Mean river inputs to the three (sub-) estuaries are 12.3, 5.6, 0.4 m^3/s respectively.

The *Tamar* estuary is distinctive as a ria rather than coastal plain estuary. For its area it is relatively long and narrow, with large river flow. Future-Coast data are relied on for its characteristics as modelled.

4. Scenarios and Results

Inter-comparisons of model predictions were generally for 2050; scenarios are intended to represent possible effects of climate change 50 years hence [referring to UKCIP02, IPCC(2001), Defra (2003)]:

- *Mean sea level* (MSL): baseline as now; rises of 0.3 m (realistic over 50 years), 1 m (extreme)
- *50-year extreme level*: in practice applied as a constant addition to sea level
- *Tidal range*: baseline as at present; an increase of 2% (Flather *et al*., 2001)
- *Wind speed*: nominal value and ± 10%; in practice applied as wave-enhanced bed stress

- *River flow*: baseline as at present; an increase of 20%
- *Waves*: nominal values and increases of 10% (wave height), 5% (wave period).

We take the models in turn to discuss results.

The *Analytical Emulator* estimated changes in low water (LW), high-water (HW) and hence intertidal volumes and areas, for raised sea level (MSL); changes in flushing times; changes of in-fill times. It ran for scenarios of increased tidal range and river flow (wind and waves are not represented). The Emulator's uniform side-slope prevents a good representation of the low water channel in some estuaries; Emulator LW volumes for the Blackwater are about half of the actual LW volumes; in the Mersey, the Emulator has more HW volume but less LW volume; there are also discrepancies in the Dee. For raised MSL, the Emulator predicts equal increases in LW and HW area. In reality, present HW often intercepts walls (e.g. in the Thames); rises in sea level will not increase HW area (i.e. the Emulator is not realistic), but would raise LW level, so increasing subtidal area and reducing intertidal area (in the absence of morphological response). However, no change in intertidal area can be predicted by the Emulator with constant uniform side-slope. Emulator mean depths increase by half the MSL rise owing to the assumed triangular cross-section. Flushing times vary from a few days to a few weeks; they do not correlate with estuary size as they depend also on tidal range and river flow. In-fill times are much longer because they depend on the low concentration of transported sediment; in-fill times increased in response to rising MSL, and shortened for increased mean river flow.

TE2100 Historical Trend Analysis predictions for the Thames in 2030 show:

- Continued accretion in Leigh Channel, along the foreshore of Blyth Sands, in the entrance to Holehaven Creek, on Mucking Flats, along the northern foreshore at Coalhouse Point, intertidally between Broadness and Woolwich, locally in the deepest channel between Putney and Richmond
- Continued deepening of navigation channels: Sea Reach, Lower Hope, Broadness to Woolwich
- Varied and localised subtidal and intertidal changes between Woolwich and Putney
- Continued overall erosion of the subtidal foreshore between Putney and Richmond

Table 2 shows some estuary-wide volumetric comparisons with the 1920, 1970 and 2000 geometries, for cases with sea-level rise only, extrapolated morphological change with present MSL, and raised MSL plus morphological change. There has been a steady reduction in LW surface area (indicating a steady increase in intertidal area) and tidal volume since 1920. The predicted 2030 geometries show this trend continuing.

Bathymetry	***Surface area (m^2 x 10^6)***		***Intertidal Area (m^2 x 10^6)***	***Volume (m^3 x 10^6)***		***Tidal volume (m^3 x 10^6)***
	LW	*HW*		*LW*	*HW*	
1920	82.4	125.8	43.4	0.5639	1.2608	**0.6969**
1970	77.2	117.5	40.3	0.5212	1.1779	**0.6567**
2000	73.8	117.7	43.9	0.5203	1.1575	**0.6372**
2030 (just effect of sea-level rise)	74.7	117.7	43.0	0.5302	1.1725	**0.6423**
2030 Geometry 1* (just effect of morphology)	72.6	117.6	45.0	0.5398	1.1462	**0.6064**
2030 Geometry 2* (just effect of morphology)	72.5	117.6	45.1	0.5245	1.1339	**0.6094**
2030 Geometry 1* (sea-level rise + morphology)	72.9	117.6	44.7	0.5518	1.1675	**0.6157**
2030 Geometry 2* (sea-level rise + morphology)	**72.9**	**117.6**	**44.7**	**0.5364**	**1.1552**	**0.6188**

TABLE 2. Volume and surface area of historical and future bathymetries in the Thames Estuary (HRW, 2006a). *Geometry 1 extrapolates the subtidal bathymetry assuming there is no overall effect of dredging on the morphological trend. Geometry 2 assumes that because of dredging the channel-bed part of the subtidal area will remain constant in depth over time.

The *Regime-Shell* model predicts losses of intertidal area for raised MSL: 4.8 km^2 in the Thames (Figure 2) after 0.18m of sea level rise (compared with 1.2 km^2 loss predicted by TE2100 if no morphological response); also in the Humber, Mersey and especially the Blackwater,. In all these cases the Regime-Shell prediction of HW area is constrained, whereas the Emulator cannot predict a change of intertidal area under MSL rise; the Regime-Shell results are intuitively correct – intertidal area decreases with sea-level rise ('coastal squeeze'). Predicted changes to intertidal and channel area are similar for Southampton Water where the difference between HW and LW areas and volumes is relatively small. For increased freshwater flow, the Emulator predicts a significant increase in estuary areas and volumes whereas the Regime-Shell predictions are relatively insensitive. For 2% increased tidal range, Regime-Shell predicted changes are

O(2%) but typically somewhat greater than those of the Emulator, and more positive for LW values (the Emulator with unchanged morphology necessarily has a decrease in LW area and volume).

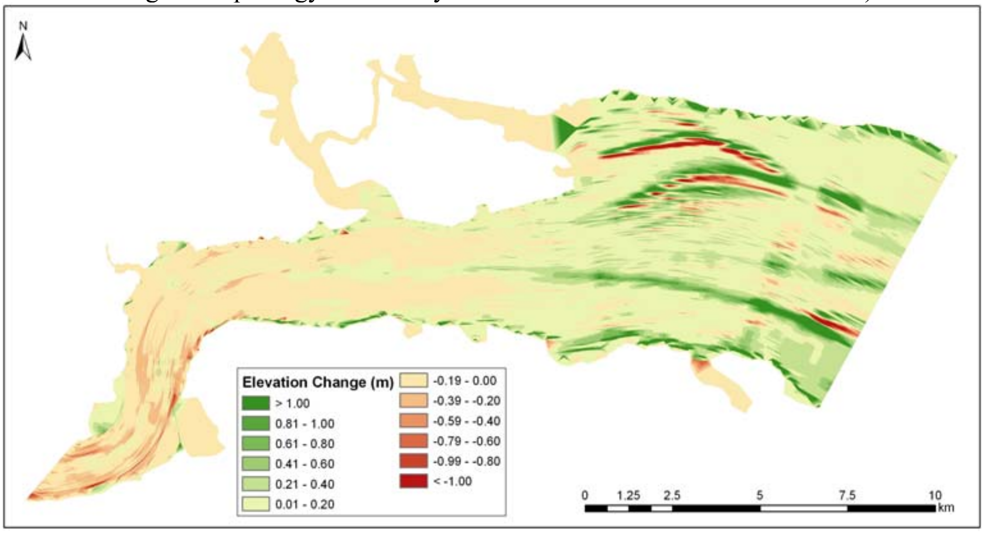

FIGURE 2. Regime-Shell Thames bathymetry change to 2050 (6 mm/yr MSL rise).

The *"2.5-D"* model was applied to the Mersey, Dee and Ribble. It has no morphological change for raised MSL, in common with the Emulator. Thus for raised MSL changes (necessarily increases) in HW and LW volumes and areas are broadly comparable between the two models, depending only on their fixed geometries. Unlike the Dee and Ribble, the "2.5-D" model predicts an intertidal area decrease in the Mersey for raised MSL. Increased tide range likewise gives comparable changes (albeit % changes are sensitive to low baseline values and LW volumes and areas necessarily decrease). Saltmarsh area (covered at Highest Astronomical Tide but uncovered at mean HW) notably decreases in the Mersey for raised MSL and increased tidal range; the sides of the estuary are steeper above mean HW. The mean (spring-neap) suspended sediment flux into the Mersey (Figure 3) is estimated by the "2.5-D" model as 117000 tonnes per tide, approximately five times that in the Dee and 16 times that in the Ribble. All increase as expected with increased tidal range (and hence currents), but trends with MSL vary and values for the Mersey are remarkably insensitive to wind-(wave) enhanced bed stress. Sediment deposited (per tide) in the Mersey and Dee is ~10% of "flux in"; ~14% in the Ribble. There is little change over the different scenarios in the Mersey and Ribble, but deposition in the Dee decreases markedly with increasing mean sea level.

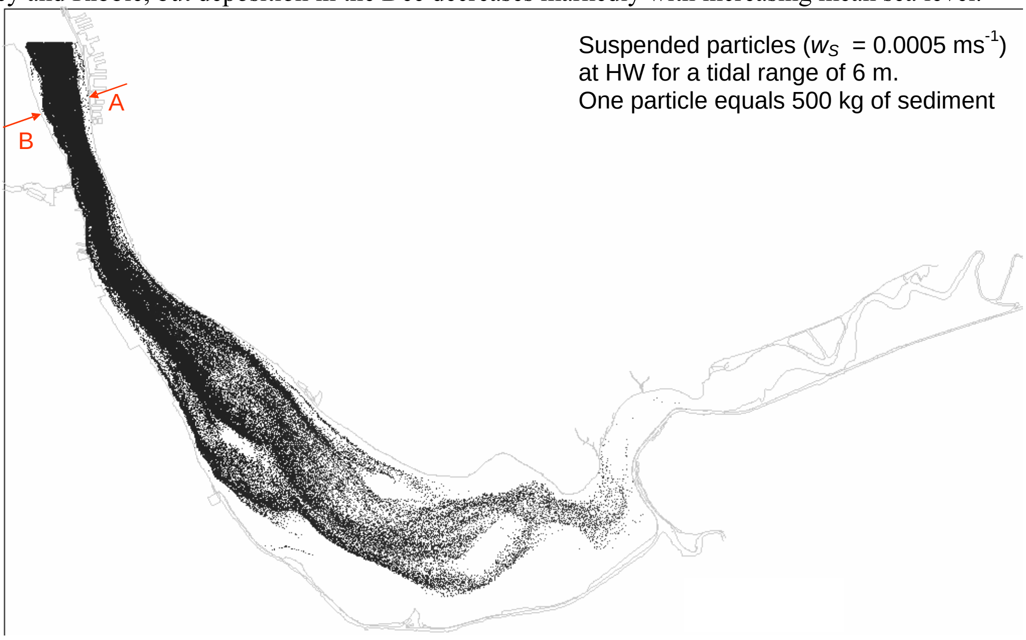

FIGURE 3. 'Active' particles represent suspended sediments.

The *ASMITA-type* model was applied to the Thames. It predicts a loss of 0.6 km^2 of intertidal area after 0.18m sea level rise, compared with TE2100 predictions of 0.9 km^2 loss (if no morphological response) or

0.8km^2 gain (if sea level rise and morphological change are both accounted for). However, the TE2100 prediction extrapolates present sea level rise ~ 2mm/yr, for which ASMITA predicts 0.3km^2 gain in intertidal area (Rossington and Spearman, 2007). ASMITA predicts a time-scale of 300 years before the estuary reaches dynamic equilibrium with the higher rate of sea level rise.

SandTrack predictions for the Thames estuary (Soulsby *et al.*, 2007) are of relatively coarse resolution (due to heavy computing needs) preventing close comparison with observed trends. Landwards of Southend, visual comparison is inconclusive; predicted rapidly developing accretion along Grain Spit (extending further eastwards) seems too extreme and may be an effect of the coarse resolution. In the outer Thames estuary, Sandtrack seems to reveal a relatively stable future system of channels and banks, except for the region around the Edinburgh Channels crossing Long Sand (Figure 4). The TE2100 studies (HRW, 2005) concluded that the system of channels and banks appeared relatively stable (some banks extending seawards), except for a dynamic region around the Edinburgh Channels. Thus SandTrack appears to represent the main features.

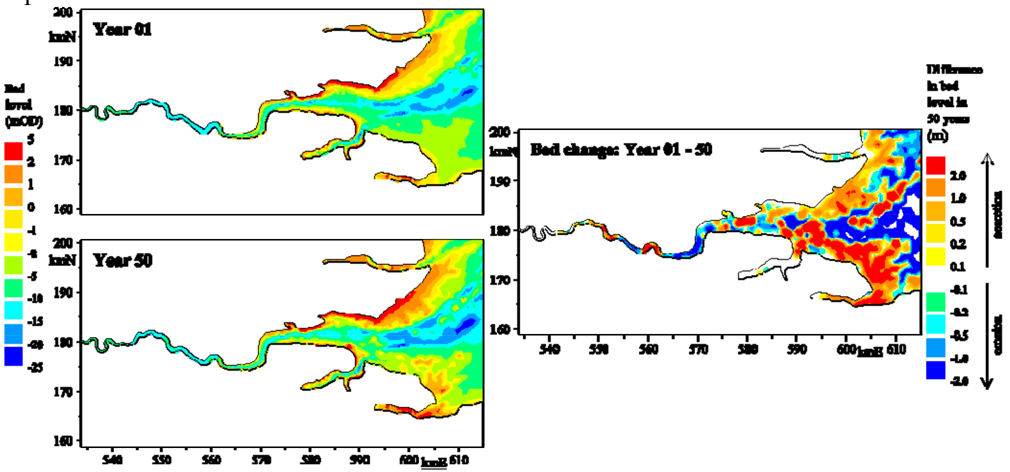

FIGURE 4. SandTrack evolution of the Thames over 50 years, using yearly bed updates

The *Realignment* model was applied to Tollesbury Creek (in the Blackwater) only (Figure 5). Its prediction of the evolution of this managed realignment compares reasonably with that observed. The modelling is described in detail in Spearman (2007).

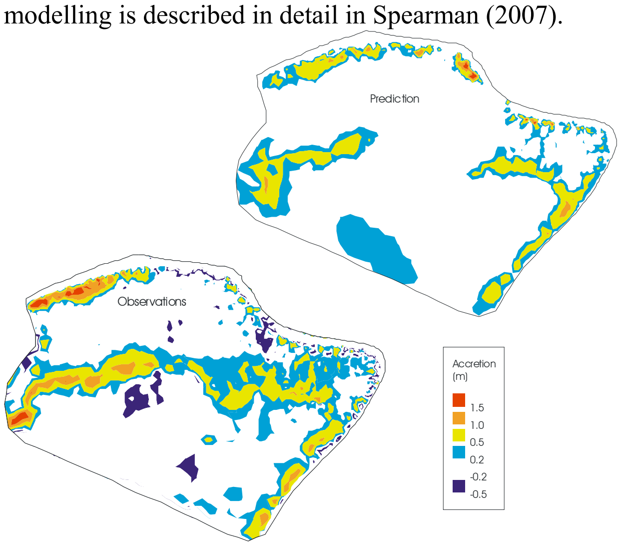

FIGURE 5. Observed and predicted bed level change in Tollesbury Managed Realignment site 1995-2002

The *Inverse model* was applied to the Humber (only). Bathymetry changes between successive charts show alternate erosion and accretion in the periphery of the outer and middle estuary. Prior to 1925 these areas are mostly accretive; from 1925 to 1966 erosion and accretion took place in approximately 10-year cycles. After 1966, these areas show alternate accretion and erosion to 1986. From 1986 to 1998, changes in these peripheral areas were almost negligible. A small amount of accretion took place from 1998 to 2000. Accumulation in the main channels and erosion of shallow flats are prominent throughout. The source functions for each successive interval show several broad features: a significant structure is persistent throughout the entire set of results. Overall, there is no rapid variation of source function from one interval to the other. Large scale features such as tidal channels, tidal flats and linear banks in the estuary are persistent. Smaller-scale structures are apparent than in bathymetric data itself. Other large-scale elongated features, possibly mud banks, are also visible in the middle estuary. Applying Principal Component Analysis to the source functions, the first six Components collectively capture 97% of the mean square of the data. 92% is contained in the first Component, which corresponds to the temporal mean source function for the whole period (its amplitude is almost constant in time). The second Component depicts the shape of the strongest variation in the source function; it shows a strong spatial structure with areas of maxima and minima. Most of these spatial patterns are few kilometres long and are elongated along the estuary. Direct comparison with results from the Emulator or the Regime-Shell models is not possible; the outputs from the different models are different in type.

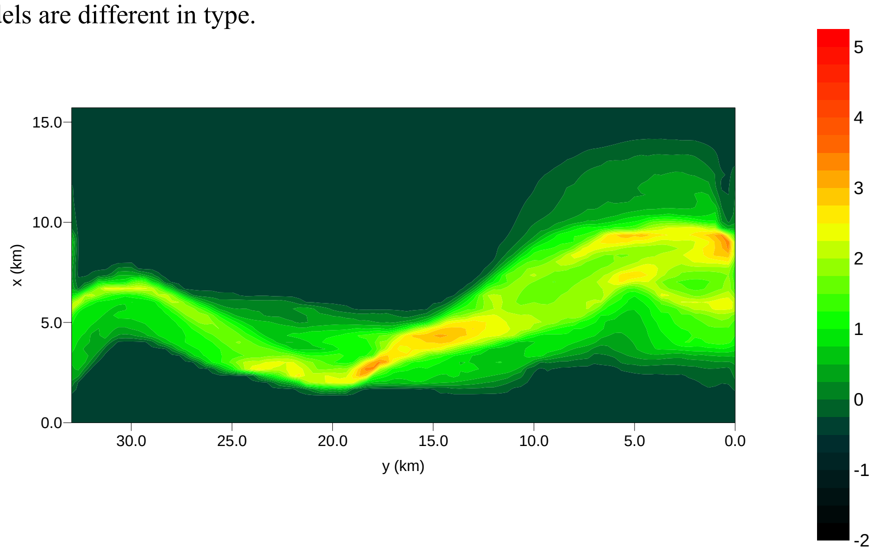

FIGURE 6. First spatial principal component for Humber source function for diffusion-type evolution.

6. Discussion

The Thames including TE2100 studies provided intercomparisons between the greatest number of models. The alternative predictions illustrate the possible range of outcomes, and suggest intertidal area changes in the range +/- 1 km^2 to 2030, possibly much more longer-term. This range is small compared with the Emulator and Regime-Shell model predictions of 5-6 km^2 (5-10%) increase in Thames LW area by 2030.

HW area increases by 2 km^2 in Regime-Shell predictions, 6.2 km^2 in emulator predictions (excessive) but does not increase significantly in the TE2100 prediction; HW intercepts tidal defences at most locations. The relatively small Regime-Shell increase, which is constrained by tidal defences, probably includes areas above current HW – e.g. saltmarsh around Canvey.

The *Emulator* may not represent intertidal areas consistent with HW and LW areas; it cannot represent loss of intertidal areas. It is also liable to represent channel volume and mean depths poorly (e.g. 1.7-4.8m compared with the more typical 8m for the Thames). Hence it is difficult to apply some aspects of model responses meaningfully. These limitations arise from the triangular cross-section, assumed for simplicity in the analysis underpinning the Emulator. In fact any fixed geometrical form could be used; alternatives could enable a better quantitative match to baseline areas and volumes. However, the present Emulator would require the geometrical form in the scenarios to be similar to the baseline form (only scale variations can be accommodated). There is no scope for constraint of HW area by fixed structures. Moreover, the only change in morphology is the depth increase in response to increased river flow.

The *Regime-Shell* model has many individual cross-sections and hence more flexibility to represent LW and HW areas and volumes accurately. Moreover, fixed surfaces can represent solid geology or structures where erosion is not allowed. Thus if HW area is constrained by sea defences, it will not increase under sea level rise in reality or in the model. However, initial response of the Regime-Shell model to changed inputs was more than might be expected. This suggests that much predicted evolution was a response to the initial estuary condition (i.e. an artefact of the model still being investigated).

For greater sea level rise in the Thames, the Regime-Shell model predicts more erosion. However, in other estuaries, increases in volumes are no more than for the Emulator with no morphological change. Indeed, the Mersey at HW appears to shoal in this scenario.

The *"2.5-D"* model is able to represent LW and HW areas and volumes, limited only by the chosen resolution. Differences from the Emulator arise from the latter's geometric limitation and possibly from differences of definition; differences from the Regime-Shell model (in the Mersey) should be primarily due to definitions. "2.5-D" model results for changes under raised MSL and tidal range can generally be interpreted in relation to the Emulator, because neither has morphological change. However, there are predictions of sediment transport and deposition (from which morphological change could be inferred until deposition patterns change significantly). Thus in-fill times to baseline HW level are inferred: respectively 152, 555, 685 years for the Mersey, Dee, Ribble. In practice deposition would change before this level were reached; times to a lower level will be less. These values are comparable with those of the Emulator.

The present *(Morpho-)SandTrack* model is a research-level version, which could usefully be run for comparison purposes alongside more conventional Eulerian morphodynamic models, to gain experience of its relative performance (speed and results). It has some useful capabilities, and is complementary to the "2.5-D" model with Lagrangian transport. Both have their place in the overall modelling tool-kit.

The issue of having to continually repeat flow model runs for 2D morphological models is not confined to Lagrangian models such as SandTrack; it holds more widely for B-U-based morphological modelling. Finer resolution is needed than was used in SandTrack for the Thames. To address the issue, continuity might be used to alter current speeds for small bathymetric changes, so reducing the required number of flow model runs and making finer resolution feasible. However, such methods have yet to be proven.

Historical trend analysis makes use of morphological change hitherto to guide expectations of future trends. However, as an empirical approach it should not be applied outside the range of experience. Hence it is not suited to estimates for scenarios of faster sea level rise, for which the ability of an estuary to "keep up" in the same way could be in doubt. As applied here, it was simply extrapolation of a present trend.

The *Inverse* model uses morphological change hitherto, but with reference to dynamics in the form of a bed evolution equation. In the Humber, large positive source functions indicate accretion; tidal channels in the outer and middle estuary draw sediment from surrounding mud flats and external sources. This is in line with earlier findings where infill of the estuary was observed during the last 150 years. The source functions derived from the inversion of the governing equation have significant differences from the corresponding bathymetry changes; the large-scale sediment diffusive process is significant in the long term evolution of estuary morphology. Sensitivity of the source function to the diffusion coefficient was investigated by reconstructing the source function using coefficient values ± 50% for several cases; there was no apparent change to the structure of the source function. The Principal Component analysis on the source function suggested strong spatial and temporal structure as a basis for prediction, dependent on no future intervention of unprecedented form. In practice, such application of the *Inverse* model appears to need bathymetry about every 10 years (this interval might have to be shorter for – e.g. small – estuaries with more rapid change). Unfortunately, few UK estuaries are completely surveyed this frequently.

Selection of the study area is important. Whereas the TE2100 study area included 42 km^2 of intertidal areas in the Thames estuary (and the Regime-Shell 57 km^2), the outer Thames estuary between the TE2100 boundary and a line from Margate to Clacton-on-Sea contains another 230 km^2 of intertidal area. Thus discrepancies between model predictions of estuary volume and area can arise from minor differences in definitions of the estuary limit.

7. Conclusions

Estuary LW volumes and areas invariably increase for raised MSL.

HW volumes and areas generally increase, but less so.

Inter-tidal area decreases.

Regime-Shell results do not suggest infill keeping pace with sea-level rise, except for the Mersey. ASMITA results suggest that Thames infill keeps up with sea-level rise.

Likely effects of realistic changes in tidal range (e.g. +2%) are relatively modest.

A 20% increase in river flow gives small changes in LW and HW areas and volumes, but the Mersey and Blackwater lose substantial inter-tidal area.

Estimated flushing times to replace the water in the estuary are between 6 and 21 days.

Emulator-estimated in-fill times are 182 years (Mersey) to 765 years (Southampton Water); in most cases enough sediment supply to keep pace with sea-level rise.

ASMITA results for the Thames indicate a time scale ~ 300 years (0.3m rise) to ~ 800 years (1m rise). ASMITA also predicts that the Thames will be unable to keep pace with sea level rise faster than 21mm/yr.

Among *models*, the Emulator struggles to represent intertidal areas consistent with high and low water areas. It cannot represent loss of intertidal areas or constraints on high-water area by fixed structures. The Regime-Shell overcomes these limitations.

The 2-D and 3-D particle-tracking models can represent LW and HW areas and volumes, limited only by the chosen resolution. They predict sediment transport and deposition. They suffer from having to continually repeat flow model runs as bathymetry evolves.

Historical trend analysis can guide expectations of future trends if applied within the range of experience. The Inverse model also uses previous changes, with more reference to dynamics via a bed-evolution equation. Predictions depend on relatively frequent surveys.

Generation of an ensemble of possible outcomes is recommended, to test model results against alternative techniques and validate predicted future morphologies.

Estuaries do not all respond in the same manner.

Acknowledgements

This work owes much to its initiator, David Prandle. It was funded by Defra: project FD2107 in the ERP.

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