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Project identification

1. Defra Project code: FD2107
2. Project title: Development of Estuary Morphological Models
3. Contractor organisation(s):
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4. Total Defra project costs (agreed fixed price): £ 539,190
5. Project: start date .... 01 January 2004
   end date .... 30 June 2007

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Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

Estuaries (and associated flood risks, sediment regimes and morphology) impact on local populations and economic activity. Management to minimise flood risk and threats to habitats (from various human activities and climate change scenarios, for example), needs to be informed by robust, well-founded tools. Outcomes depend on hydrodynamics and on sediments. However, sediment dynamics, and especially longer-term changes in morphology, are challenging to predict; well-validated predictive models have been lacking.

The UK Estuaries Research Programme (ERP) was formulated to develop techniques to predict large-scale, long-term morphological changes and resulting sediment-related impacts in estuaries (including water quality aspects), and assess their consequences for estuarine management. ERP Phase 1 (1998-2000) included a critical analysis of process-based "bottom-up" (B-U) model limitations alongside a review of "top-down" (T-D) models. ERP Phase 2 recognised the need to use both approaches and gave priority to developing "Hybrid" models combining elements and advantages of B-U and T-D approaches. Project FD2115 provided an updated vision for ERP Phase 2, comprising: (i) uptake of Phase 1, (ii) improved data, (iii) enhanced Hybrid models, (iv) process studies (ESTPROC), (v) enhanced T-D models, (vi) morphological systems – and dissemination and management.

This project FD2107 links with ERP2 aspects (ii), (iv), (v) but addressed mainly (iii): (Hybrid) models developed for (50-year) morphological prediction were:

- An *Analytical Emulator*, based on one-dimensional (1-D) hydrodynamics and a schematic estuary form. It indicates total area/volume response to water levels and tidal range with minimal computation. The estuary form is constant (except for deepening with increased river flow); results give a reference for other predictions with changing morphology. However, the present schematic estuary form (triangular cross-section with uniform side-slope) limits its realism in representing high- and low-water areas; the following Hybrid Regime and 2-D (or 3-D) models can represent these areas much better if used with fine-enough resolution.
- A *Hybrid Regime* model, combining 1-D hydrodynamics with *regime* relations between discharge, cross-section area and width. For changed sea levels, tidal range, river flow or engineering works, individual cross-section changes are predicted, constrained by solid surfaces and the overall regime relations. A *Shell* provides a user interface facilitating set-up, coupling, application, assessment and visualisation.
- *Morpho-SandTrack*, enhancing a pre-existing sediment dynamics and particle-tracking model *SandTrack.* These models use 2-D (horizontal) hydrodynamics; the enhanced model predicts changing morphology (depth as a function of 2-D horizontal location); the flow model is re-run as bathymetry evolves. *Morpho-SandTrack* has shown reasonable success on larger scales (outer Thames estuary, adjacent North Sea) but has scope to improve representation on smaller scales.
- A *Managed Realignment* model, predicting local changes in morphology and saltmarsh due to managed realignment. The model uses 2D flow and waves to spread sediment in a localised area; it also represents sediment trapping by vegetation. The model was shown successfully to reproduce the evolution of an example realignment, and to enable prediction over a period of

several decades. On this performance the model appears to be a promising basis for informing management decisions on realignment projects, particularly where it is necessary to demonstrate the nature of the habitat that will be created within the site.
- *ASMITA*, a pre-existing model now programmed in Matlab for wider availability. ASMITA evolves the size of aggregated elements ("boxes" for intertidal area, channels, ebb-tidal delta interacting through sediment exchange); sea-level rise creates accommodation space so that the estuary is a sink for available sediment. Exchange and other coefficients can be calibrated to match known behaviour.
- An *Inverse* model evolving depth as a function of 2-D horizontal location. It uses a diffusion equation with a "source" derived from depth changes between past bathymetric surveys, which need to be frequent (relative to changes in the estuary); only the Humber has hitherto been found to qualify. Prediction is limited like Historical Trend Analysis: to auto-correlation times of time-series corresponding to spatial pattern(s) accounting for most the "source"; to scenarios with precedents.

These models, and a pre-existing *"2.5-D"* particle-tracking model with constant bathymetry, were applied to eight varied UK estuaries (not all models in all estuaries). Different scenarios were run to identify impacts (e.g. on water levels and estuary form) and sensitivities (e.g. to sea level and sediment properties).

The model results suggest that intertidal area usually decreases as sea level rises. Predicted sediment supply is usually sufficient for infill keeping pace with sea-level rise, but models differ in whether such infill occurs. ASMITA, which matches past Thames behaviour reasonably, predicts that the Thames' overall form can keep pace with sea-level rise up to 20 mm/yr (assuming there is no change in sediment supply). Effects of small changes in tidal range are small. More river flow (+20 per cent) gives mostly small changes; the Hybrid Regime model predicts intertidal area loss (Mersey, Blackwater).

Historical trend analysis can guide expectations of future trends if there are precedents. Models should be validated against historic change or by intercomparison if data are lacking. This model intercomparison improved confidence in the models.

In case studies of morphological-change effects on flood risk, it was found that:
- the impact of (even extensive) dredging on flood risk is usually small, but in some cases (especially near tidal limit) may be beneficial or deleterious depending on the characteristics of the estuary;
- particular estuarine features may be critical;
- in practice flood risk and coastal protection issues manifest themselves on the local scale at specific vulnerable locations.

The FutureCoast database has been augmented. Appendices to the full Technical Report describe model developments in detail. Access to data sets and model developments is described in the Report.

Estuaries do not all respond to imposed changes in the same manner.

Project Report to Defra

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:
- the scientific objectives as set out in the contract;
- the extent to which the objectives set out in the contract have been met;
- details of methods used and the results obtained, including statistical analysis (if appropriate);
- a discussion of the results and their reliability;
- the main implications of the findings;
- possible future work; and
- any action resulting from the research (e.g. IP, Knowledge Transfer).

Development of Estuary Morphological Models, FD2107

1. Objectives

Scientific Objectives of FD2107 (as in the contract) were:
Development of models capable of delivering 50-year forecasts of morphology integrated into new HYBRID models examining the combined influences of Global Climate Change and intervention on flood forecasting, defences and habitats.
1 A framework for application of B-U models
2 Development of new HYBRID models via integration of B-U and T-D models
3 Estimates of impacts of (2) on potential for flooding

1.1 Meeting of Objectives

The first objective (framework for application of B-U models) was met through application of hydrodynamic models (POLEST2D, POLEST"2.5D") to estimate water levels in the Mersey, Dee and Ribble due to tides, surges and waves. POLEST "2.5-D" was applied to compute suspended sediment concentrations and net fluxes in the Mersey; Lagrangian particle tracking was included; tests were carried out for sensitivity to aspects of the model formulation; results were published in the refereed scientific literature. *Guidelines for application of Bottom-Up estuarine models* forms an Appendix to the FD2107 Technical Report.

Achievement of the second objective (development of new HYBRID models) is represented by:
- improved capability of the pre-existing model *SandTrack* (sediment dynamics, particle-tracking), to predict estuarine morphodynamic development; the flow model is re-run as bathymetry evolves;
- a Hybrid Regime model combining 1-D hydrodynamics with "regime" relations between discharge, cross-section area and width. For changed (e.g.) sea levels or engineering works, changed cross-sections are predicted allowing for Holocene and solid surface constraints. A Shell provides a user interface facilitating set-up, coupling, application, assessment and visualisation;
- an "Inverse" diffusion-equation-plus-"source" model which may predict bathymetry *if* (i) bathymetry data exist at frequent intervals (relative to changes in the estuary), (ii) one (or more) principal-component spatial patterns account for most the inferred "source". Prediction is limited to the auto-correlation time of the corresponding time-series and to scenarios with precedents;
- programming of an Analytical Emulator using 1-D hydrodynamics and a schematised estuary. It indicates area/volume response to water levels and tidal range (for unchanged morphology).
- programming (in MATLAB for wider availability) of ASMITA, evolving the size of aggregated elements (intertidal area, channels, ebb-tidal delta; interacting through sediment exchange);
- a Realignment model predicting local changes in morphology and saltmarsh due to managed realignment, including the effects of waves and sediment trapping by vegetation.

The third objective (estimates of impacts on potential for flooding) is represented by intercomparison and evaluation of model predictions for 2050 morphologies, and in particular comparison of predicted high water levels with and without predicted changes in bathymetry (as well as scenarios of changed sea level and tidal forcing). In addition, case studies were carried out for effects of morphological change: the impact of dredging on flood risk may be deleterious (especially near tidal limit), small or beneficial, depending on the characteristics of the estuary; particular features may be critical; defences may become more vulnerable to wave attack.

2. Methods and Results

2.1 Application of Bottom-Up models

The objective here was to find sensitivities of model predictions of water levels and sediment transports in (three) estuaries. Sensitivities were assessed by runs with different values of climate-related variables: sea level, tidal range, river flows. Particularly for sediment transports, sensitivities were also assessed by runs with different fluid-dynamical and sediment properties, over ranges indicated by climate change scenarios, context variability or uncertainties in model formulation.

2.1.1 Hydrodynamic model application to predict levels in the Mersey, Dee and Ribble

Models applied were:
- POLEST 2D, a finite-difference hydrodynamic model allowing for changing sea area as levels rise and fall. It solves equations for conservation of mass and momentum discretised on a depth-averaged grid. Its 120-m resolution bathymetry for the estuaries has been gridded from Lidar/echo sounder surveys provided by the Environment Agency (Mersey 2002, Dee 2003 and Ribble 2004). The model was applied separately to each of these three estuaries.
- POLEST"2.5-D", a three-dimensional (3-D) version of the above model, in which the vertical current structure is derived from the sea surface slope and assumed forms of friction (so the vertical structure is controlled by the 2-D solution).

- POLCOMS (POL Coastal Ocean Modelling System), fully a 3-D model, has been run for Liverpool Bay and used for information on open boundary conditions for the estuary models; not for sensitivity tests.
- SWAN (Simulating WAves Nearshore), a third-generation spectral wave model (Booij *et al*., 1999; Ris *et al*., 1999). It includes wave generation by wind, dissipation by wave breaking and bottom friction, and wave-wave interactions. Its application here, for waves with various combinations of wind speed and water level (tide + mean sea level + surge), is detailed in Appendix A1 to the FD2107 Technical Report.

Simulations and sensitivity tests were completed using the POLEST models and SWAN. The most comprehensive results are for the Mersey and described further in Lane (2004).

Modelled Mersey responses to *raised mean sea level* (MSL) are most notable in the mean and principal semi-diurnal (M_2) tidal constituents; amplitude differences are small near the mouth of the estuary but increase upstream. Changes in surface area and volume between high and low water (tidal prism), for MSL increases of 0.3 and 1 m, were calculated for the Mersey, Dee and Ribble. The shape and morphology of the Ribble are most sensitive, because it is relatively empty of water at low tide. As the Mersey, Dee and Ribble estuaries are relatively short and deep at High Water, high levels adjust quickly; extreme high levels should closely follow external levels.

River flows (Q_f ranging from 25 to 300 $m^3 s^{-1}$ for the Mersey) are typically of order 1 per cent of tidal flows except in the upper estuary. Changes in tidal propagation are small even for $Q_f = 600 m^3 s^{-1}$.

The *wave* modelling generally showed monotonic increase of wave height, period and set up with increasing wind speed and water depth.

Prediction of flood levels combining tides, surges and waves requires the use of a 'Joint-Probabilities' method (Dixon and Tawn, 1997) to calculate return periods and was not considered.

2.1.2 Lagrangian particle-tracking model and application to the Mersey

Application of a B-U sediment transport model using Lagrangian particle tracking was demonstrated. Sensitivity was explored to fluid-dynamical and sediment properties that may vary with climate, context or model uncertainty, so indicating which factors need close estimation for B-U model applications.

POLEST "2.5-D" was applied to compute suspended sediment concentrations and net fluxes. Simulated particles (typically 10^5 of them) moving with the flow were tracked; erosion, suspension and deposition were simulated. Erosion is a conventional function of bed shear stress. Suspended particle dispersion is represented by random vertical excursions. Deposition is via settling velocity. Particles' origin, size, shape, attached chemistry, time since deposition etc. can be stored.

Sensitivities were studied, to: vertical shear, depth-varying eddy viscosity, time-varying eddy viscosity, additional density-driven estuarine circulation, rate of marine sediment supply, sediment size, consequent settling velocity. The simulations all assumed an unlimited supply of sediment at the mouth of the estuary.

Results of these simulations are listed in Lane and Prandle (2006). Average suspended concentrations decrease a little faster than d^{-2} (d is the median sediment diameter). The fraction of exchange deposited is minimal (2.8 per cent) for diameter d near 30 μm; net deposition then varies moderately for larger grain sizes until d > 100 μm. [Smaller particles may form flocs with larger settling velocity than assumed here].

There is rather little effect of estuarine circulation in the Mersey. By contrast, frictional shear $\partial \mathbf{u}/\partial z$ reduces suspended coarse concentrations slightly and net deposition considerably, whereas it slightly increases suspended fines and their deposition. Time-varying eddy diffusivity generally gives moderate increases in sediment concentrations and deposition. Increases with depth-varying eddy diffusivity are much greater, especially for the finer material (up to four-fold). Increasing bed friction affects the currents and increases suspended concentrations, exchange and deposition (total; reduced as a fraction of exchange). Suspended concentrations and exchange are dependent on marine supply, hence obviously sensitive thereto; net deposition is reduced to less than a half by halved marine supply.

The POLEST "2.5-D" Lagrangian particle-tracking model was applied to the Mersey for fine and coarse sediments (settling velocity 0.5 mm/s, 5 mm/s respectively). Results for sediment fluxes at the mouth, and suspended sediment concentrations along the estuary, are detailed in Lane and Prandle (2006).

These results (for the Mersey) may not be applicable to all estuaries. However, the strong dependence of modelled sediment transport on particle size, source and frictional effects has general implications. These quantities need to be known or modelled well for B-U model applications; forms of representation and values should be checked in context.

2.2 Development and application of new Hybrid models

2.2.1 Development of Shell Hybrid Regime model

The *"Shell"* is an interface designed to allow users to link results from a 1-dimensional (1-D) hydrodynamic model (process based; B-U) to regime relationships (T-D; goal orientated). This Hybrid approach enables informed decisions as to morphological effects of climate change, engineering works and so on.

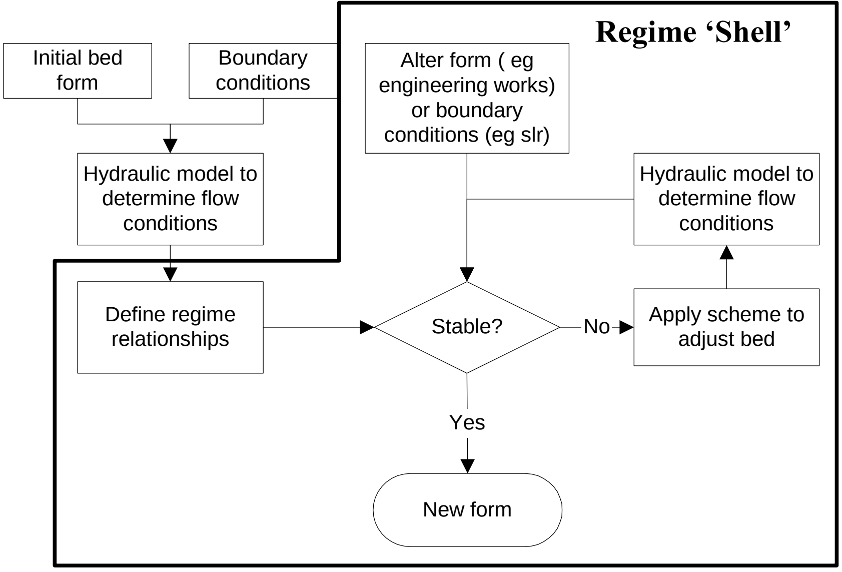


Figure 2.2.1 Hybrid Regime flow diagram.

Figure 2.2.1 represents the process based hydraulic model (Mike11, ISIS) on the left; on the right within the Shell interface is the Regime model. The Interface translates and imports the information from the hydrodynamic model into the Regime model. Ultimately, a new bathymetry of the estuary form is provided, based on some perturbation to the system. The Shell has been designed to work in Windows and is written in the program language Visual Basic and Matlab. The interface (a series of forms) allows the user to select a type of regime algorithm and couple this to a specific model simulation. Routines provide the user with additional information about the estuary under investigation: intertidal area, tidal asymmetry. The modular code with an open architecture approach allows users to add to or develop routines.

Regime theory characterises links between hydrodynamics and estuary morphology by a simple empirical formula (or formulae), describing an estuary (quasi-) equilibrium. Thus

$$A \propto Q_{max}^{\,p}, \qquad B \propto Q_{max}^{\,q}, \qquad H \propto Q_{max}^{\,r}.$$

for cross-sectional area A, top width B and mean hydraulic depth H in terms of discharge Q. The constants (p, q, r) are obtained by a fit to the results of the initial model run. The theory thereby predicts how the estuary will respond to changes (reclamation, engineering works, etc.) or in forcing conditions (sea level, tidal range, etc.) in order to return to the existing regime condition. It assumes:

- the estuary will achieve some form of equilibrium state
- the existing estuary form can be characterised by such equilibrium relations.

If individual cross-sections deviate initially from the best-fit regime relationship, relative rather than absolute adjustments can be made.

Morphological updating of a cross-section not meeting the regime condition is constrained as follows.

- Cross-section geometry is not adjusted above the maximum water elevation there.
- A horizontal and vertical limit may be applied, preventing adjustment beyond a specified extent relating to a Holocene surface, sea walls, cliffs, bridge piers etc. (important to coastal squeeze, for example)
- The cross-section adjustment routine uses linear stretching (vertically and horizontally).
- The section is adjusted according to the regime-required width and cross-sectional area.
- The new cross-section geometry forms the basis of the next iteration of the hydrodynamic model.

There is iteration (figure 2.2.1) until the cross-sections converge close (as specified) to the regime criteria. The model calculates intertidal and plan areas, volumes and hydraulic information, and provides information on the hydrodynamics and regime simulation. A graphical user interface (GUI) has been developed to allow the user to view and amend cross-sections. Wright and Townend (2006) give a more detailed description of the Hybrid Regime model. Details of how to use the model are given in Appendix B of the FD2107 Technical Report.

2.2.2 Application of Shell with regime constraints as a Hybrid model

Hybrid Regime models of five estuaries have been constructed to investigate how a range of estuaries evolve in response to changes in the forcing conditions. The five estuaries are: Blackwater, Humber, Mersey, Southampton Water, Thames. The forcing scenarios are listed in table 2.2.2.

Table 2.2.2 Scenarios used in 1-D Hybrid Regime modelling of the five estuaries

Scenario ID	Scheme
Baseline	Existing conditions, 1-D hydrodynamic model calibrated with measured data
MSL + 0.30 m	Driving boundary water level is raised 0.3m over 50 years (as 6 mm/yr)
MSL + 1m	Driving boundary water level is raised 1m over 50 years (as 20 mm/yr)
Tidal range + 2%	Tidal range at the seaward boundary is increased by 2% over 50 years
River flow + 20%	Freshwater discharge is increased by 20% over the next 50 years
All changes (MSL + 0.3 m)	Discharge + 20%, tidal range + 2% and 6 mm/yr MSL rise over 50 years
All changes (MSL + 1 m)	Discharge + 20%, tidal range + 2% and 20 mm/yr MSL rise over 50 years

The existing regime state was derived from the existing hydraulic parameters before changed driving conditions were applied. Where possible, stability of the existing regime was assessed by comparison with the regime conditions from a previous time.

6mm/yr sea-level rise. The Humber and Thames estuaries respond similarly, losing intertidal area at less than 0.1 per cent per year. Intertidal areas within the Mersey Estuary are predicted to increase over an initial period of 35 years; this can be accommodated within the form of the estuary. However, by 2050 a small net loss of intertidal area is predicted. Southampton Water also shows an initial trend of increasing intertidal area, but the capacity of the estuary is exceeded after 2025 leading to a small net loss by 2050. The Blackwater Estuary is different; it appears to experience faster intertidal loss, more than 0.15 per cent per year, over the initial period of 45 years followed by a rapid increase over the next 5 years.

20mm/yr sea-level rise. This faster sea-level rise shows broadly the same trends in intertidal response as found with 6mm/yr sea-level rise. Over the 50-year period considered, this exaggerated rate of sea-level rise is predicted to result in intertidal losses of 7-17 per cent for four of the five estuaries. The Blackwater has intertidal loss up to 35 per cent over the 50 years.

2 per cent increase in tidal range. For most of the estuaries there is limited intertidal change as a result of the moderate increase in tidal range. An exception is Southampton Water which is predicted to have a net gain in intertidal area of almost 4 per cent over a 50-year period. This predicted fast gain in intertidal area, which peaks in 2025, appears to be related to the position of relatively shallow bed slopes relative to the modified tidal frame. Conversely, the Thames Estuary is predicted to lose 5 per cent of intertidal area over the 50 year period.

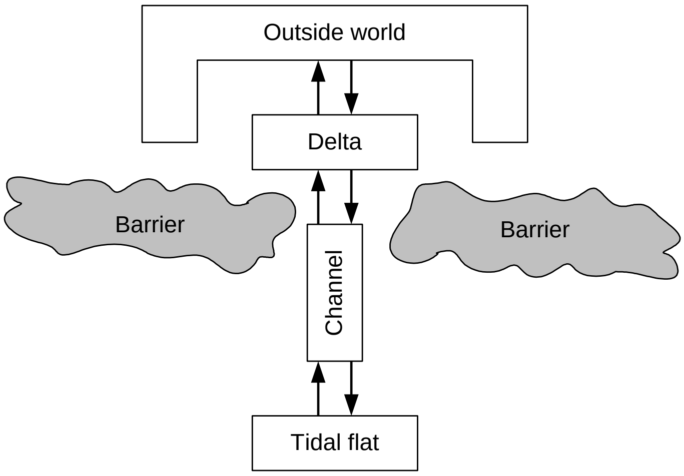
20 per cent increase in river flow. The Humber and Thames estuaries are least sensitive to a change in river flow, probably because they are larger and experience variable river inflow. The Mersey is predicted to experience a loss in intertidal area with increased river flow. Again the Blackwater seems particularly sensitive; after initial intertidal loss, a net gain of 0.6 per cent over the 50-year period is predicted.

2.2.3 Development and application of ASMITA-type model

ASMITA (Aggregated Scale Morphological Interaction between a Tidal inlet and the Adjacent coast) was first presented as a behaviour-based model “describing morphological interaction between a tidal lagoon or basin and its adjacent coastal environment” (Stive *et al*., 1998). The model schematises a tidal inlet system, the main morphological elements being viewed at an aggregated scale (Figure 2.2.3). Under constant hydrodynamic forcing (in particular constant mean sea level), each element is assumed to tend towards a morphological equilibrium, a function of hydrodynamic forcing and basin properties (van Goor *et al*., 2003). Empirical relationships define the equilibrium volume of each element (Stive *et al*, 1998).

Sea-level rise creates accommodation space within the estuary; the estuary becomes a sink for available sediment. ASMITA represents this by an increase in the difference between elements’ actual volume and equilibrium volume, causing sediment demand. A gradient of sediment demand drives sediment transport; sediment diffuses into the estuary, changing the morphology. Hydrodynamics are represented by integral properties (tidal range, tidal prism).

The morphological elements in ASMITA (intertidal area, channels, ebb-tidal delta) interact through sediment exchange, evolving the whole system as well as the individual elements (van Goor *et al*., 2003). If morphological elements are not present (e.g., ebb tidal delta), reduced models can be applied. Development of the tidal inlet is assumed not to affect availability of sediment in the outside world (van Goor *et al*., 2003). Equations describe volume changes (referred to sea level) dependent on element area, vertical exchange and concentration difference from equilibrium. Sediment moves laterally between elements (respecting mass balance) according to concentration differences and exchange coefficients.



Element definitions:

Ebb-tidal Delta: Excess sediment volume above a hypothetical non-inlet shoreface

Channel: Water volume below mean low water

Tidal flat: Sediment volume above mean low water

Figure 2.2.3 ASMITA schematisation and element definitions (from van Goor *et al*., 2003)

Coding of ASMITA in Matlab (version R2007a) has been carried out in FD2107, utilising only functions present in Matlab. A manual has been written, and a document detailing the relationships between the routines making up the ASMITA program. Through a graphical interface (or from the workspace window) the user can view information entered (type, properties, flow, diffusion rates etc.) and control all aspects of the model: element definition, properties and driving forces. Users have full access to the code that will enable them to make adjustments to the controlling algorithms (e.g. other driving forces) or add more functionality. The user specifies system properties (not specific to particular elements): tidal range, global sediment equilibrium concentration, water density, sediment density, sea level rise (SLR), cyclic information (number of cycles, phase, amplitude, period). The user must define each element: type, initial volume and area, bed slope, element length, import density, bulk bed density, transport coefficient, vertical exchange, slope of wall, toe level, regime coefficients. Since many of these values may not be known, tool tips (e.g. default values) are provided. Sensitivity runs should be performed to determine how sensitive the system is to the information specified. Constraints (e.g. coastal defences) can be represented. In the present version, at most 10 elements can be specified; at least two are recommended. The user specifies flow/diffusion rates (and thereby connectivity) between any two elements and between an element and the “outside world”. Known changes to element volume can be specified with their timing. The user specifies the run: time step (years), number of time steps, start year.

To apply ASMITA to the Thames Estuary, a six-element scheme was used: flats and channels in each of three sections thereby distinguished (Rossington and Spearman, 2007). Teddington to Broad Ness receives the majority of the river input and has had the most dredging historically. This section, the “inner estuary”, is relatively narrow with limited intertidal areas and a bed consisting mainly of gravel, stones, clay and chalk, excepting Gravesend Reach and the Mud Reaches. The “middle estuary” between Broad Ness and Lower Hope Point is wider, with some large intertidal areas. The “Sea Reach” between Lower Hope Point and Southend is wider and sandier than the landward sections and has large areas of intertidal sand flats as well as some muddier creek systems and saltmarsh. In the outer section of the estuary, almost all the intertidal areas are backed by sea defences and are at or below mean water level.

ASMITA was applied to the Thames Estuary to investigate the potential response of the estuary to sea-level rise, the sensitivity of this response to fluvial and marine sediment supply and possible mechanisms for trapping sediment within the estuary. Equilibrium relationships for the channel equilibrium volume (proportional to tidal prism) and the flat equilibrium volume (proportional to mean-spring tidal range and basin area) were estimated from historic data, with best-fit coefficients. Sediment transport coefficients were estimated according to the dynamics of sediments in context. A global equilibrium concentration is used to fit the model to the observed morphological time scale. Van Goor *et al.* (2003) suggest that the uncertainty associated with the various parameters is approximately ± 50 per cent.

The ASMITA model was thus calibrated to historical variation in Thames Estuary morphology, using the historical variation in dredging, disposal, sewage inputs and fluvial input collated by the Thames Estuary 2100 studies (HRW, 2006a-c). Under 2 mm/year sea-level rise, ASMITA was able to reproduce the evolution of the estuary reasonably successfully (Rossington and Spearman, 2007).

2.2.4 Development and application of *Inverse* Hybrid model

An INverse Model for EStuarine Morphodynamics (INES) has been developed and applied to the Humber Estuary. The model focuses on morphodynamic evolution of the estuary. It is based on an equation describing a tendency for the bed to level out “diffusively” in both horizontal dimensions through time. [This is suggested by combining sediment transport having a down-slope bias with conservation of sediment]. It is assumed that the morphodynamics can be described by such an equation with a suitable “source”; the source represents the aggregate of all non-diffusive phenomena that lead to long term evolution of estuary morphology.

The model requires that the estuary has bathymetries covering a long period, frequently enough not to alias changes in form or in management practices (e.g. dredging). Calculation of the time-averaged "source" for a time-interval, from initial and final bathymetries, has been formulated and tested.

The model has been applied to the Humber (the largest estuary studied in FD2107) on which there has been a wealth of research. Humber bathymetry data were gathered and processed (20 sets in all since 1851; 15 since 1936). The source function was derived for each survey interval. Large-scale features such as tidal channels, tidal flats and linear banks in the estuary are persistently visible in the source function. Overall, there is no rapid variation of source function from one interval to the other. Smaller-scale structures are apparent than in bathymetric data *per se*. Structure of the source function was not very sensitive to values of the diffusion coefficient.

To predict future morphology, the evolution equation can be used in principle; however, the coefficients and source function should be defined. If past historical behaviour is accepted as a useful basis for prediction, then extrapolating the sequence of source functions into the future is one means to estimate the source function in the bed evolution equation used predictively. To assess this approach, the sequence of source functions was investigated. EOF analysis (e.g. Horrillo-Caraballo and Reeve 2002, Reeve and Horrillo-Caraballo 2003) of the source function showed that 92 per cent of the mean square data is in the first spatial-structure eigenfunction; the corresponding time-series is nearly constant. Hence this form was used as the representative source function for prediction via the evolution equation. Predictions of the Humber bathymetry were made for 1 year, 3 years and 10 years into the future. 1-year and 3-year predictions were compared with the most recent measured bathymetries of the estuary (2002 and 2004).

2.2.5 Development and application of an estuarine Analytical Emulator

An Analytical Emulator has been developed, the main equations have been coded (Manning, 2007a) and applied to many UK estuaries. The Emulator is largely based on 1-D equations for conservation of water and along-estuary momentum (Prandle, 2004, 2006). It assumes (as commonly observed) that tidal amplitudes are broadly uniform along estuaries. On this basis, tidal timing, along-estuary changes and current are derived from tidal range Z and estuary depth D (for given friction coefficient and tidal period). Change of depth $\partial D/\partial x$ and hence estuary length is likewise derived from Z and D. Prandle (2004) also related saline intrusion length to depth, bed roughness, current U and river flow Q_f – eventually deriving

$$D_{\text{Estuary mouth}} \quad = \quad 12.8\,(Q_f\, a)^{0.4}$$

where *a* is the side-slope of the estuary (assuming a triangular cross-section). Thus the Emulator partly explains how estuarine bathymetries have developed in response to tidal and riverine inputs (Prandle *et al*., 2006). A modification by Manning (2007a) allows time-averaged river flow $<Q_f>$ input values to estimate the average estuary depths $<D_{AE}>$:

$$<D_{AE}> \quad = \quad 12.8\,(<Q_f>\ a_{\text{mean}})^{0.4}\ M.$$

Baseline conditions were from a newly enhanced Future-Coast database of UK estuaries (section 3.11). This was used to compute the mean estuary length, depth $<D_{\text{data}}>$ and width. From these were estimated the estuary side slope. The Emulator assumes that the estuary length and side slope remain constant. The Emulator-derived $<D_{AE}>$ was equated to $<D_{\text{data}}>$ by choice of *M*. This allowed the Emulator equations for the breadth, $<D_{AE}>$ and associated channel bathymetry to be solved reasonably accurately. Among the scenario changes, the morphology responds only to changes of river flow $<Q_f>$ in this formulation.

Sea-level rise (+ 0.3m or 1m to 2050; all imposed at once) gives new values for estuary volume and area. The constant side-slope implies that intertidal area remains constant under sea-level rise. Mean depth increases by half the sea level rise for the assumed triangular cross-section.

For infill by suspended particulate matter (SPM), a half-life in suspension is a function of settling velocity W_S, D and diffusivity proportional to UD, i.e. a function of W_S, D, Z. Hence the SPM concentration C is a function of W_S, D, Z. A minimum infill time was estimated from flushing time and mean concentration <C> (Prandle, 2004); <C> increases with tidal range but is assumed unchanged with raised sea level. Manning (2007a) gives more detail.

2.2.6 Development and application of a hybrid morphological capability for Lagrangian particle-tracking models

At start of FD2107 HRW had a *SandTrack* model for Lagrangian particle-tracking of sand-grains including bedload, suspended load, incipient motion and burial processes. *SandTrack* tracks "tagged" grains of sand, each representative of many billions of similar grains, as they move driven by the flow (predicted by a numerical model; *TELEMAC* here). *SandTrack* was extended in FD2107 to associate a volume of sediment with each tagged grain, and deposit it on the bed as a sediment "lens" with defined maximum thickness and extent. The lenses add to give the morphodynamic development of the estuary. By repeating this process at intervals of (say) 1 year, and re-calculating the hydrodynamics at each step, this has become a Hybrid morphodynamic model: *Morpho-SandTrack* (Soulsby *et al*., 2007).

In areas of deposition (tidal flats, saltmarshes), *Morpho-SandTrack* thus predicts the *source* of deposited sediment as well as its thickness. The tagged particles can carry a marker to indicate whether they are polluted (not utilised in FD2107). The characteristic dimensions of the lenses of transported sediment have been calibrated against the well-established Van Rijn sediment transport formula, by running Morpho-SandTrack for an idealised flume case with various steady current speeds and sediment grainsizes. The present model does not include effects of waves; they could be added (waves are already included in a version of *SandTrack*).

Morpho-SandTrack was tested in the Thames Estuary, to predict morphological changes over a 50-year interval, with a one-year update frequency for the bed and the flow.

2.2.7 Development and application of Realignment model

Partly in FD2107, a model was developed to predict evolution of morphology and habitats at managed realignment sites (Spearman, 2007). Such sites have specific complexities with significant roles of tides, waves, sediment, vegetation and biology at small spatial and temporal scales. The model methodology builds on the conceptual approach to modelling habitat development used successfully for lagoons by di Silvio (1989), di Silvio and Gambolati (1990). It combines B-U and T-D aspects to describe essential inlet functioning, with flexibility to incorporate effects of waves and vegetation, and future developments.

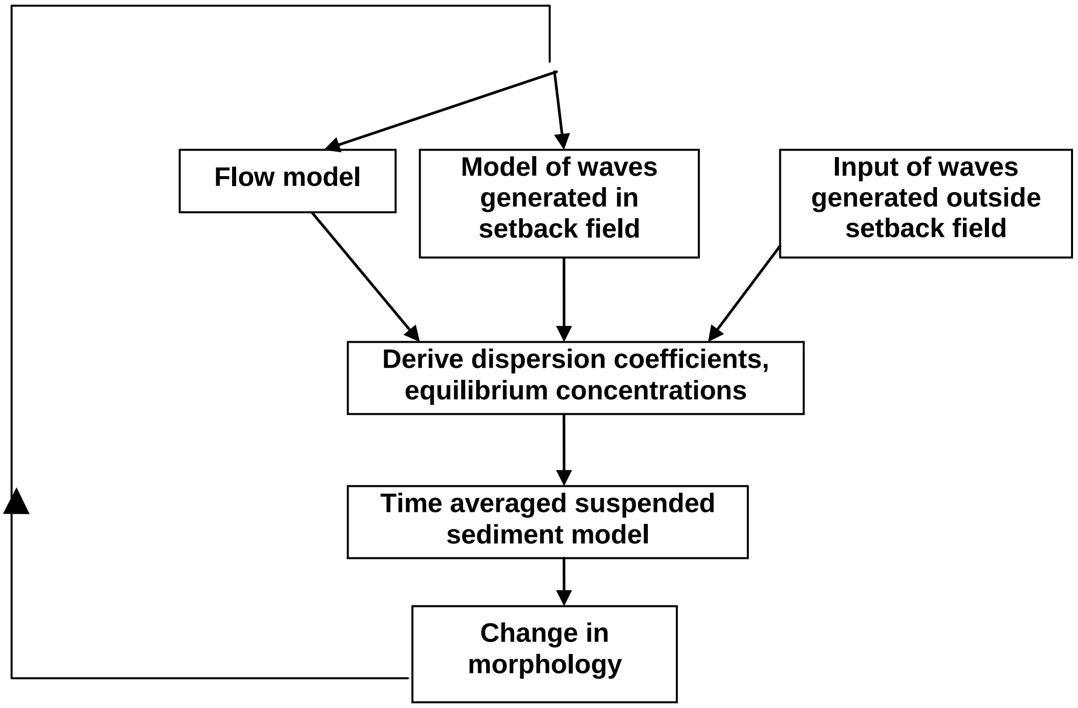


Figure 2.2.7 Basic structure of morphological Realignment model

The model structure is based on a simple UNIX shell script which controls application of the model elements in figure 2.2.7. The shell script allows flexibility – the user can implement their own software rather than proprietary software – and is simple to adapt to the Windows equivalent (e.g. Visual Basic). The run sequence is:

a) Set up initial bathymetry;
b) Work out time-averaged wave heights and periods (Young and Verhagen, 1996);
c) Use TELEMAC-2D (commercial) flow model to get flow conditions in set back field;
d) Post-process the flow and wave results
  - for time-averaged distribution of diffusion coefficients (Dronkers *et al*., 1982)
  - for distribution of time-averaged equilibrium concentrations C_E
  - saving values in a form suitable for input to SUBIEF-2D (commercial) model;
e) Run “di Silvio-type” time-averaged sediment transport model SUBIEF-2D with net erosion E as given by Galappatti and Vreugdenhil (1985): $E = w (C_E – C)$ where $E < 0$ is deposition, w is settling velocity, C_E is an equilibrium concentration, C is the actual concentration; derived time-averaged diffusion coefficients and zero residual currents are used (i.e. diffusive process only); bathymetry is updated during the model simulation;
f) Extrapolate predicted change in bathymetry over a much longer time step;
g) Use new bathymetry (f) as basis to run TELEMAC-2D again – go to (b).

As there is no residual transport in the model setback fields, time-averaged sediment transport into the field is modelled as a diffusive process, controlled by the (spatially varying) diffusion coefficient. The diffusion coefficient is assumed to be proportional to the square of the time-averaged current speed in the setback field (Dronkers *et al*, 1982). The magnitude of the diffusion coefficients was calibrated along with the other model parameters. In the absence of any previous/empirical basis or general empirical law governing the evolution of muddy tidal inlets, the equilibrium concentration C_E is given by equating the deposition occurring during slack water with the erosion during the rest of the tide:

$$\int_{\tau>\tau_e} M_e\left(\tau-\tau_e\right)\,dt=\int_{\tau<\tau_d} w_s C\left(1-\frac{\tau}{\tau_d}\right)\,dt=C_E\int_{\tau<\tau_d} w_s\left(1-\frac{\tau}{\tau_d}\right)\,dt\,.$$

Thus C_E depends on (spatially varying) current speed, wave action and the friction parameter (together determining bed shear stress), erosion and deposition thresholds, settling velocity and the erosion rate. There is inherent uncertainty in the (literature) values of the friction and sediment parameters; C_E will remain somewhat uncertain.

The effect of biology on bed shear stress is not presently included; nor are erosion (via geotechnical processes) of the sea walls at the entrance to the set back site, or erosion of the initial bathymetry (re-erosion of deposited sediment *is* reproduced);

Modelling to predict evolution of a managed realignment at Tollesbury Creek, and good comparison with the observed evolution, is detailed in Spearman (2007).

2.3 Intercomparison and evaluation of model predictions for 2050 morphologies

The models developed as in section 2.2, and two pre-existing models, were run to predict eight UK estuaries' responses to possible future scenarios. The 'ensemble' of applications is shown in table 2.3. The Thames provided intercomparisons between the most models including TE2100 studies.

Table 2.3 Models, estuaries and their properties in the intercomparisons.

Model	*Type*	*Section*	*Thames*	*Blackwater*	*Humber*	*Mersey*	*Dee*	*Ribble*	*S'ton Water*	*Tamar*
Emulator	Hybrid	3.5	Y	Y	Y	Y	Y	Y	Y	Y
Hybrid Regime	Hybrid	3.1	Y	Y	Y	Y			Y	
"2.5-D"	B-U	2.2				Y	Y	Y		
ASMITA-type	Hybrid	3.3	Y							
SandTrack	Hybrid	3.6	Y							
TE2100	Trend	4.1	Y							
Realignment	process	3.7		Tollesbury						
Inverse	Hybrid	3.4			Y					

Entries Y show the estuaries in which each model was run. Model predictions were generally inter-compared for 2050. Scenarios to represent possible effects of climate change 50 years hence were:

Mean sea level: present as baseline; rises of 0.3 m (realistic), 1 m (extreme);
Tidal range: present as baseline; an increase of 2 per cent (Flather *et al*., 2001);
River flow: baseline as at present; an increase of 20 per cent.

In addition, historical trend analysis (HTA) was carried out for in the Thames, based on TE2100 studies (HRW, 2006d). Model results were compared for changes to estuary high-water and low-water volumes and areas. Intertidal area was emphasised as an important habitat and indicator of coastal "squeeze". Some models also gave an indication of exchange rates and sediment "infill" times and/or whether estuary morphology is likely to keep pace with sea-level rise.

3. Discussion of results and reliability

3.1 Overview of results - models

Some trends are inevitable in those models (Emulator, "2.5-D") that do not evolve the morphology. LW and HW areas and volumes, the tidal prism and fluxes of water at the mouth will increase with raised MSL. The Emulator mean depth increases by half the rise in MSL. Intertidal and saltmarsh areas will increase or decrease with raised MSL as cross-sections are convex or concave. Increased tidal range increases HW volume and area, intertidal area, the tidal prism, fluxes of water at the mouth and suspended sediment concentrations; LW volume and area must decrease. Increased river flow increases LW volumes and areas. These trends form a reference against which to infer effects of evolving morphology.

3.2 Analytical Emulator

In its form with constant side slope (zero convexity), the Emulator may not represent consistent high and low water areas and volumes. It has fixed intertidal area (unless tidal range is changed) and so cannot assess changes therein. The Emulator is also liable to represent channel volume and mean depths poorly (e.g. 1.7-4.8m depth compared with a more typical 8m for the Thames). Hence it is difficult to apply some aspects of the 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 Emulator would still 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. The only change in morphology in these Emulator runs is a depth increase in response to increased river flow.

The Emulator was applied to all eight estuaries and is thus generally *applicable*, needing only gross estuary dimensions, mean sea level, tidal range and river flow. Minimal computer capacity is needed. However, *appropriateness* is limited (as implied above) to estuaries where volumes and areas are fairly represented by the Emulator's fixed geometry and are not constrained by fixed structures.

3.3 Hybrid Regime model

The Hybrid Regime model has many individual cross-sections and hence more flexibility to represent LW and HW areas and volumes accurately. Fixed surfaces can be defined to represent solid geology, structures preventing erosion (e.g. sea defences) and hence limitations on HW area. With raised MSL, LW area increases and so intertidal area decreases (unless the estuary fills in to compensate); i.e. intuitively correct 'coastal squeeze'. The model predicts mean depths to increase in most estuaries as MSL rises; however, it predicts substantial infill for the Mersey (where infill is known historically) and accords with "2.5-D" and Emulator predictions of relatively short infill times. The Hybrid Regime model also predicts a (usually) small decrease in intertidal area with increased river flow. To accommodate greater flow but maintain its regime state, the estuary widens and deepens, losing intertidal area.

To avoid excessive initial response to changed inputs, a later version of the Hybrid Regime code runs the baseline condition first, rather than taking the baseline conditions as posed. This "stabilises" the model for the initial conditions and should hardly change longer-term predictions.

The Hybrid Regime model was applied to five estuaries and is thus widely *applicable*; it needs mean sea level, tidal range and river flow but more data than the Emulator on estuary form: cross-section areas, breadths and depths at along-estuary intervals short enough to resolve variations in these statistics and desired output features. It can accommodate branching (a requirement on the underlying 1-D hydrodynamic model). Computing requirements are relatively moderate. The approach is most *appropriate* if there is confidence that a regime condition holds and should persist; if the estuary is subject to rapid change or instability then regime modelling is unsuitable. It predicts changes in the statistics of individual cross-sections; the allowance for hard constraints is especially useful in heavily modified estuaries (e.g. Thames, Southampton Water) which do not follow a simple along-estuary profile. Currently the model does not simulate waves and so lacks their effects. It also lacks explicit treatment of sediments. Care is required in the interpretation of the Hybrid-Regime findings; there are limitations of the morphological updating routines in the version applied here. The Blackwater as modelled appears to be particularly sensitive to accelerated rates of sea-level rise.

3.4 ASMITA

ASMITA also gives intuitively correct results (loss of intertidal area with faster sea-level rise). Its analytical formulation enables *a priori* evaluation of the uncertainty inherent in the model prediction. Equilibrium coefficients were selected to give the best representation of the Thames estuary geomorphology during the period of data availability. They describe equilibrium on timescales of 10s to 100s of years, but may not be valid for predictions over longer periods. Then ASMITA was validated against past morphological change in the Thames; it could reproduce the current trend of increasing intertidal area for present sea level rise (around 2mm/yr).

In FD2107, ASMITA was applied only to the Thames estuary and Tollesbury Creek set-back field. However, it has previously been applied elsewhere and is thus widely *applicable*; it needs mean sea level, tidal range and river flow, and gross dimensions (volumes, areas) of the aggregated elements (channel, intertidal flats, delta). [There is scope for some disaggregation, e.g. channel and intertidal elements for each of three reaches in the Thames Estuary, but too much division forfeits analytic "transparency" and probably robust calibration]. A vertical exchange coefficient for each aggregated element must be set, and an overall sediment concentration calibrated to match past evolution (for which data are required). Minimal computer capacity is needed. *Appropriateness* is limited to studies where volumes and areas are fairly represented by a few aggregated elements; probably also calibration on past behaviour implies that scenarios should not diverge far from past experience. The underlying control by accommodation space places implicit reliance on continued sediment supply.

3.5 "2.5-D" model

The "2.5-D" model can represent LW and HW areas and volumes, limited only by the chosen resolution, to which flow in channels at LW is most sensitive. It differs from the Emulator owing to the latter's geometric limitation and possible differences of extent; different boundaries should account for differences from the Hybrid Regime model (in the Mersey). "2.5-D" model results for changes under raised MSL and tidal range can generally be interpreted in relation to the Emulator; neither has morphological change. Predictions of sediment transport and deposition suggest trends of morphological change until deposition patterns change significantly; infill times comparable with those of the Emulator can be inferred. These times are on the basis of essentially unrestricted marine sediment supply according to current strengths at the estuary mouth; net deposition may be slower if marine supply is restricted. However, there may be other (riverine, lateral) sediment sources and (e.g.) dredging disposal could increase marine supply and deposition rates (Lane and Prandle, 2006).

In FD2107 the “2.5-D” model was applied to three estuaries and similar models have been applied in many others; thus the model is widely *applicable*; it needs mean sea level, tidal range and river flow; it also needs bathymetry over the whole (2-D) estuary area, fine enough to resolve channels and banks of interest and desired output features. Sediment sources need to be explicit (usually erosion in the estuary and river and/or marine supply). Computing requirements are relatively large. The approach is most *appropriate* if detail is required, scenarios are relatively short-term in the future (longer-term prediction requires morphological updates) and there is a lack of historical guidance.

3.6 Morpho-SandTrack

Resolution of the (Morpho-)SandTrack model applied to the Thames landward of Southend was coarse for representing changes to this intertidal area. However, in the outer Thames estuary the model appears to represent the main features of the system. Addition of waves might re-distribute sediments here. Morpho-SandTrack has some useful capabilities, and is complementary to the “2.5-D” model with Lagrangian transport. There were valuable exchanges of ideas and methodologies between the two models in the project. Both have their place in the overall modelling tool-kit.

Continually repeated flow model runs are needed for 2-D morphological models (whether or not Lagrangian like SandTrack). Such models need finer resolution than was used for SandTrack in the Thames. To reduce this computing demand, 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.

In FD2107 Morpho-SandTrack was applied only to the Thames. However, it should be *applicable* just as widely as the “2.5-D” model, having the same requirements [mean sea level, tidal range, river flow; fine enough bathymetry over the whole area, explicit sediment sources]. Likewise computing needs are relatively large and may constrain how fine a resolution is practicable. As with the “2.5-D” model, the approach is *appropriate* for detail and if there is a lack of historical guidance, but morphological updating allows longer-term prediction.

3.7 Historical trend analysis

HTA uses morphological change hitherto to guide expectations of future trends. Hence it is *applicable* (only) if past morphological data for the variables of interest are frequent enough to resolve past changes without aliasing. [As applied here, it was simply extrapolation of a present trend, as may often be feasible. Mean sea level, tidal range and river flow data are not necessary but might be used in the analysis to separate out related trends]. Minimal computer capacity is needed. HTA being empirical is not *appropriate* outside the range of experience. Hence it is not suited to estimating scenarios of faster sea level rise; ability of an estuary to “keep up” in the same way could be in doubt.

3.8 Inverse model

The Inverse model also uses morphological change hitherto, but with more reference to dynamics, using a diffusion-type equation to evolve the bed. In the Humber, some evidence (section 2.2.4) supports using the diffusion equation to predict morphology with future extrapolation of the source function (representing processes not modelled by diffusion): the source function was insensitive to the selected diffusion coefficient; 92 per cent of the mean square source function resided in the first spatial-structure eigenfunction with nearly constant corresponding time-series. In such cases, past behaviour may be a useful basis for prediction.

The Inverse model is (only) *applicable* with past bathymetric data for the (2-D) estuary area, frequent enough to resolve past changes without aliasing, fine enough to resolve channels and banks of interest and desired output features. In practice, exemplified in FD2107 only for the Humber, bathymetry seems to be needed about every 10 years; perhaps more often for a rapidly-changing (e.g. small) estuary. This is rarely so (the Humber is an exception); hence the practical usefulness of the Inverse method may be somewhat diminished. [Mean sea level, tidal range and river flow data were not used]. Moderate computer capacity but substantial analysis effort is needed. As with HTA, the Inverse model depends on past behaviour; it is only *appropriate* for predicting the morphological response if (i) future interventions have precedents, i.e. within the range of experience, and (ii) the eigenfunctions used (corresponding time-series having an integral time longer than the period predicted) comprise a large majority of the source function hitherto (as for the Humber).

3.9 Realignment model

The managed realignment model was able to predict the evolution of the Tollesbury Creek managed realignment site under the action of tides, waves and sediment supply. Results over the seven-year validation period were good, given the uncertain nature of the sediment supply from the Tollesbury Creek system. As such it seems a promising basis upon which to base management decisions involving managed realignment. Simple vegetation effects have been incorporated and the model represents a framework for further developments into wave, vegetation and biological processes.

Sensitivity tests undertaken using the model have considered how variations in waves, friction and model resolution affect the predicted evolution. Longer simulations were used to see how the growth of saltmarsh itself affects the evolution of the setback field.

The model as presented does not consider the evolution of the breach itself as a result of extreme events, weathering and dessication, but breach evolution is potentially important. A widened breach would reduce flow speeds through the breach and lengthen flood tides. This would introduce more sediment into the managed realignment site, but potentially reduce the amount of this sediment that settled in the site. In addition a wider breach could lead to larger waves entering the setback field from outside, tending to reduce the rate of accumulation and reduce the potential for salt marsh growth.

The model is *applicable* where there are data for waves and sea level (mean + tide) at the breach, and bathymetry over the whole (2-D) set-back area, fine enough to resolve channels and banks of interest and desired output features. [Sediment supply is implicit]. Computing requirements are moderate. The approach is most *appropriate* over a small area (sediment is "diffused", not advected), if detail is required (if not, ASMITA deserves investigation) and if there is a lack of historical guidance.

3.10 Overview of results – estuaries

The following describes overall trends. Differences between the estuaries were shown especially by the Emulator and Hybrid Regime models, run on eight and five estuaries respectively.

3.10.1 Effects of raised Mean Sea Level

LW volumes and areas invariably increase for raised MSL; so usually do HW volumes and areas, but less so. Factors in the different response are: hard structures often constrain HW area; effects are relatively larger in shallow water, i.e. at LW and in shallow estuaries generally. Thus intertidal area generally decreases ("coastal squeeze"; e.g. over 50 years in the Thames, Blackwater, Humber, Mersey, Southampton Water in the Hybrid Regime predictions; the Blackwater decrease is large). However, ASMITA predicts a smaller loss of Thames intertidal area – indeed, an increase for the present rate of MSL rise, comparable with small changes from trend analysis. The Thames exemplifies constrained HW area; HW meets tidal defences in most places. Predictions then vary according to the extent to which models take this into account (as a constraint and further in dynamics affecting lower-level morphology).

Depth in most estuaries is predicted (by the Hybrid Regime model) to increase; comparably with MSL rise for High Waters in the Thames, Blackwater and Humber; otherwise infill reduces the depth increase (especially in the Mersey). For Southampton Water, the Hybrid Regime HW area increases; the shallow-water area increases as MSL rises, so reducing the average depth increase.

3.10.2 Effects of tidal range and river flow

These effects are proportionally greater in shallow water, i.e. at LW compared with HW. Otherwise, likely effects of realistic changes in tidal range (e.g. +2 per cent) are moderate, O(2 per cent). Southampton Water has larger gains of intertidal area, apparently related to the position of relatively shallow bed slopes. The Thames Estuary loses intertidal area in the Hybrid Regime model.

A 20 per cent increase in river flow gives only O(2 per cent) changes in LW and HW areas and volumes in the Hybrid Regime model; however, the Mersey and Blackwater lose intertidal area. [The Emulator predicts much larger increases in areas and volumes].

3.10.3 Flushing and infill

Flushing times as estimated by the Emulator are just a few weeks, and do not correlate with estuary size, as they depend also on tidal range and river flow[1].

Related infill times are some centuries (also from "2.5-D" model predictions), lengthening slightly for rising MSL and shortening slightly for increased mean river flow. Most infill times indicate enough sediment input to enable the morphology to keep up with sea-level rise; additional lateral sources may reinforce this suggestion. However, estuarine dynamics may determine that morphology does not keep up with sea-level rise (c.f. Hybrid Regime results other than the Mersey). In the Mersey, scope for infill is known historically, the Emulator and "2.5-D" model predict a relatively short infill time, and Hybrid Regime results suggest infill keeping pace with sea-level

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[1] *Different definitions of flushing and related time-scales are possible. The Emulator estimate is the time to replace by freshwater, half of the salinity content over the saline intrusion length. Typically for freshwater flow Q, whole estuary volume V, tidal prism V_T and period T,*

$$TV/V_T < \text{Emulator estimate} < V/Q.$$

rise. ASMITA for the Thames predicts a time-scale ~ 300 years to reach dynamic equilibrium with 6 mm/yr MSL rise; longer for faster MSL rise up to a maximum 21 mm/yr for which the Thames is predicted to keep pace. The Humber Estuary has been surveyed frequently for past trends to give a good guide to future development; its size and probable longer time-scale may help.

3.11 Data

Data requirements for FD2107 were primarily concerned with expanding the original Future-Coast (F-C) database (Burgess *et al*., 2002). F-C was largely based on data from JNCC (Buck and Davidson, 1997), augmented by tidal prism volumes. For 96 English and Welsh coast estuaries, the F-C data-base includes values of the following: surface area, intertidal area, saltmarsh area, shoreline perimeter length, channel length, Spring tidal range, mean river flow, mouth width, HW and LW volumes.

During FD2107, the F-C database has been further augmented as follows (Manning, 2007b):

- more detailed freshwater flows (seasonal statistics) from the Centre for Ecology & Hydrology (CEH) archives for 65 England and Wales coast estuaries
- saline intrusion lengths for most estuaries from literature review and Marine Nature Conservancy Review
- neap tide equivalent tidal ranges, based on tidal range information from Admiralty Tide Tables
- tidal amplitudes calculated for most estuaries as (Spring tidal range)/3.1
- mean estuary depths D, corresponding to MSL, calculated for most estuaries as $0.5(V_H/S_H + V_L/S_L)$, where V_H, V_L = HW, LW volume, S_H, S_L = HW, LW surface area
- mean estuary breadth B, calculated for most estuaries as $(S_H + S_L)/2L$
- average side-slopes of most English and Welsh estuaries, determined as 2D/B
- LW and HW values were added for: D, B, surface area.

The expanded database has been used in comparison with estuarine morphological theory (Prandle *et al*., 2005), assessing dynamical controls on UK estuaries (Prandle, 2006) and for typology (Prandle *et al*., 2006). Other characteristics of the estuaries have been derived using the Analytical Emulator equations (Manning, 2007a). The expanded database includes also JNCC data for the main Scottish estuaries and 110 Scottish sea lochs.

4. Implications

4.1 Modelling practice

4.1.1 Factors in model choice

Models developed and used in FD2107 have varied character, strongly affecting their suitability according to context. If the *shape* of the estuary is to be described, the Emulator and ASMITA are not applicable; the Hybrid Regime model resolves along the estuary but the shape of any cross-section remains self-similar; the other models all describe bathymetry as a function of (2-D) horizontal location.

There is a *process*-basis to all the models, but with limitations. The Emulator is based only on simplified 1-D hydrodynamic equations (along the estuary) assuming uniform tidal range. The Hybrid Regime model uses 1-D hydrodynamics assuming regime relations between discharge and cross-section parameters. In ASMITA, evolution is according to accommodation space into which sediment is transported. ASMITA, Realignment and Inverse models all have only diffusive sediment transport. The “2.5-D” and Morpho-SandTrack models have explicit hydrodynamics carrying particles; they entail the largest computing requirements and possibly time-limited validity of predictions. As applied here, none of the models take explicit account of estuarine circulation (due to salinity gradients).

Morphological evolution in the Emulator (as run) only occurs if river flow changes. As applied here, the “2.5-D” model does not evolve morphology. However, both models can indicate infill time-scale. The time-scale of evolution in Hybrid Regime predictionsl is not clear. ASMITA, Morpho-SandTrack and Realignment models explicitly evolve the morphology. Hard structures (geological or man-made) can constrain Hybrid Regime and ASMITA evolution of morphology. The Inverse model may also predict morphology if (i) the predicted scenarios have precedents, (ii) past bathymetry is available with consistent analysed trends and (iii) these trends have an integral time longer than the period predicted.

All the models *require* certain basic *information*: bathymetry, mean sea level and tides, hence related quantities – width, length and (e.g. intertidal) areas and volumes. The Inverse model (and Historical Trend Analysis) depends on often-repeated bathymetry (but little else). Resolution of the bathymetry is a matter of choice, but limited in practice by what is available, complexity (ASMITA) or computing cost (Morpho-SandTrack, “2.5-D” or 3-D models). River flow is often important, especially to the functioning of the Emulator and Hybrid Regime model. The representation of sediment sources, type and erosion is critical to Lagrangian particle-tracking models (SandTrack, “2.5-D”) and deposition rates may be sensitive to these factors.

Outputs relate closely to the character of the model, especially its treatment of space and time.

Scenarios of raised mean sea level and altered tidal range are treated by all except the Inverse model. River flow is variable in all except the Inverse and Realignment models. Waves are treated by the Realignment model and could be added to the "2.5-D" and Morpho-SandTrack models. For any one model, all its treatable changes can be handled in combination.

4.1.2 Gaining assurance

Estuaries have varied individual responses to climate change scenarios, hence morphological change effects on flood risk also vary between estuaries. This puts an onus on modelling the particular estuary studied. Available models are all limited in their own ways (section 4.1.1 above). No one model is likely to satisfy all aspects and be validated. An ensemble can provide validity and scope.

Care is required when interpreting results from any one model. Unpredictability inherent in bed-morphology, and limitations of routines updating the bed, can cause questionable results. To assess model uncertainty, validation is needed. Successful validation gives some confidence that the model represents the key processes controlling morphological change. Validation against historic change is good practice if attempting to predict long-term changes. If historic change data do not serve, alternative models' predictions should be compared, to help establish the validity of predicted morphologies. Predicted trends should be broadly consistent with B-U model results. Thus generation of an ensemble of possible outcomes is likely to become best practice when attempting to predict long-term changes in estuaries. Intercomparison gives confidence, if results agree or differences can be explained, e.g. by discrepancies in model area (an important factor) or model limitations (processes, estuary form); it is another means of validation.

Results in FD2107 are from morphological predictions founded on diverse concepts. All can be valuable: to develop an ensemble of possible future scenarios; to broaden the range of quantities predicted. Confidence levels for specific outputs should be applied while synthesising the results.

Model runs here are not definitive for any of the estuaries. Results should not be relied on for management decisions without more specific studies.

4.2 Impacts of future morphologies on changes in flood risk and habitats

The study of how and why changes to estuary morphology occur is of great interest to those seeking to maximise the potential of estuaries for development, while preserving or even improving the quality of habitat and biodiversity in these systems. There is current concern regarding the continuing loss of important habitats, such as saltmarsh; development can change the nature of nearby estuarine habitats. However, the relationship between morphological change and flood risk is more complex and less well studied. When considering the nature and performance of any of the models considered in this report, it is helpful to consider the context and relative significance of the management issues which the models are to be used to address.

To this end FD2107 included a discussion (HRW, 2007) of the influences that estuary morphological change can have on flooding, using examples from around the UK and beyond. The account is not definitive but highlights how a range of flooding risks, from estuary-wide to the local scale, can be induced by different modes of morphological change. In addition, it shows how flood-defence and coastal-protection measures can affect estuary habitat and how this impact is being addressed (in particular through the use of managed realignment).

As an example, predicted water levels along the Humber Estuary have been compared; for existing conditions, for 2050 assuming fixed estuary morphology, and for 2050 accounting for predicted changes in estuary morphology over the 50-year period using the Hybrid Regime model. Assuming fixed morphology apparently results in over-prediction of peak water levels, relative to changed 2050 morphology. A similar previous result holds in the Severn Estuary (Wright and Townend, 2006). In the Thames, however, morphological trends apparently amplify High Water levels. Distinctions should be noted here: use of historical morphological trends (Thames) rather than model predictions; infill keeping pace with sea-level rise (Thames) rather than predicted erosion in the Humber. In short estuaries (e.g. Mersey, Dee and Ribble), extreme high levels, i.e. flood risk, should closely follow external levels with little effect of changing morphology.

The HRW (2007) examples indicate that large-scale change resulting from extensive dredging has not been found to cause extensive or significant changes in flood risk. Indeed, where natural siltation is very rapid, such as in the Parrett Estuary, dredging can alleviate flood risk rather than increase it.

Flood risks in estuaries with natural flood and coastal protection features commonly entail preservation of these features; consequences of breaching (e.g.) spits or bars could be extensive, to the hinterland, valuable habitat and shorelines currently protected. Such preservation is often localised as extra protection for vulnerable or degrading parts of the feature.

Manifestation of flood risk is commonly at the local scale. Often flood and coastal management issues are localised, e.g. degraded walls made more vulnerable to wave attack as foreshores erode. Causes of foreshore erosion vary but sea-level rise, saltmarsh-loss and development are typically involved.

Many of the underlying issues governing flooding and coastal protection are the legacy centuries of land reclamation - originally for agricultural land and more recently for urban housing and industry. The sea wall/dyke structures enabling this reclamation often protect an extensive hinterland, but many reclamations are so long-standing that they are now part of (what we think of as) the natural estuary system. However, these seawalls have changed the morphology of many estuaries dramatically, and the act of building behind this coastal protection has created the flood risk.

A major impact of sea level rise on a defended shoreline is a reduction in mudflat and salt marsh; sea walls prevent these environments keeping pace with the rise in water level. Managed realignment is the main instrument used to mitigate this reduction in intertidal area (*coastal squeeze*). If a scheme is well-designed, intertidal land will turn over some years into a habitat with mudflat and saltmarsh.

5. Possible future work

Recommendations on good practice when predicting long-term morphological changes in estuaries have been made (section 4.1.2). These emphasise estuaries' individuality, hence an onus on specific modelling. Moreover, models' limitations and uncertainties entail validation; if possible against historical change, and/or by comparison of alternative models' predictions in a range of scenarios. In FD2107, model validation against historical changes in bathymetry was limited; reliable and suitable historic data that exclude the influence of human intervention (dredging etc.) are scarce. A detailed review of historical data suitable for model validation would be useful, followed up by comparison of such "'good" historical data with hybrid models' hindcasts for the historical scenario.

The following are more specific recommendations to enhance the models developed in FD2107.

To enable the Emulator to represent HW and LW (hence intertidal) areas and volumes, the assumption of a triangular cross-section with uniform side-slope could be relaxed to some other uniform shape of cross-section. It might be feasible to allow (e.g.) power-law dependence of breadth and depth on along-estuary distance, implying self-similar rather than congruent cross-sections.

It is desirable and possible that the Hybrid Regime model be developed to give rates of morphological evolution. If sediment transport, flow-dependent erosion and deposition were added to the underlying 1-D hydrodynamic model, a rate of change of area for each cross-section would be predicted. Work in FD2116 has already set out how the Hybrid Regime model could give rates of morphological evolution and has shown how regime theory is an approximation to sediment transport (HRW *et al*., 2006).

The possible influence of density-driven gravitational *estuarine* circulation could be investigated, adding a (formulaic) supplement to the calculated flow in the Hybrid Regime and SandTrack models, as in the "2.5-D" model (Lane and Prandle, 2006).

Lagrangian particle-tracking as in the "2.5-D" model is being implemented in POLCOMS, a fully 3-D model with density effects (e.g. estuarine circulation is modelled, given fresh river inflow).

The "2.5-D" model could be enhanced to predict evolving morphology, using (a modified form of) bed evolution as developed for Morpho-SandTrack in FD2107.

It is desirable and possible to add waves to Morpho-SandTrack; they are already in SandTrack. Morpho-SandTrack could usefully be run alongside more conventional Eulerian morphodynamic models, for comparisons to gain experience of its performance (speed and results).

The computing demand of Morpho-SandTrack, and other 2-D or 3-D models evolving the bed, implies merit in reducing the required number of flow model runs, making finer resolution feasible. Continuity (for example) might be investigated as a basis to alter current speeds for small bathymetric changes.

The project's extension of ASMITA to predict changes of element areas (as well as volumes) should be fully validated.

The managed realignment model, shown to be a promising basis for decisions regarding managed realignment, would be improved further inclusion of:
- a more sophisticated model of saltmarsh growth;
- evolution of the breach itself;
- erosion of the initial bed, particularly foreshore just outside the breach.

If the Inverse model is to be used for prediction, there should be some hindcast tests (against some past data not used in the EOF analysis of Section 2.2.4) and trials for other estuaries. Application to other datasets and possibly other types of data, such as beaches, would help to resolve some of the questions arising from the particular application in FD2107.

Appropriate components of the FD2107 expanded database should be incorporated in the *Simulator* developed in FD2117.

Wider-ranging recommendations regarding estuary *Impact Assessment* and *Management* systems are the subject of FD2119 *Development and Dissemination of the Estuaries Research Programme.* Discussion of such implications of the FD2107 modelling has contributed to the FD2119 report.

6. Actions arising: access to model developments and data

The *"2.5-D"* model with particle tracking can be disseminated. The easiest way for others wanting to use the model is to contact POL directly (A. Lane: ale@pol.ac.uk).

The *Hybrid Regime* model is described most fully in Appendix B to the FD2107 Technical Report and is available on the *Estuary Guide* website www.estuary-guide.net.

ASMITA is described most fully in Appendix C to the FD2107 Technical Report and is available on the *Estuary Guide* website www.estuary-guide.net.

The *Inverse model* analysis was written in MATLAB. This is available "as is", to others wanting to use the model, on request from the University of Plymouth (dominic.reeve@plymouth.ac.uk).

Application of the *Analytical Emulator* is reported in Manning (2007a). For further enquiries about implementation, contact Dr. A.J. Manning (University of Plymouth and HR Wallingford: andymanning@yahoo.com).

Morpho-SandTrack's new lines of code that operate the morphological updates are necessarily interleaved with existing (non-open) SandTrack code. The development and application is described in Soulsby *et al.* (2007). The easiest way for others to make use of the new model developments is to contact HRW directly (Dr. C.T. Mead; ctm@hrwallingford.co.uk).

The *Realignment Model* and provision of code is described most fully in Spearman (2007). In summary, the model as used is based on proprietary software (in this case TELEMAC) but the methodology used is to show how to combine flow model, wave and sediment models so as to be software-independent. The code to establish the wave stresses, dispersion and equilibrium concentration inputs to the sediment transport model is supplied. Changes to the TELEMAC code have been supplied (so that those with TELEMAC could run the model directly) and the Shell script linking the models together is also supplied.

For enquiries about Thames Estuary (TE2100) data, or Tollesbury Creek in the Blackwater Estuary, contact HRW (Dr. J. Spearman; js@hrwallingford.co.uk).

The *expanded Future Coast data* base (as expanded in FD2107) is available from BODC, also via the POL ERP Web pages at http://www.pol.ac.uk/erp/. It is being made available to the Estuary Simulator (FD2117) and for wider dissemination (FD2119). This data base is most fully reported in Manning (2007b). For further enquiries, contact Dr A.J. Manning (University of Plymouth and HR Wallingford: andymanning@yahoo.com).

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