Development of estuary morphological models

R&D Technical Report FD2107/TR

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Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme

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Statement of use

This document provides information for Defra and Environment Agency staff, researchers and consultants about the research project *Development of Estuary Morphological Models* and constitutes an R&D output from the joint Defra / Environment Agency Flood and Coastal Erosion R&D Programme, Modelling and Risk Theme.

Outputs from FD2107 comprise morphological model developments, some predictions from these models for the form of eight UK estuaries in 2050, an extended database of UK estuary characteristics, and an assessment of effects of changed morphology on flooding risk and habitats. It is expected that models and data will be used in predictions of future estuary form, flood risk and habitat; in order to underpin policy, inform estuary management and assess impact of schemes; by consultancies acting for Defra, the Environment Agency and local authorities. The work in this project owes much to its initiator, David Prandle.

This report is a contribution to research, and it would be imprudent for third parties to rely on it in specific applications without first checking its suitability. Various sections of this report use data supplied by or drawn from third party sources. The research team (POL, HR Wallingford, ABPmer and University of Plymouth) accepts no liability for loss or damage suffered by the client or third parties as a result of errors or inaccuracies in such third party data.

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Executive summary

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 this report describe model developments in detail. Access to data sets and model developments is described in a concluding Section 7.4 of the report.

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

Contents

Figures

Tables

Appendices

Acronyms

ABPmer	ABP (former Associated British Ports) marine environmental research
ASMITA	Aggregated Scale Morphological Interaction between a Tidal inlet and the Adjacent coast
B-U	"Bottom-up" or process-based model using continuity and momentum equations
CD	Chart Datum
CDV2075	Coastal defence vulnerability – 2075 (project)
CEH	Centre for Ecology and Hydrology
CHaMP	Coastal Habitat Management Plan
CIRIA	Construction Industries Research and Information Association
Defra	Department of the Environment, Food and Rural Affairs
EA	Environment Agency
EMPHASYS	Estuarine Morphology and Processes Holistic Assessment System
EOF	Empirical Orthogonal Function
ERP	Estuaries Research Programme
ESTPROC	Estuary Processes Research Project
EstSim	Development and Demonstration of Systems based Estuary Simulators (project)
F-C	Future-Coast
HRW	HR Wallingford (former Hydraulics Research)
HTA	Historical Trend Analysis
HW	High water (tide)
JNCC	Joint Nature Conservancy Council
LW	Low water (tide)
LNHE	(Electricité de France) Laboratoire National d´Hydraulique et Environnement
MHWS	Mean high water (level) at spring tides
MSL	Mean sea level
NERC	Natural Environment Research Council
OD	Ordnance Datum
POL	Proudman Oceanographic Laboratory
POLCOMS	POL Coastal Ocean Modelling System
SLR	Sea-level rise
SPM	Suspended particulate matter
T-D	"Top-down" approach using broad-scale concepts or empirical relations.
TE2100	*Thames Estuary 2100* (project)
UK	United Kingdom
UKCIP	UK Climate Impacts Programme
UoP	University of Plymouth
1-D	one-dimensional (along estuary)
2-D	two-dimensional (usually here the two horizontal dimensions)
3-D	three-dimensional

x

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 transport, renewable energies, cooling water abstraction, aggregate mining, fishing, habitats, agriculture, waste disposal, and leisure activities. Estuarine environments are facing increasing rates of change: raised temperature, changing freshwater runoff, changes in sea level, likely increases in flooding events.   Outcomes depend on hydrodynamics and on sediments, which affect the ecosystem (through intertidal / subtidal morphology, dynamics of biogenic particles and scattering of light) and affect water quality (as many pollutants adhere to fine sediments or a contaminated bed is eroded). However, the sediment regime is challenging to predict.

Methods are needed to predict changes in estuary functioning and so improve our ability to manage estuaries sustainably (EA and Defra, 2006). For example, measures to minimise flood risk and threats to habitats (from human activities and climate change) need 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 Estuaries Research Programme (ERP) was formulated
>   (i) to develop techniques to predict large-scale, long-term morphological changes and the resulting sediment related impacts in estuaries (including water quality aspects) and
>   (ii) to assess their consequences for estuarine management (HRW, 1996; Pye, 2000; EMPHASYS consortium, 2000a,b).

1.1 Approaches to predicting morphology

"Bottom-Up" (B-U) process-based models are mathematical (usually numerical), spatially-resolving and predictive (usually time-stepping). For hydrodynamics, sediment transport and evolution of the bed, they use fluid-dynamical and related equations. 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, simulating sediment transports is more problematic. Moreover, evolving morphology often depends on small imbalances between ebb and flood transports; errors accumulate, so the validity of longer-term (decadal) simulations is uncertain. Net sedimentation depends on subtle and complex interactions, e.g. intra-tidal between surficial sediments and bed roughness, spring-neap variation in salinity intrusion, seasonal sediment supply and river flow, episodic events and underlying bed structure.

"Top-Down" (T-D) approaches are generally either geomorphologically-based, derived from statistical analyses of observed long-term morphological evolution, or 'rule-based', derived from a whole-estuary regime concept such as volume, energetics, entropy etc. They range over concepts of trend analysis, form characterisation, regime relationships, translation or "rollover" with rising sea level, accommodation space, sediment budgeting, tidal asymmetry and

equilibrium along-axis profile. Such approaches may be stable for long-term predictions; however, some concepts (regime relationships, equilibrium) are in principle limited to their basis in data; the extent to which they can be extrapolated is uncertain; they may also 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 and distributions given by B-U models. An Inverse method uses a sequence of bathymetries to infer an effective source distribution for bed evolution according to a B-U – based diffusion-type equation.

ERP Phase 1 (1998-2000; HRW, 1997) included a critical analysis of B-U model limitations alongside a review of T-D models. ERP Phase 2 recognised the need to use both approaches and gave priority to developing Hybrid models combining B-U and T-D elements. French *et al.* (2002; FD2115) provided an updated vision of Phase 2: (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 *Development of Estuary Morphological Models* addressed (iii) by developing Hybrid (50-year) mophological prediction models. The developed models were used to assess impacts of intervention and of global climate change on flood forecasting and associated defences and habitats. FD2107 links with ERP2 aspects (ii), (iv), (v) and includes
- extensions to the FutureCoast database
- coupling of hydrodynamic and morphological models;
- better representation of estuarine sub-systems (including intertidal);
- alternative concepts of equilibria;
- improved representation of sediments in models.

In this report we describe B-U and Hybrid model developments and applications (Sections 2 and 3). In Section 4 we seek to improve confidence through results from eight varied UK estuaries, applying existing and new B-U, T-D and Hybrid models; an ensemble approach with attendant sensitivity analysis. Impacts of future estuarine morphologies on changes in flood risk and habitats are outlined in Section 5. Extensions to the Future-Coast database are described in Section 6. A *Discussion and Conclusions* Section 7 completes the main report. Appendices expand on sections of the report:

A) *Guidelines for application of Bottom-Up estuarine models to assess impacts of global climate change and interventions on flood risks and sediment regimes*, and a supplement *SWAN modelling of Liverpool Bay including Dee, Mersey and Ribble Estuaries* relate to Section 2;

B) *Shell Hybrid model Interface manual* relates to Sections 3.1-3.2;

C) *ASMITA manual*, *Area and volume changes in an estuary* and *Application of ASMITA to the Thames Estuary* relate to Section 3.3;

D) *Development of a Lagrangian morphodynamic model for sandy estuaries and coasts* relates to Section 3.6;

E) *Hybrid Modelling of Managed Realignment* relates to Section 3.7;

F) *Intercomparison of models predicting estuarine morphology* relates to Sections 3 and 4;

G) *Predictions of estuarine morphology* relates to Section 4;

H) *Morphological change and estuary management* relates to Section 5;

I) *Morphological modelling scenario comparisons using the Analytical Emulator for WP2.7 FD2107* relates to Sections 3.5 and 4;

J) *Enhanced UK Estuaries database: explanatory notes and metadata* relates to Section 6.

[The numbering of sections in this report does not correspond to contracted project work-package numbering, although the work-package structure is followed closely].

2. Application of Bottom-Up models in estuaries subject to morphological changes

The objective here is to explore sensitivities of model predictions of water levels and sediment transports in (three) estuaries. Components of water level are mean sea level, tides, surges and waves (Section 2.1). 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 values of fluid-dynamical and sediment properties affecting sediment dynamics, over ranges indicated by climate change scenarios, context variability or uncertainties in model formulation (Section 2.2). Existing B-U models (developed outside FD2107) were used for these studies. Comparison with similar runs of a Hybrid model developed in FD2107 is in Section 4. Appendix A, *Guidelines for application of Bottom-Up estuarine models to assess impacts of global climate change and interventions on flood risks and sediment regimes*, gives more detailed discussion of factors to consider, such as climate-change scenarios, when applying B-U models.

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

Hydrodynamic models have been applied to predict mean-sea-level, tidal and wave contributions to water levels in the Mersey, Dee and Ribble. Sensitivities were investigated: to sea level; to tidal range; to river flows (Mersey case); of waves to wind strength. The models were as follows.

POLEST 2D is a finite-difference hydrodynamic model with wetting and drying, based on a rectangular 'C-grid'. It solves equations for conservation of mass and momentum discretised on a depth-averaged grid. Finite-difference solutions are explicit. Rectangular (strictly polar) grids are used horizontally. 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. Model boundaries are generally in water depths of 20m: for the Mersey, an east-west line between New Brighton and Gladstone Lock; for the Dee, lines north from Hoylake and Rhyl with a northern boundary through Hilbre Swash; for the Ribble, lines west from Lytham and Formby Point to a north-south line approximately 3 km offshore.

POLEST "2.5-D" is a three-dimensional (3-D) version of POLEST 2D; the vertical current structure at ten equally-spaced levels is derived from the sea surface slope using an assumed bed-friction coefficient and viscosity (i.e. the vertical structure is controlled by the 2-D solution). Vertical diffusivity = vertical eddy viscosity (E) = fUD, where f is the bed friction coefficient, U the tidal current amplitude and D water depth. [With a Lagrangian particle-tracking sediment-transport module, this model is the basis of simulating suspended sediment concentrations and fluxes in the next Section 2.2].

POLCOMS (POL Coastal Ocean Modelling System) is a 3-D 'B-grid' baroclinic model. It 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) is 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. SWAN was developed especially for shallow water areas and has been used extensively. It was applied here for waves with various combinations of wind speed and water level (tide + mean sea level + surge); see Appendix A1 *SWAN modelling of Liverpool Bay including Dee, Mersey and Ribble Estuaries*.

Simulations and sensitivity tests were completed using the POLEST models and SWAN. The most comprehensive results are for the Mersey (Lane, 2004). Further results are described in Section 4 and accompanying reports: Appendix F *Intercomparison of models predicting estuarine morphology* and Appendix G *Predictions of estuarine morphology*.

Modelled responses to *raised mean sea level* (MSL) were outlined by Lane (2004; Section 4.2.1 and figure 5 therein) for the Mersey. Differences are most notable in the Z_0 (mean level) and M_2 tidal constituents; amplitude differences are small near the mouth of the estuary but increase upstream; an additional 1-2 m here is a sizeable fractional increase in water depth. Changes in surface area and tidal prism from 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. For example, Ribble low-water (LW) channel volume increases by 80 per cent for 1 m MSL rise. The Mersey is the least sensitive, e.g. an increase of 18 per cent in mean LW volume for 1 m MSL rise.

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 when Q_f is increased to 600 and then 900 $m^3 s^{-1}$ (Lane 2004, Section 4.2.4).

In lieu of simulating dynamical *storm surges*, a 50-year surge level +1.73 m was added to present levels (including tides). The results generally extend the trend from MSL + 0.3 m and + 1 m. [Such a simple increase may underestimate inner-estuary levels, after funnelling in narrows and shallows. However, the Mersey, Dee and Ribble estuaries are short (lengths L = 45.6, 37.0, 28.4 km) and deep (H > 8 m) at High Water. Thus high levels adjust in a time $O(L/(gH)^{1/2}$ < 1.5 hours; extreme high levels should closely follow external levels].

The *wave* modelling generally showed monotonic increase of wave height, period and set up with increasing wind speed and water depth (Appendix A1).

Prediction of flood levels for coastal defence involves total water levels from tides, surges and waves, which have complex interactions. Hence calculation of return periods for particular flood levels requires use of a *Joint-Probabilities* method (Dixon and Tawn, 1997), not considered further here.

2.2 Lagrangian particle-tracking model and application to the Mersey

This section demonstrates application of a B-U sediment transport model using Lagrangian particle tracking. It also explores sensitivity 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. Lagrangian particle tracking was included via a 'random-walk' module, simulating erosion, suspension and deposition of (typically) 10^5 independent sediment particles. In the simulations, erosion is the conventional function of excess bed shear stress. Suspended particle motion is represented by random vertical excursions, magnitude $\sqrt{(2\,E\,dt)}$ each time-step dt, and advection horizontally with the flow. Deposition is via settling velocity; $W_s\,dt$ in each time-step. The (horizontal and vertical) location of each particle is logged. Their origin, size, shape, attached chemistry, time since deposition etc. can also be stored. Hence this approach helps to incorporate (e.g.) consolidation and time-varying bed roughness as a function of surficial sediments. Bathymetry updates and explicit wave modelling were not part of this application.

Sensitivities to the following dynamical and sediment properties were studied:
- vertical shear (normally included; calculations repeated with $\partial \mathbf{u}/\partial z = 0$)
- depth-varying eddy viscosity $E(1+2z-3z^2)$,
- time-varying eddy viscosity (1/4-diurnal amplitude $0.25E$ peaking 1 hr after peak current),
- additional estuarine circulation
  $U(z)^E = g\,S_x\,D^3/E(-z^3/6 + 0.2687z^2 - 0.0373z - 0.0293)$
  where (S_x, D, z) are (salinity gradient, depth, vertical coordinate/D),
- rate of marine sediment supply (halved),
- sediment size d (in µm); W_s (in m/s) $= 10^{-6}\,d^2$.

The simulations all assume an unlimited supply of sediment at the mouth of the estuary; in reality, supply is more likely to be limited, e.g., consolidation, other shielding, etc. It may be that the class of sediment being modelled is finer than the actual sediment (coarser sediment does not travel as far in to the estuary, and concentrations are less).

Table 2.2.1 "2.5-D" results for Mersey sediment quantities
(units 10^3 tonnes) **with various grain sizes** (W_s (m/s) $= 10^{-6}d^2$ (µm)).

Diameter d (µm)	In suspension			Input, mouth		Deposited			
	Neap	Spring	Average	Neap	Spring	Neap	Spring	Per year	% of Exchange
10	156.2	1531	640	57.53	2509	28.40	420.8	66,400	10.5
20	21.5	206.6	75.75	9.80	490.1	-0.99	61.07	5000	5.9
30	3.97	34.77	15.03	5.86	107.0	-0.67	4.93	1000	2.8
50	1.77	18.07	7.47	4.14	71.20	-0.05	6.12	1400	6.2
70	0.79	9.28	3.69	2.93	43.83	0.56	6.49	1800	12.3
100	0.26	4.48	1.64	1.15	25.09	0.10	5.62	1400	18.6

Results of these simulations are listed in Lane and Prandle (2006) and tables 2.2.1-3. Here *In suspension* is a mean through the 12.4-hour tidal cycle; *Input* is the quantity entering the estuary per tide.

Table 2.2.1 shows average suspended concentrations decreasing a little faster than d^{-2} (where 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. [In practice the smaller particles are liable to aggregate to flocs with settling velocity W_s larger than the calculated values assumed here].

Table 2.2.2 "2.5-D" results for Mersey sediment quantities
(units 10^3 tonnes) **with varied model assumptions (W_s = 5mm/s)**

	In suspension			Input, mouth		Deposited			
	Neap	Spring	Average	Neap	Spring	Neap	Spring	Per year	% of Exchange
$\partial \mathbf{u} \partial z = 0$ (2-D)	0.91	10.62	4.23	3.11	46.85	0.38	8.76	3000	18.1
$E(z)$ $= E(1+2z-3z^2)$	2.09	19.57	8.29	5.09	80.80	-0.24	8.87	2500	9.0
$E(t)$	1.36	10.73	4.80	2.76	47.71	0.33	7.12	2400	15.2
$U(z)^E$	0.83	10.13	3.99	3.10	47.32	0.37	7.52	1900	12.5
Bed friction x 0.5	0.37	4.09	1.66	1.18	20.31	0.25	2.72	1200	15.2
Bed friction x 2	1.37	16.06	6.39	4.31	64.85	-0.26	7.90	2200	9.7
Marine supply x 0.5	0.37	5.14	1.96	1.09	25.25	-0.32	3.28	500	7.4
Baseline	0.76	9.78	3.81	2.83	46.97	0.43	7.08	1900	12.6

Table 2.2.3 "2.5-D" results for Mersey sediment quantities
(units 10^3 tonnes) **with varied model assumptions (W_s = 0.5mm/s)**

	In suspension			Input, mouth		Deposited			
	Neap	Spring	Average	Neap	Spring	Neap	Spring	Per year	% of Exchange
$\partial \mathbf{u} \partial z = 0$ (2-D)	8.58	70.21	31.03	9.14	182.7	-0.88	10.73	2200	3.8
$E(z)$ $= E(1+2z-3z^2)$	21.91	476.7	167.6	11.49	1020	-1.20	118.2	9300	5.9
$E(t)$	8.60	124.6	47.21	8.41	289.5	-1.17	30.70	3200	5.1
$U(z)^E$	7.78	121.2	45.21	7.72	285.8	-0.99	26.61	2700	4.3
Bed friction x 0.5	4.08	23.55	11.84	4.44	60.80	-0.58	2.83	800	3.5
Bed friction x 2	19.11	134.8	62.73	17.92	310.1	-1.51	23.94	3000	3.6
Marine supply x 0.5	6.62	61.39	26.10	5.28	134.4	-0.48	6.31	800	2.6
Baseline	8.32	116.8	44.54	6.71	271.4	-1.59	24.30	2500	4.2

Tables 2.2.2 and 2.2.3 show rather little effect of the estuarine circulation $U(z)^E$ in this case (the Mersey). By contrast, there is an effect of assuming $\partial \mathbf{u}/\partial z = 0$; frictional shear (in the Baseline simulation) reduces suspended coarse concentrations slightly and net deposition considerably, whereas it slightly increases suspended fines and their deposition. There are effects via current amplitude and more subtly via phase changes (Prandle, 2004b). 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 by halved marine supply to a yet-smaller fraction.

Further effects are discussed in Prandle and Lane (2005):
- varied numbers of elastic reflections off the bed that a particle is allowed if the random vertical displacement would take it below the bed;
- mixed sediments and consolidation (as decreasing erosion rate)
- extreme river flow 2000 m^3s^{-1} (c.f. 20 m^3s^{-1}) not greatly affecting the sediment regime.

Effects of raised mean sea level (+ 0.3 m, +1 m) and greater tidal range are treated in the Section 4 comparisons of models and of estuaries.

POLEST "2.5-D" with Lagrangian particle-tracking was applied to the Mersey (figure 2.2). Separate simulations were run for fine and coarse sediments (settling velocity 0.5 mm/s, 5 mm/s respectively). [Corresponding grain sizes d are 22 and 70 µm with the above formula]. Sediment fluxes at the mouth of the Mersey, and suspended sediment concentrations at regular intervals along the estuary, were compared. Results are summarised in table 2.2.4 and detailed in Lane and Prandle (2006).

Table 2.2.4 POLEST "2.5-D" results for fine and coarse sediments in the Mersey

	Mean exchange (tonnes/tide)	Deposited (tonnes/tide; %)	At estuary mouth	
			Main period(s) of variation	Time of peak concentration
Fine	110,000	7000 (~6%)	Semi-diurnal (advection) + quarter-diurnal at springs	3 cycles after highest spring tide
Coarse	22,000	3000 (~12%)	quarter-diurnal (local resuspension)	At highest spring tide

Upstream in the estuary, the fine sediment also shows quarter-diurnal variations and concentration is maximal up to seven cycles after the highest spring tide. Section 4 describes the results for effects on sediment flux of raised MSL (+ 0.3 m) and winds (as enhanced bed-stress only; surges and waves were not considered). It was assumed that the marine supply of sediment is unlimited (corresponding to the flow at the estuary mouth), and that bathymetry remains fixed over the short time-scale effectively considered.

These results (specific to the Mersey) may not be applicable to all estuaries. However, the strong dependence of modelled sediment transport on particle size, source and frictional effects (eddy viscosity and shear here; turbulence in more complex models) 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. Such a B-U particle-tracking model may usefully be one of an ensemble of methods for prediction in estuaries.

Figure 2.2 Modelled suspended tracked particles at hourly intervals in the Mersey

3. Development and application of new Hybrid models

This section describes developments in FD2107 of several new Hybrid models, albeit some build on previously developed models. The following are described in turn: Hybrid Regime model, ASMITA, Inverse model, Analytical Emulator, Morpho-SandTrack, Realignment model (in the order of project work packages). As indicated in respective sections, more detail in four cases is given in a corresponding Appendix. Outline characteristics of these models, and the "2.5-D" model (Section 2) developed previously, are drawn together as Table 7.1.

3.1 Development of Shell Hybrid Regime model

A description of the developed model, its basis in HRW *et al.* (2006) discussion of regime theory, and especially how to use the model, is given in Appendix B *Shell Hybrid model Interface manual*.

3.1.1 'Shell' interface conceptual design

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). The purpose is to predict long-term (decades to centuries) change in estuaries. This Hybrid approach enables the user to make informed decisions as to morphological effects of climate change, engineering works and so on.

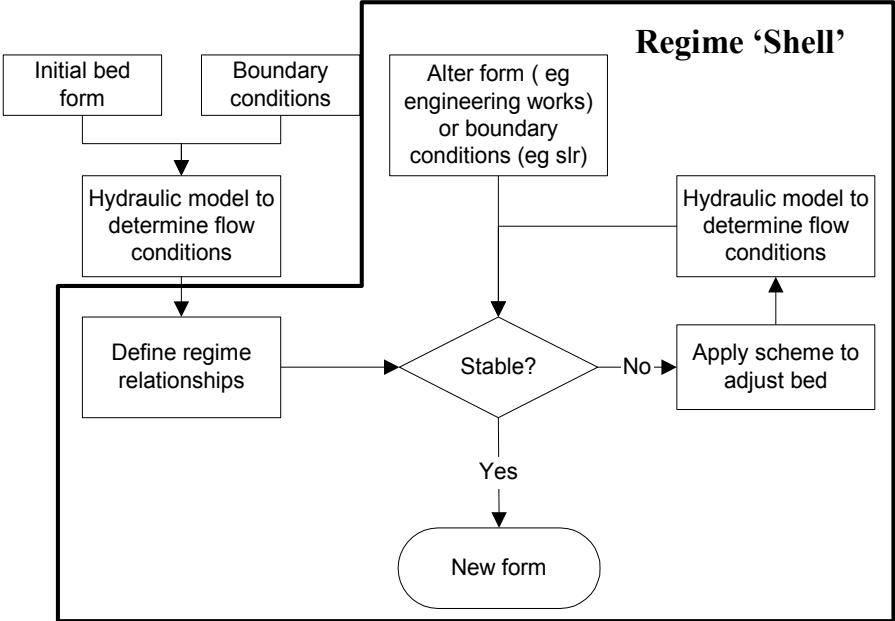**Figure 3.1.1 Hybrid Regime flow diagram.** This shows the process undertaken to perform an analysis. The Shell interface provides a mechanism to control this process in one standard interface.

Figure 3.1.1 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 within a Microsoft Windows environment and is written in the program language Visual Basic and Matlab. The interface is designed as a series of forms that allow the user to select a type of regime algorithm and couple this to a specific model simulation. In addition, routines have been incorporated that provide the user with additional information about the estuary under investigation; this includes intertidal area and tidal asymmetry. The code has been written in a modular format with an open architecture approach to allow other users to add to and develop upon the existing routines.

3.1.2 Regime theory for estuaries

Regime theory characterises links between hydrodynamics and estuary morphology by a simple empirical formula (or formulae), describing an estuary equilibrium (or quasi-equilibrium) and subsequent evolution following a disturbance to the system. The theory thereby predicts how the estuary will respond to changes in estuary form (reclamation, engineering works, etc.) or in forcing conditions (sea level, tidal range, etc.) in order to return to the existing regime condition. The theory makes two basic assumptions:
- the estuary will achieve some form of equilibrium state
- the existing estuary form can be characterised by a function describing the equilibrium relation.

Regime theory for estuaries was first described by Langbein (1963) who related cross-sectional area A, top width B and mean hydraulic depth H to discharge Q (but the exponents' derivation from entropy theory is flawed; HRW *et al.*, 2006):

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

The constants (p, q, r) are obtained by a fit to the results of the initial model run.

These exponents (p, q, r) form the basis of regime theory for use in estuaries. Within the Shell interface, the regime condition is defined as the initial estuary geometry and hydrodynamic conditions, assuming that the current estuary geometry is in a stable equilibrium. The existing regime is thus defined in terms of a power law relationship between the maximum discharge during the tidal cycle and the simultaneous cross-sectional area of flow. The power law relationship is assumed to represent the equilibrium condition prior to the change in forcing conditions.

Thus far it has been assumed that the relationship between estuary geometry is based on the maximum discharge through the cross-section. However, it may be better to represent the relationship of the estuary morphology in terms of cross-sectional area at maximum velocity (i.e. expected maximum sediment mobilisation). The Shell interface allows the user to select either peak discharge or velocity as the means to characterise the estuary regime.

Another option in the Shell is to use a polynomial relation between maximum discharge and cross-section area, so allowing greater freedom in estuary form. A power-law relation between A and Q may not apply due to the specific nature of the estuary in question. HRW *et al.* (2006) discuss factors that may prevent a simple relation: non-uniform influence of waves, geological constraints, local

sediment supply, varied sediment characteristics with (erosion) depth, different deposition-erosion processes in upper intertidal areas.

Scatter around the derived best-fit regime relationship (between peak discharge and simultaneous cross-sectional area data points) is an outcome of such factors. Thus validation exercises for the Shell interface on estuaries along the east coast of England have shown significant scatter. Forcing the regime relationship on the existing form-discharge variation along the estuary would, in certain cases, imply a substantial change in some of the cross-sections, before any perturbation were introduced. To overcome this, options have been implemented within the Shell interface. These are:

- iterate the model (figure 3.1.1) with no change in the forcing conditions until the fit of the characteristic regime equation is within a specified limit (typically about 5 per cent);
- assume the initial estuary is in an equilibrium state and retain the cross-section deviations from the best-fit regime relationship by making relative, rather than absolute, adjustments.

HRW *et al.* (2006) discuss these options, and other aspects of best practice for applying regime theory in general, in view of these factors and uncertainties; they describe some case studies but do not focus on the Hybrid approach here with an underlying detailed hydrodynamic model.

3.1.3 Morphological adjustment

Morphological updating of the cross-sections within the Shell interface occurs if the regime condition for that particular cross-section is not met. The update procedure has a number of conditions applied, and assumes some physical constraints, including the following.

- The cross-section geometry is not adjusted above the maximum water elevation; this high-water value will typically vary along the estuary.
- A horizontal and vertical limit may be applied to the individual cross-sections preventing adjustment beyond a specified extent. This extent may be defined by a Holocene surface, sea walls, cliffs, bridge piers etc.
- The cross-section adjustment routine uses linear stretching (vertically and horizontally). No variation in the flow velocity over the section is considered. The routine adjusts the section according to the required width and cross-sectional area, based on the regime parameters.
- The new cross-section geometry forms the basis of the next iteration of the hydrodynamic model. If the regime criterion has not been achieved then another iteration of the hydrodynamic model is performed (figure 3.1.1). This iterative process continues until the change in successive cross-sectional geometries has converged to within a specified margin of the regime criteria.

3.1.4 Geological and physical constraints

In order to understand any future morphological response to sea-level rise, or engineering works, the sub littoral geology and physical constraints of the estuary need to be considered. Underlying clay, bedrock or other hard substrata can prevent the estuary from widening or deepening. Equally, physical constraints imposed on the estuary, by sea-defence walls, quay walls etc., will also prevent the estuary geometry changing. Long-term predictions

must take these factors into account before any future morphological adjustments can be determined. The importance of such constraints is highlighted by work undertaken for the Severn Estuary Coastal Habitat Management Plan (CHaMP), which showed the significance of the physical constraints in preventing development of intertidal areas under a range of sea-level rise scenarios. Without the constraints in place, the estuary continues to widen, whereas in reality this would be prevented from happening by the presence of physical constraints. Application of the physical constraints is essential, particularly when considering coastal squeeze and estuary rollback, for example. Wright and Townend (2006) give a more detailed description of the Hybrid Regime model in this context.

3.1.5 Outputs and limitations

The dynamic approach allows the estuary to evolve without the need for the user to undertake any further actions. A new estuary morphology is created based on the change or changes in the forcing conditions within the estuary. However, the new shape of the estuary is subject to interpretation, because the morphology of the estuary is based on achieving the correct area/discharge relationship. The estuary shape is altered based on a set of parametric fits and not by the physical conditions (threshold of sediment motion). The bed update uses linear stretching (with consideration of the geological constraints) to match the updated dimensions.

The software calculates intertidal and plan areas, volumes and hydraulic information, and provides information on the hydrodynamics and regime simulation. With Mike11 software this information is broken down into individual network branches (if present). A graphical user interface (GUI) has been developed to allow the user to view and amend cross-sections. An analysis of the tidal asymmetry (tidal excursion, net slack duration, slack gradient and Dronker's asymmetry ratio) can be undertaken within the Shell interface. The morphological tidal period can also be determined; this routine calculates the theoretical period within the simulation that represents the 'morphological tides'. These tides alone can be run to cover the entire simulation period. The 1-D energy terms are also calculated.

Currently the Shell cannot simulate waves and so lacks their effects:
- extra subtidal transport at the estuary entrance causing widening there (De Jong and Gerritsen, 1984);
- influence on the upper profile of intertidal areas.

It also lacks explicit treatment of sediments. The project FD2116 proposed distinct regime algorithms for sandy and muddy estuaries (HRW *et al*., 2006).

3.1.6 Software and operating environment

The software is open source code. The majority is in Visual Basic 6. Graphical plots have been created using Matlab Version 2006b. Neither Visual Basic nor Matlab is required by the user to install or run the Shell Hybrid Model interface.

The code is annotated and designed to allow experienced users to alter or add code. Modularity allows experienced users easily to add to or modify existing

routines. The software has been designed for Microsoft Windows allowing a familiar and easy-to-operate setting.

Minimum requirements for running the Shell Interface are:
- 200 MHz Pentium PC;
- 128 Mb memory minimum; 256 Mb memory recommended;
- Hard disk with 200 Mb space available;
- 1024x768 resolution, high-colour (16 or 24-bit) graphics card and screen;
- CD-ROM drive;
- Windows 2000 or Windows NT 4.0 (or later versions).

The Shell interface can be run on any standard Windows-based network, but this may require longer run times. When modelling many cross-sections, a faster processor and more memory will improve performance. Running simulations locally is recommended; some additional tools and graphical components may not be available if operated via a network connection. Detail to run the system is given in Appendix B *Shell Hybrid model Interface manual*.

3.2 Application of Shell with regime constraints as a Hybrid model

3.2.1 Estuaries studied

Hybrid Regime models of five estuaries have been constructed to investigate how a range of estuaries evolve in response to changes in forcing conditions. The estuaries are: Blackwater, Humber, Mersey, Southampton Water, Thames. The hydrodynamic models of the estuaries are shown in figures 3.2.1a-e. The changes to either the water level or discharge driving boundaries made in the hydrodynamic model are described in table 3.2.1.

Table 3.2.1 Scenario conditions applied in 1-D Hybrid Regime modelling of the five estuaries

Scenario ID	Scheme
Baseline	Existing conditions, the 1-D hydrodynamic model is calibrated against measured data
MSL + 0.30 m	An increase of 0.3m (6 mm/yr) over 50 years is added to the water level driving boundary
MSL + 1m	An increase of 1m (20 mm/yr) over 50 years is added to the water level driving boundary
Tidal range + 2%	An increase in the tidal range of 2% over 50 years applied at the seaward boundary
River flow + 20%	A 20% increase in freshwater discharge over the next 50 years
All changes together (MSL+0.3 m)	A 20% increase in discharge, 2% increase in tidal range and a 6 mm/yr increase in MSL over the next 50 years
All changes together (MSL+1m)	A 20% increase in discharge, 2% increase in tidal range and a 20 mm/yr increase in MSL over the next 50 years
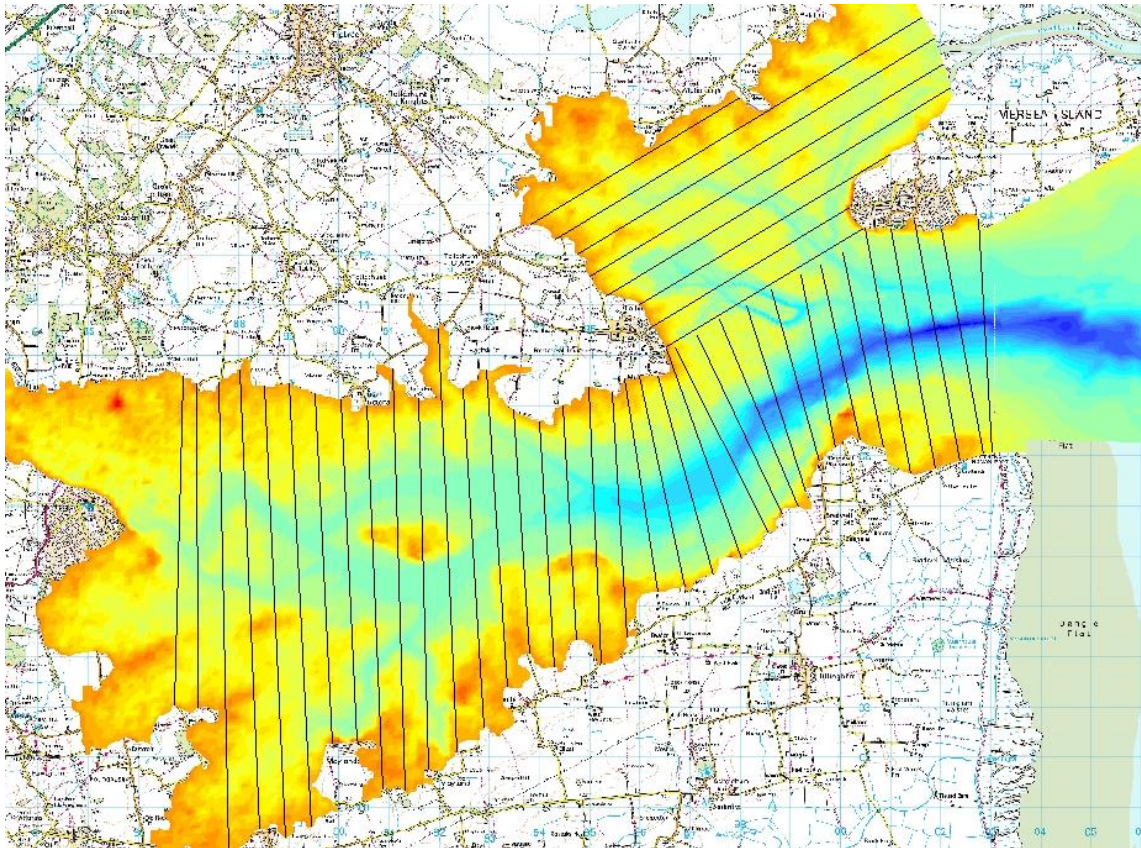
Figure 3.2.1a 1-D hydrodynamic model of Blackwater Estuary. Cross-section positions are shown.
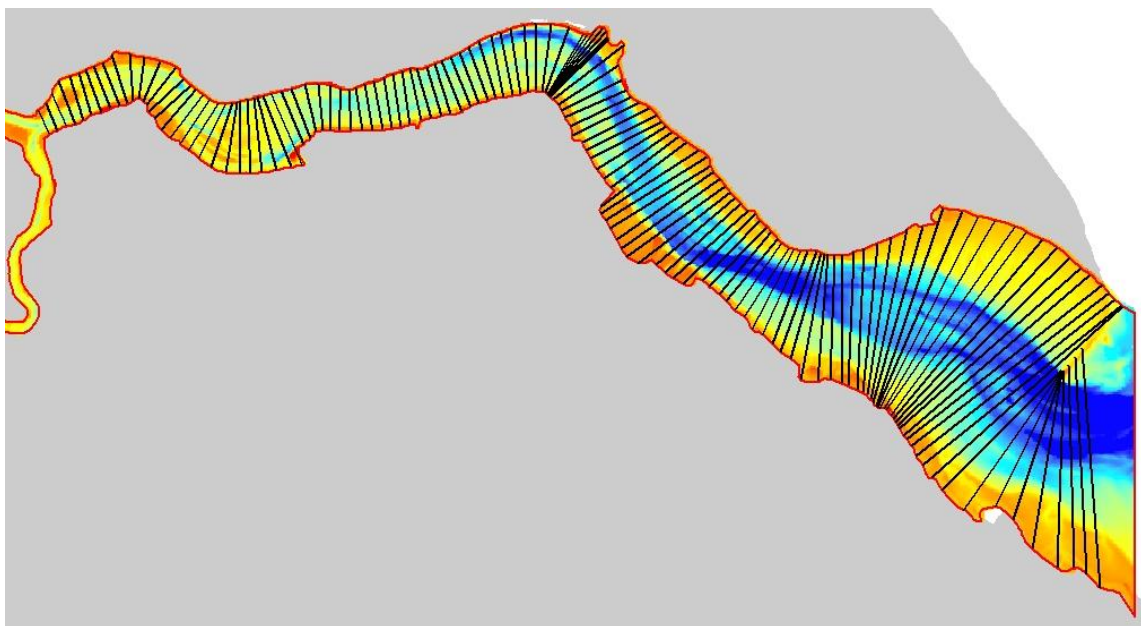
Figure 3.2.1b 1-D hydrodynamic model of the Humber Estuary. The black lines represent the cross-section positions used in the Hybrid Regime model.   The Humber model extends from the mouth at Spurn to Trent Falls. The rivers Ouse and Trent were included only as discharges into the main estuary.
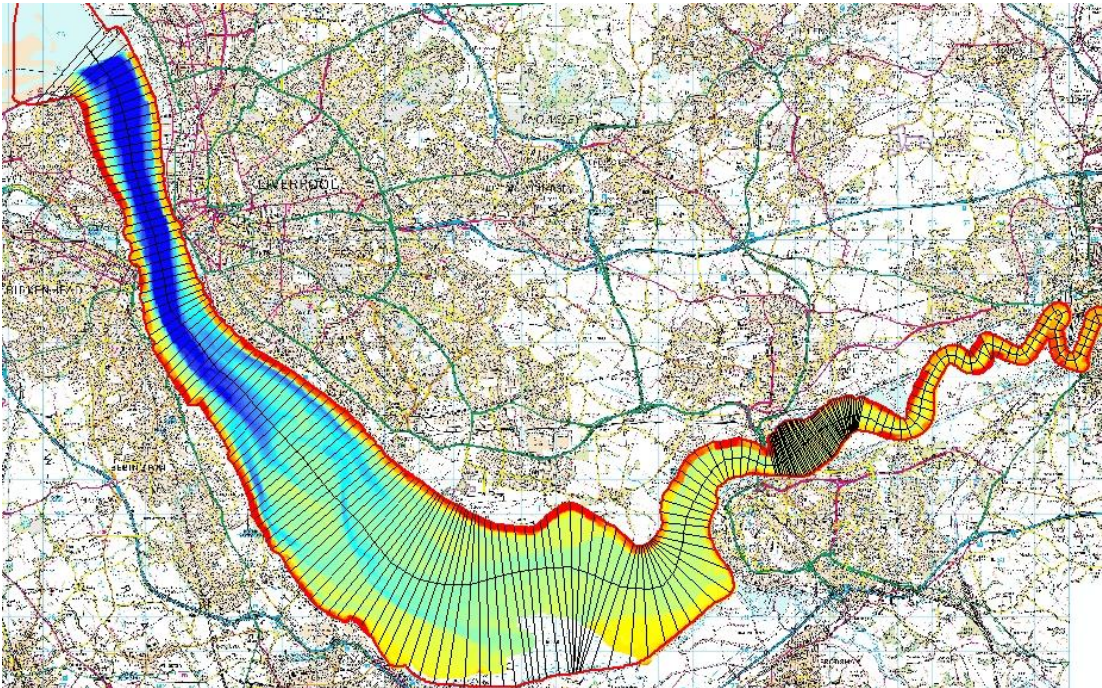
Figure 3.2.1c 1-D model of the Mersey Estuary. Cross-section positions are shown. The estuary extends from Gladstone Dock to Howley Weir. Finer-resolution cross-sections were applied in the inner estuary around Widnes in order to test applicability of the model to varying spatial information.
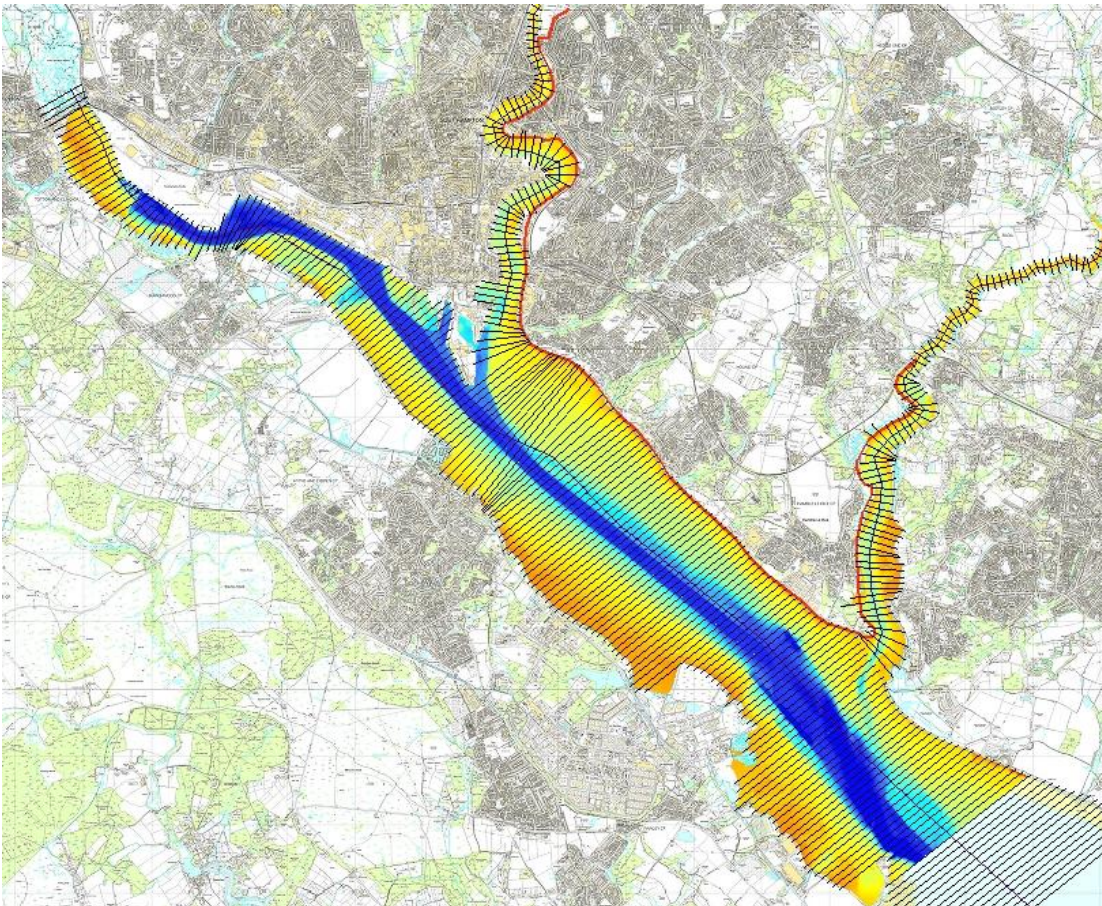
Figure 3.2.1d 1-D model of Southampton Water. Cross-section positions are shown. The 1-D model includes the Hamble, Itchen and Test tributaries; the Shell allows for multiple branching.
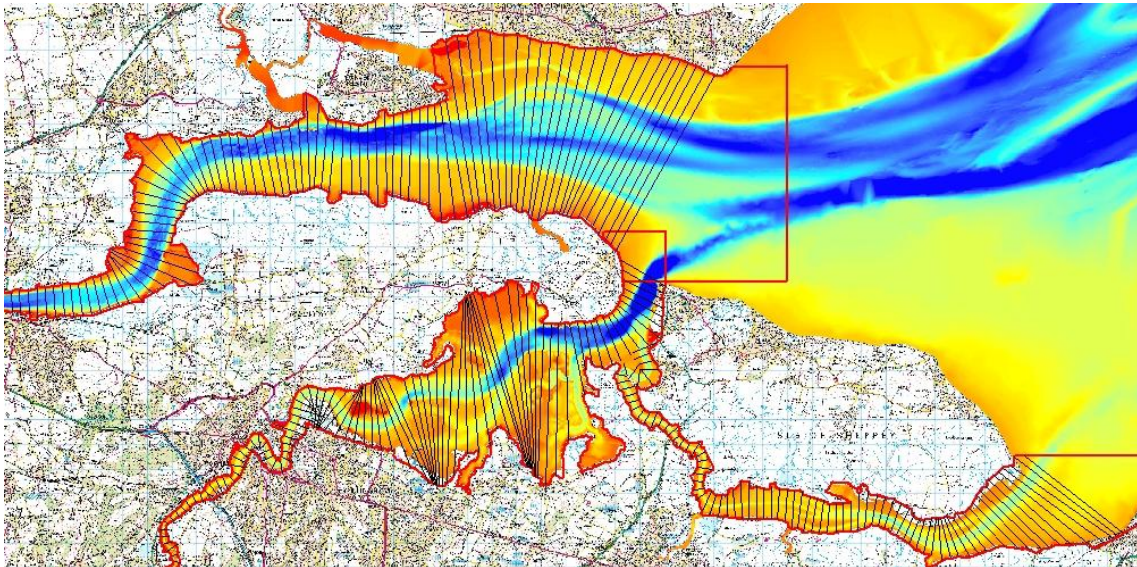
Figure 3.2.1e The outer Thames Estuary. The selected cross-section positions are shown. The Thames model extends from Southend to the tidal limit at Teddington. Also shown is a model for the Swale and Medway Estuaries; these estuaries were not tested.

Calibration/validation was undertaken for the underlying 1D hydrodynamic model, ensuring the correct water levels and discharges were simulated.

Hindcasting would be the best approach to validate the Hybrid Regime model. Good historical data would provide means for model validation. However, this has proven difficult to achieve in practice, because:

- all changes in morphology shown in available historical bathymetry were influenced by anthropogenic activities (all had undergone significant engineering works or modifications);
- typically, the estuaries studied (especially Southampton Water, Thames, Humber, Mersey) have been (and continue to be) heavily engineered with regular maintenance dredging. Hence natural trends in estuary behaviour are disguised in historical records.

3.2.2 Application

Model outputs are:

- Volumes (m^3) (HW, LW, Peak Discharge)
- Areas (m^2) (HW, LW, Peak Discharge)
- Intertidal area (m^2)
- Water levels (m)
- Velocity (m/s)
- Discharge (m^3/s).

The existing estuary state is assumed in regime theory to be in a stable regime. If the estuary is in a period of rapid change or instability then regime modelling is unsuitable. In this study 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.

For the assessment of potential future morphological change in the selected estuaries, the predicted percentage change in intertidal area is considered in each case. Rates of loss have been calculated using a spatially-varying water surface and dynamic estuary morphology. Direct comparisons with previous estimates obtained using alternative methodologies may not be appropriate.

3.2.3 Results

Scenario 1 - 6mm/yr sea-level rise. The Humber and Thames estuaries respond in a similar manner to sea-level rise with a consistent rate of loss in intertidal area of 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 since this can be accommodated within the form of the estuary. However, by 2050 there is predicted to be a small net loss of intertidal area. 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 response of the Blackwater Estuary is quite different from the others; it appears to experience a consistently higher rate of intertidal loss, in excess of 0.15 per cent per year, over the initial period of 45 years followed by a rapid increase over the next 5 years. Care is required in the interpretation of these findings; the Blackwater response could be due to the unusual form of the estuary and limitations of the morphological updating routines used in the current version of the Hybrid Regime model as applied here.

Scenario 2 – 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 out of the five estuaries. The Blackwater is an exception, with a much greater extent of intertidal loss, up to 35 per cent over the 50 years. From this assessment it thus appears that the Blackwater is particularly sensitive to faster sea-level rise.

Scenario 3 – 2 per cent increase in tidal range. For most of the estuaries there is limited response in terms of intertidal change as a result of the moderate increase in tidal range. An exception is Southampton Water which over a 50-year period is predicted to have a net gain in intertidal area of almost 4 per cent. The high rate of predicted 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.

Scenario 4 – 20 per cent increase in river flow. The Humber and Thames estuaries are least sensitive to a change in river flow, probably because these are larger estuaries and experience much variability in river inflow. The Mersey is predicted to experience a loss in intertidal area with increased river flow. The Blackwater again appears to be particularly sensitive to future changes in environmental conditions; after an initial period of intertidal loss, a longer term net gain in intertidal area is predicted, 0.6 per cent over the 50-year period.

3.2.4 Conclusions

An aim of FD2107 is to provide a better understanding of estuary change (habitats, water levels, etc.) over periods of decades. An example of the change in future flood risk for the Humber Estuary is given in Section 5.

The Shell Hybrid Regime model has been extensively used and tested (with calibration of the 1-D hydrodynamics) on the key estuaries identified in the ERP. It has provided a successful basis in which to assess the likely change in estuary hydrodynamics and morphology over decades.

3.3 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 3.3). Under constant hydrodynamic forcing (in particular constant mean sea level), each element is assumed to tend towards a morphological equilibrium definable as a function of hydrodynamic forcing and basin properties (van Goor *et al*., 2003). Empirical relationships are used to 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).

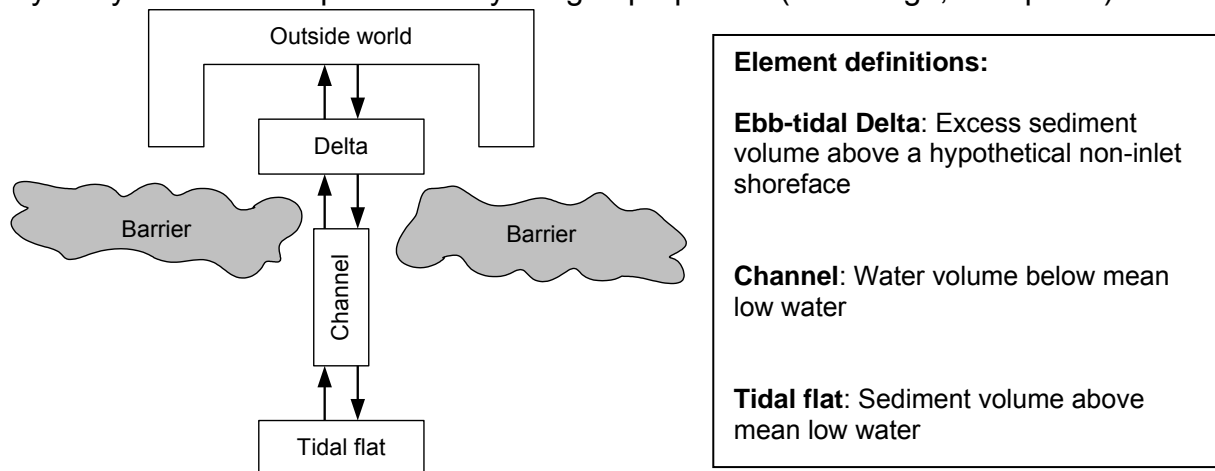**Figure 3.3 ASMITA schematisation and element definitions** (from van Goor *et al*., 2003)

The morphological elements in ASMITA (intertidal area, channels, ebb-tidal delta) interact through sediment exchange. This interaction plays an important role in the morphological evolution of the whole system, as well as that of the individual elements (van Goor *et al*., 2003). If morphological elements are not

present (e.g., ebb tidal delta), reduced models can be applied. Long-term, residual sediment exchange is assumed to occur between adjacent model elements; development of the tidal inlet is assumed not to affect availability of sediment in the outside world, represented by a global equilibrium concentration (van Goor *et al.*, 2003). Volume changes within elements are described by equations 3.3(1-3).

$$dV_f / dt = Ws_f * A_f * (c_f - c_{fe}) - A_f * (d\xi / dt) \qquad 3.3(1)$$

$$dV_c / dt = Ws_c * A_c * (c_c - c_{ce}) + A_c * (d\xi / dt) \qquad 3.3(2)$$

$$dV_d / dt = Ws_d * A_d * (c_d - c_{de}) - A_d * (d\xi / dt) \qquad 3.3(3)$$

Here A_n is the area of element n; Ws_n is the vertical exchange coefficient for element n; c_n is the actual concentration; ξ is sea-level; c_{ne} is the element's local equilibrium concentration, defined in equations 3.3(7-9). Subscripts, f, c and d, refer to the tidal flat, channel and ebb-tidal delta elements, respectively. Sediment is transferred between elements to satisfy mass balance equations 3.3(4-6).

$$\delta_{fc} * (c_f - c_c) = Ws_f * A_f * (c_{fe} - c_f) \qquad 3.3(4)$$

$$\delta_{fc} * (c_c - c_f) + \delta_{cd} * (c_c - c_d) = Ws_c * A_c * (c_{ce} - c_c) \qquad 3.3(5)$$

$$\delta_{do} * (c_d - C_E) + \delta_{cd} * (c_d - c_c) = Ws_d * A_d * (c_{de} - c_d) \qquad 3.3(6)$$

Here δ_{fc}, δ_{cd} and δ_{do} are coefficients for horizontal exchange between the flat and channel, the channel and delta, and the delta and outside world.

$$c_{fe} = C_E * (V_f / V_{fe})^r \qquad 3.3(7)$$

$$c_{ce} = C_E * (V_{ce} / V_c)^r \qquad 3.3(8)$$

$$c_{de} = C_E * (V_d / V_{de})^r \qquad 3.3(9)$$

Here V_n is elements n's current volume; V_{ne} is elements n's equilibrium volume; C_E is the global equilibrium concentration; $r > 1$ and usually r = 2 to comply with sediment transport as a third power of flow velocity (van Goor *et al.*, 2003).

3.3.1 Software development

ASMITA has been coded in Matlab (version R2007a), utilising only functions present in Matlab. A manual has been written, and a Word document detailing the relationships between the routines making up the ASMITA program. Information entered into the model (type, properties, flow, diffusion rates etc.) is stored as global variables and can be viewed through the graphical interfaces provided or from the workspace window. Through the interface, the user can control all aspects of the ASMITA model: element definition, properties and driving forces. Users have full access to the code that will enable them to make fine adjustments to the controlling algorithms (e.g. driving forces not described in the current setup) 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), project details (name, scenario, date). To set up the schematised elements in the model, the user must define the 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. Coastal defences constrain how far the system can move in response to SLR; this can be represented by providing relevant information: system length, integral length, scale coefficient, shape coefficient, valley slope, constraint distance.

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, fixed surface calculation (option to calculate volumes and areas based on a fixed water level rather than the equilibrium). More information is given in Appendix C *ASMITA manual*.

3.3.2 Six-element version

To apply ASMITA to the Thames Estuary, a six-element scheme (figure 3.3.2) was used to capture the variation between the different areas of the estuary (Appendix C2 *Application of ASMITA to the Thames Estuary*, i.e. 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 at the margins. The bed of this section consists 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; it includes Mucking Flats, which have shown rapid accretion in the past. 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 along the northern shore where saltmarsh grows. 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.

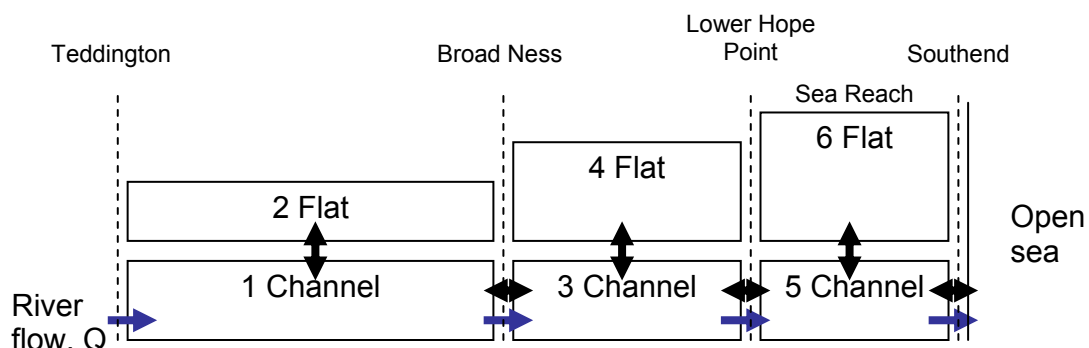**Figure 3.3.2 Schematisation in six-element ASMITA for the Thames**

3.3.3 Model Application

ASMITA was applied to the Thames Estuary (Appendix C2) to investigate the potential response to sea-level rise, the sensitivity of this response to fluvial and marine sediment supply and possible mechanisms for trapping sediment within the estuary. The initial volume and area conditions are given in Table 3.3.3a.

Table 3.3.3a Initial volume and area conditions used in ASMITA
(from HRW, 2006c)

Section	Channel Area (km^2)	Flat Area (km^2)	Channel Volume (10^6 m^3)	Flat Volume (10^6 m^3)
Teddington to Broadness	17.8	6.1	102.8	13.7
Broadness to Lower Hope Pt.	19.8	6.2	153.6	14.6
Sea Reach	35.8	31.3	276.9	61.6

Equilibrium relationships 3.3(10, 11) for the channel equilibrium volume (V_{ce}) and the flat equilibrium volume (V_{fe}) were estimated from historic volume and area data. Equilibrium coefficients were selected to give the best representation of the estuary geomorphology during the period of data availability (table 3.3.3b). They describe equilibrium on time-scales of tens to hundreds of years, but may not be valid for predictions over longer periods.

$$V_{ce} = a_c * P \qquad\qquad 3.3(10)$$

$$V_{fe} = H * a_f * (A_{Basin}) \qquad\qquad 3.3(11)$$

Here H is the mean spring tidal range, A_{Basin} is the basin area, a is an empirically derived coefficient; subscripts f and c refer to flats and channels respectively; P is the tidal prism:

$$P = (1 - a_f) * (A_{Basin}) * H \qquad\qquad 3.3(12)$$

$$a_f = (A_f / A_{Basin}) * (h_f / H) \qquad\qquad 3.3(13)$$

where A_f is the flat area and h_f is the equilibrium flat height.

Table 3.3.3b Equilibrium parameters used in ASMITA

Section	a_f	a_c
Teddington to Broadness	0.11	0.88
Broadness to Lower Hope Point	0.11	0.60
Sea Reach	0.17	0.48

Sediment transport coefficients (Ws_n, δ_{nm}, C_E) were estimated based on Wang (2005).
- Vertical exchange coefficient Ws_n: same order of magnitude as, and proportional to, the average fall velocity (in m/s). For the muddy inner and middle estuary, Ws = 0.0006. For the sandier Sea Reach, Ws = 0.003.
- Coefficient r: equal to the power law in the sediment transport formula; typically 3 for mud and 5 for sand.
- Horizontal exchange coefficient δ_{nm}: estimated based on the area available for sediment exchange A, the length scale of exchange L and a diffusion coefficient D: $\delta = DA/L$; the diffusion coefficient D is given by $D = u^2 H/Ws$ where u is the peak velocity and H is the average water depth.

Once the other parameters have been estimated, the Global equilibrium concentration C_E is used to fit the model to the observed morphological time-scale. Van Goor *et al.* (2003) suggest that the uncertainty associated with these parameters is approximately +/- 50 per cent. Model calibration was carried out based on the estimated parameter values and this estimate of uncertainty. The "goodness of fit" was measured using a Brier's skill score (BSS; Sutherland and Soulsby, 2003):

$$BSS = 1 - (MSE(P,O) / MSE(B,O)) \qquad\qquad 3.3(14)$$

Here MSE(P,O) is the mean square error between the predicted and observed and MSE(B,O) is the mean square error between a baseline condition and the observed data. The baseline is taken here as the initial volume for each element. The skill score compares the goodness of fit by the model prediction against that of a null hypothesis (that the estuary bathymetry continues to be the same as the baseline condition).

Table 3.3.3c gives the parameter values used for each element. Values of D are larger in the inner estuary because Ws_n is smaller. The outside-world boundary equilibrium concentration C_E is taken as 0.000085, derived from
          [Southend measured concentration, O(50mg/l)]
                                        / [typical Thames bed density, 600kg/m^3].
The river concentration C_R available to the upper estuary section is 0.00014, derived from average river supply from all tributaries ~ 200,000 dry tonnes/year = 0.014 m^3/s (assuming a sediment dry density 440 kg/m^3) in river flow 100 m^3/s. This is the lower limit of likely sediment densities (HRW, 2006a) and was used during model calibration.

Table 3.3.3c Sediment exchange coefficients used in ASMITA. Ws$_n$ is the coefficient for vertical sediment exchange, δ$_{nm}$ is the coefficient for horizontal sediment exchange between elements n and m. (Subscripts f, c and o refer to the flats, channel and outside world.)

Section	Ws$_n$	D$_{fc}$	δ$_{fc}$	D$_{cc}$	δ$_{cc}$ or δ$_{co}$
Teddington to Broadness	0.0006	125	15000	1200	260
Broadness to Lower Hope Point	0.0006	125	1350	4400	5000
Lower Hope Point to Southend	0.003	50	825	700	1270

The ASMITA model was calibrated to the 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). This calibration process of choosing model values and the match with historical data (1910-1990) is described further in Appendix C2 *Application of ASMITA to the Thames Estuary*, i.e. Rossington and Spearman (2007).

Following the calibration, ASMITA could reasonably successfully reproduce evolution of the estuary under 2 mm/year sea-level rise. It was used to predict the evolution of the Thames Estuary under various scenarios for sea level rise as discussed in Section 4 (Rossington and Spearman, 2007 = Appendix C2).

3.4 Development and application of *Inverse* Hybrid model

An INverse Model for EStuarine Morphodynamics (INES; Karanurathna *et al*., 2008) has been developed and applied to the Humber Estuary. The model is based on a diffusion equation for the height of the bed as a function of position (x, y) and time:

$$\partial h/\partial t \ = \ K(\partial^2 h/\partial x^2 + \partial^2 h/\partial y^2) \ + \ \text{source} \qquad (3.4).$$

[Such an equation is suggested by applying sediment continuity to sediment transport having a down-slope bias]. The "source" represents the aggregate of all non-diffusive phenomena that lead to long term evolution of estuary morphology.

The model depends on measured bathymetries: spanning a long period, and often enough not to alias changes in form or in management practices (e.g. dredging). Bathymetry at two times allows "inversion" for the time-averaged source in (3.4) between those two times.

The model has been applied to the largest estuary studied in FD2107: the Humber (north-east England), using 20 bathymetry data sets since 1851.

Sensitivity of the source function to the diffusion coefficient (uniform, constant) was investigated by reconstructing the source function with ± 50 per cent of the selected value. There was no apparent difference to the structure of the source function when the diffusion coefficient was varied.

To predict future morphological evolution, (3.4) was used. The diffusion coefficient was assumed constant. The first Empirical Orthogonal Function (EOF) indicated average source strength (it is almost constant in time), included almost 92 per cent of the source function and was used as the representative source function, in effect extrapolating past behaviour. More details are given in Appendix F *Intercomparison of models predicting estuarine morphology.*

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).

 [A nodal tidal cycle was previously identified in the Humber and given some theoretical basis, e.g. Townend et *al*. (2007). In the Inverse model results this is naturally to be sought in the EOF time series. However, the first EOF is essentially the time-averaged source; it shows little variation in time. The second and third EOFs exhibit "oscillatory" behaviour in 1940-1980 (Appendix G); however, the period of "oscillation" is about 10 years, close to twice the sampling interval over this time. Before then, sampling is more erratic; recently, sampling is more frequent; both before and since 1940-1980 the EOFs are less "oscillatory". It is possible that the "oscillations" are a product of aliasing].

It was considered that predictions for the Thames and Mersey would not be particularly meaningful; bathymetry was not at intervals short enough for the computed forcing term to change fairly smoothly from interval to interval.

3.5 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 using the Future-Coast database.

The Emulator is largely based on 1-D equations of axial momentum and continuity (Prandle, 2004a, 2006). It assumes (as commonly observed) that tidal amplitudes are broadly uniform along estuaries. On this basis, changes of phase, along-estuary wave-number and current U are functions of the tidal range Z and estuary depth D (and of friction coefficient and tidal frequency, but these may be considered as uniform between the estuaries considered;

Prandle, 2004a). Along-estuary change of depth $\partial D/\partial x$ is a function of the same variables. Thus Prandle (2004a) derived estuary length as a function of the tidal range Z and estuary depth D (by integrating $\partial D/\partial x$ to where D=0). Neglecting axial mixing, he also related saline intrusion length to the remaining variables – depth, bed roughness, current U and river flow Q_f – eventually deriving (Prandle, 2004a)

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

where *a* is the side-slope of the estuary (triangular cross-section assumed). 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 $<D_{AE}>$:

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

Baseline conditions were from a newly enhanced Future-Coast database of UK estuaries (Manning, 2007b). This was used to compute the mean estuary depth $<D_{data}>$ and width. From these were estimated the estuary side slope. The Emulator assumes that the estuary length (from the enhanced Future-Coast database) and side slope remain constant. The Emulator-derived $<D_{AE}>$ was equated to $<D_{data}>$ by choice of the calibration coefficient *M*, so providing a good starting position. $<D_{AE}>$ is equivalent to a MSL datum. 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: depth $<D_{AE}>$ changes, and hence width proportional to $<D_{AE}>/\ a_{mean}$.

Sea-level rise was imposed on the Emulator channel geometry, giving new values for estuary volume and area. All of the change in water level to 2050 (0.3m or 1m) was imposed at once, rather than through time in parallel with resulting changes in bathymetry.

For infill by suspended particulate matter (SPM), time in suspension depends on settling velocity W_S, depth D and diffusivity proportional to UD, i.e. on W_S, D and tidal range Z. Hence 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, 2004a); $<C>$ increases with tidal range but is assumed constant for the scenarios with raised sea level. Manning (2007a) gives more detail. In application of the Emulator, several estuaries' low-water channel is poorly represented. The assumed constant single side slope (everywhere in the estuary) involves a compromise between HW and LW volumes or areas (or intertidal values); in general not all of these can be correct. 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.

The triangular cross-section is assumed for simplicity in the underlying analysis. 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). In particular, there is no scope for constraint of HW area by fixed structures. Moreover, the only

change in morphology in the present Emulator formulation is the depth increase (and consequent width increase) in response to increased river flow.

Results of applications to the eight estuaries are described in Sections 4 and 6.

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

Prior to the start of the FD2107 project HRW had developed an existing model (*SandTrack*) for Lagrangian particle-tracking of sand-grains including bedload, suspended load, incipient motion and burial processes. The model operates by tracking "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* was used here). Runs for typically a few weeks to a few decades predict where the tagged grains end up. *SandTrack* has been extended to associate a volume of sediment with each tagged grain, and deposit it on the bed in diffuse fashion 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 = Appendix D *Development of a Lagrangian morphodynamic model for sandy estuaries and coasts*).

Morpho-SandTrack has the advantage over other Hybrid models that in areas of deposition (tidal flats, saltmarshes) the *source* of deposited sediment is known as well as its thickness. The tagged particles can carry a marker to indicate whether they are polluted with heavy metals, for example (albeit this feature was not implemented 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 newly developed and calibrated Morpho-SandTrack model was tested in the Thames Estuary, to predict the morphological changes over a 50-year interval, with a one-year update frequency for the bed and the flow. The results look plausible in some areas, although there are also some unresolved discrepancies, possibly due to the pre-existing Thames Estuary flow model having a rather coarse grid resolution within the narrower parts of the estuary. The present model does not include the effects of waves, although they could be added (waves are already included in a version of SandTrack) and might re-distribute sediments in the outer estuary.

3.7 Development and application of Realignment model

For resolving issues relating to the evolution of habitats created by managed realignment, available tools have not been well developed. These systems have site-specific complexities with significant roles of tides, waves, sediment, vegetation and biology at small spatial and temporal scales. Partly in FD2107, HRW developed a model to predict evolution of morphology and habitats at

managed realignment sites, as now described; Spearman (2007; = Appendix E *Hybrid Modelling of Managed Realignment*) gives more detail.

The model methodology builds on the conceptual approach to modelling habitat development employed successfully by di Silvio (1989), di Silvio and Gambolati (1990) for lagoons. It is Hybrid, combining B-U and T-D aspects to describe the essential inlet functioning, and has built-in flexibility to incorporate effects of waves and vegetation, and future developments.

3.7.1 Model structure
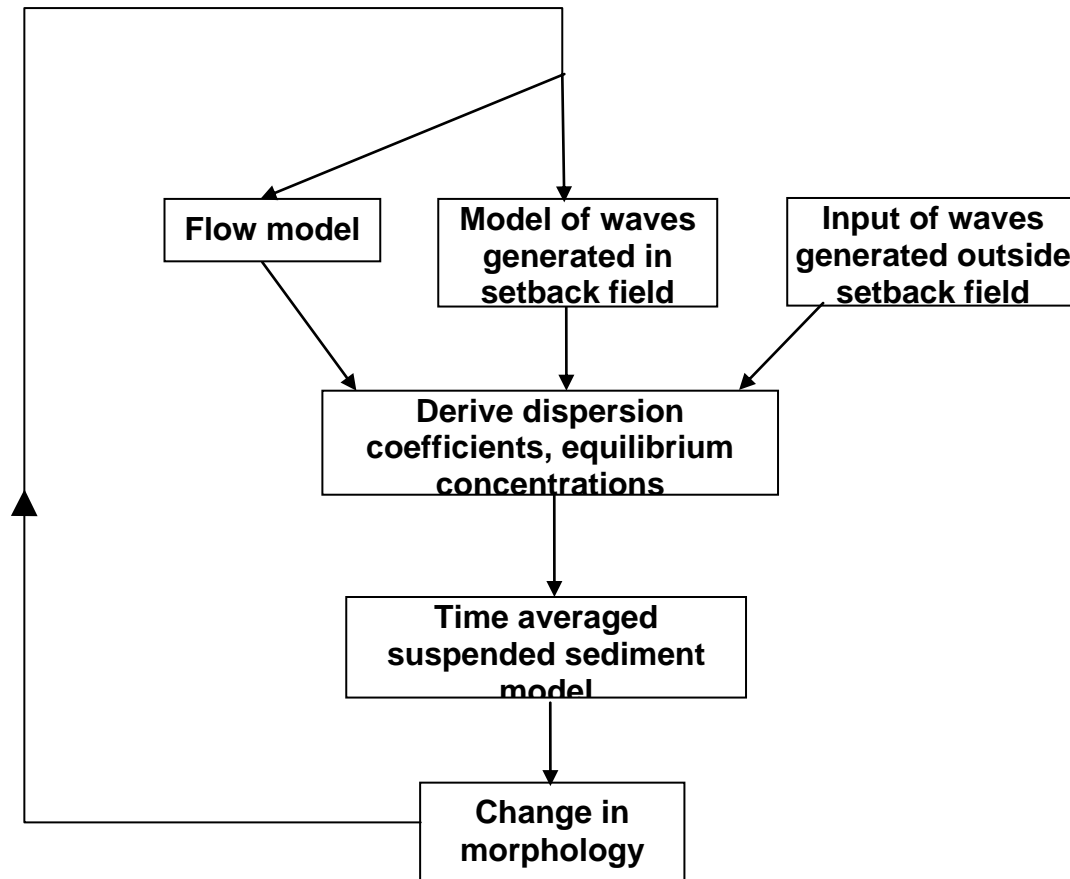
Figure 3.7.1 Basic structure of morphological Realignment model

The model structure is based on a simple UNIX shell script which controls application of the model elements in figure 3.7.1. The shell script allows flexibility – the user can implement the software which they possess 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 at every point in model
          domain (using the wave model of Young and Verhagen, 1996);
   c) Use TELEMAC-2D flow model to get flow conditions in set back field;
   d) Post-process the flow results file and wave results
       - to derive time-averaged spatial distribution of diffusion coefficients
          (Dronkers *et al.*, 1982)
       - to derive the spatial distribution of time-averaged equilibrium
          concentrations C_E (important to the morphology, Section 3.7.3)

- saving derived values in a form for use in SUBIEF-2D model;
e) Run "di Silvio-type" time-averaged sediment transport model SUBIEF-2D with net erosion E as given by Galappatti and Vreugdenhil (1985),

$$E = w \, (C_E - C) \qquad\qquad 3.7 \, (1)$$

where $E < 0$ indicates deposition, w is the 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 in the simulation;
f) Extrapolate predicted change in bathymetry from SUBIEF-2D model over a much longer time-step and save to results file;
g) Use new bathymetry (f) as basis to run TELEMAC-2D again – go to (b).

3.7.2 Method for deriving the time-averaged diffusion

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 within the setback field (based on Dronkers *et al*, 1982). The absolute magnitude of the diffusion coefficients was calibrated along with the other model parameters.

3.7.3 Method for deriving the time-averaged equilibrium concentration C_E

An equilibrium concentration has no empirical basis on a managed realignment site; any previous functioning (hydraulic, sedimentological, vegetative or biological) is unrepresentative. In the absence of a general empirical law governing the evolution of muddy tidal inlets, a simple analytical method is used, based on process. C_E is given by equating the deposition occurring during slack water with the erosion during the rest of the tide:

$$\int_{\tau > \tau_e} M_e \left(\tau - \tau_e \right) dt = \int_{\tau < \tau_d} w_s C \left(1 - \frac{\tau}{\tau_d} \right) dt = C_E \int_{\tau < \tau_d} w_s \left(1 - \frac{\tau}{\tau_d} \right) dt \qquad 3.7(2).$$

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 values of the friction and sediment parameters; values can be estimated from literature but C_E will remain somewhat uncertain.

3.7.4 Processes not presently included in the model

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);

3.7.5 Commercial software used in the model

The morphological model uses the following commercial software:
a) TELEMAC-2D finite-element model solving the shallow water equations, from Laboratoire National d´Hydraulique et Environnnement (LNHE);

b) SUBIEF-2D suspended sediment model (mud transport module of
       TELEMAC, again from LNHE). For this study, the code was altered:
- SUBIEF-2D reads the calculated dispersion coefficients and C_E;
- erosion and deposition were changed from the usual forms (Krone 1962,
       Partheniades 1965) to those of Galappatti and Vreugdenhil (1985).

3.7.6 Case study – Tollesbury Creek (Blackwater)

Figure 3.7.6 shows predicted evolution of a managed realignment at Tollesbury
Creek, compared with the observed evolution. The modelling is detailed in
Spearman (2007; = Appendix E *Hybrid Modelling of Managed Realignment*).
The results indicate that the model performs very well, given the uncertain
nature of the sediment supply from the creek system. The inference is that this
model is a promising basis for informing management decisions regarding
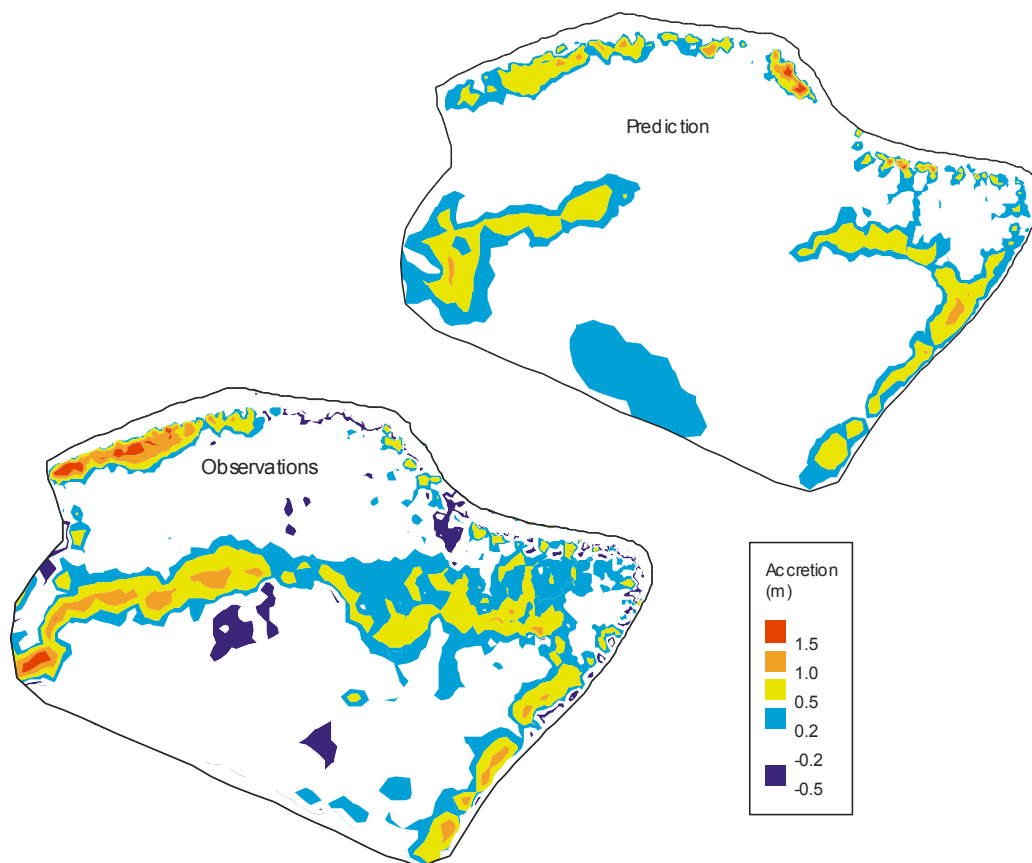realignment projects.

Figure 3.7.6 Bed-level change in Tollesbury managed realignment site
1995-2002; comparison of observed and predicted

4. Intercomparison and evaluation of model predictions for 2050 morphologies

Models of varied approach (B-U, T-D and Hybrid) have been run to predict eight UK estuaries' responses to possible scenarios 50 years hence. Changed river flow, tidal range, mean and surge levels and wave stresses were considered. The estuaries were the Thames, Blackwater, Humber, Mersey, Dee, Ribble, Southampton Water, Tamar.

4.1 The models, estuaries and scenarios

The 'ensemble' of model applications to estuaries is shown in table 4.1. The Thames has provided intercomparisons between the greatest number of models including TE2100 studies.

Table 4.1 Models, estuaries and their properties in the intercomparisons.
Entries Y show the estuaries in which each model was run.

Model	Type	Section	Thames	Black-water	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					
Estuary properties *(Future-Coast)*										
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

Information about the models is in Sections cited in table 4.1 and in Appendix F *Intercomparison of models predicting estuarine morphology*. More description of the estuaries is given in Appendix G *Predictions of estuarine morphology*.

Intercomparisons of model predictions were generally for 2050. Various scenarios are intended to represent possible effects of climate change 50 years hence [as used in TE2100, CDV2075; referring to UKCIP02, IPCC(2001), Defra (2003); the scenarios were defined prior to the latest guidelines (Defra, 2006)]:
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). Two alternatives allowed for the range of possible navigation management strategies:
  - "Geometry 1" case with HTA applied
  - "Geometry 2" as Geometry 1 except for no change in bathymetry seaward of Charlton below -5mOD (i.e. depths in the navigable river are exactly maintained to keep the *status quo*).

The "ensemble" arises from the range of models, estuaries and scenarios. 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.

An overview of results follows, more detail being in accompanying reports, model by model (Appendix F) and estuary by estuary (Appendix G).

4.2 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.

4.2.1 Analytical Emulator

In its present form with constant side slope (zero convexity), the Emulator struggles to represent intertidal areas consistent with high and low water areas and volumes. It has fixed intertidal area (unless tidal range is changed) and so the Emulator cannot assess changes in intertidal area. It 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 and difficulties arise from the triangular cross-section, assumed for simplicity in the analysis underpinning the Emulator. In fact any fixed geometrical form could be used, and 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). In particular, 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, so strengthening the trend with fixed morphology (increased LW volumes and areas for increased river flow).

The Emulator was applied to all eight estuaries (indeed to the extended *Future-Coast* database) 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.

4.2.2 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. In particular, 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' (and an increase with increased tidal range). Thus the model predicts mean depths to increase in most estuaries as MSL rises; however, it predicts substantial infill for the Mersey, where scope for infill is known historically and accords with the "2.5-D" and Emulator predictions of a relatively short infill time. The Hybrid Regime model also predicts a (usually) small decrease in intertidal area with increased river flow. To accommodate the increased flow but maintain its regime state, the estuary widens and deepens, resulting in the loss of intertidal area.

An earlier form of the model had more initial response to changed inputs than might be expected (suggesting an artificial model response to the initial estuary condition rather than a response to sea level rise). This is addressed in a later version of the Hybrid Regime code. Rather than taking the baseline conditions as posed, the model runs the baseline condition first, "stabilising" the model for the initial conditions. This should hardly change longer-term predictions.

The Hybrid Regime model was applied to five estuaries and is thus widely *applicable*. To characterise the estuary by a relationship between (e.g.) cross-section area and peak velocity, it needs mean sea level, tidal range and river flow and more data than the Emulator on estuary form: cross-section areas, breadths and depths at short intervals along the estuary to resolve variations in these statistics and desired output features. It can accommodate branching (a requirement on the underlying 1-D hydrodynamic model). Computing needs are relatively moderate. *Appropriateness* should be determined on an estuary by estuary basis: it needs confidence in 1-D hydraulic model characterisation, that a (power law) regime condition is operative and should remain so; this may imply that past changes and scenario consequences should not be rapid or large; lack of sediment supply may limit the use of regime modelling. Typically, it is not appropriate in heavily modified estuaries (with significant dredging etc.). The Hybrid Regime model predicts changes in the statistics of individual cross-sections. The allowance for hard constraints is especially useful where there is no simple along-estuary profile (e.g. Thames, Southampton Water).

4.2.3 ASMITA

ASMITA also gives intuitively correct results (loss of intertidal area with faster sea-level rise). Its analytical formulation enables better *a priori* evaluation of the uncertainty inherent in the model prediction. ASMITA was validated against

past morphological change in the Thames and 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 (as implied above) to estuaries 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.

4.2.4 "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) 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; 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.

4.2.5 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. It 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.

4.2.6 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.

4.2.7 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, the source function (representing processes not modelled by diffusion) was insensitive to the selected diffusion coefficient. EOF analysis (e.g. Horrilo-Caraballo and Reeve 2002, Reeve and Horrilo-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. In this case, past behaviour may be a useful basis for prediction, using the diffusion equation predictively and extrapolating the source function to the future.

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 form a large majority of the source function hitherto – their corresponding extrapolated time-series must have an integral time longer than the prediction period.

4.2.8 Realignment model

The Managed Realignment model was able to predict the evolution of the Tollesbury Creek managed realignment site under the action of tides and waves and sediment supply. 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. Validation of the Managed Realignment model was undertaken on the basis of bathymetric data measured over a period of seven years.

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 should be considered as 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.

4.3 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. More detail of these differences is given in Appendix G *Predictions of estuarine morphology*.

LW volumes and areas are typically more sensitive to raised MSL, increased tidal range and river flow than are HW volumes and areas (aside from any question about rigid structures constraining HW area). This is simply a matter of proportionally increased effects in shallow water. The same argument might be extended to greater sensitivity of shallow estuaries in general. [However,

estuary depth may depend on the tides and river flow, as in the Emulator and Hybrid Regime model; then depth is not an independent factor in sensitivity].

LW volumes and areas invariably increase for raised MSL, as for the most part do HW volumes and areas, but less so. Accordingly, intertidal area generally decreases (e.g. over 50 years in the Thames, Blackwater, Humber, Mersey, Southampton Water in the Hybrid Regime model); the Blackwater decrease is large. ASMITA run on the Thames predicted a smaller loss of intertidal area. Indeed, for the present rate of sea level rise, the trend analysis and ASMITA both predict an increase in Thames intertidal area.

Mean depths in most estuaries are predicted (by the Hybrid Regime model) to increase as MSL rises. However, only for High Waters in the Thames, Blackwater and Humber is this increase comparable with the rise in MSL. Substantial infill is predicted for the Mersey, where scope for infill is known historically and accords with the "2.5-D" and Emulator predictions of a relatively short infill time. For Southampton Water, the Hybrid Regime HW area seems relatively unconstrained, allowing shallow-water area to increase as MSL rises.

Likely effects of realistic changes in tidal range (e.g. +2 per cent) are moderate; O(2 per cent) in the Hybrid Regime model (and in the Emulator except for LW volume and area if LW is relatively shallow). An exception is Southampton Water; intertidal area increases, peaking in 2025 with a net gain of almost 4 per cent over the 50 years. The 2025 peak appears to be related to the position of relatively shallow bed slopes. The Thames Estuary is predicted to lose 5 per cent of intertidal area over the 50 years.

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, but the Mersey and Blackwater lose intertidal area. [The Emulator predicts much larger increases in areas and volumes].

For the Thames, TE2100 historical trend analyses predict changes for sea level rise alone (no morphological change) and for morphological change alone (no sea level rise). These two cases illustrate the possible range of outcomes; they suggest a change in intertidal area in the range +/- 1 km^2 to 2030, possibly much more longer-term. This range is small compared with the Emulator and the Hybrid Regime model predictions: 5-6 km^2 (5-10 per cent) increase in Thames LW area by 2030. HW area hardly increases in TE2100 predictions (HW intercepts tidal defences at most locations); it increases by 2 km^2 in Hybrid Regime predictions (which probably include areas above present HW – e.g. saltmarsh around Canvey Island).

Estimated flushing times (Emulator) are quite short: between six days and three weeks. They do not correlate with estuary size, as they depend also on tidal range and river flow. Prandle et al. (2005) indicate that flushing times longer than the spring-neap cycle give persistence of marine-derived nutrients[1].

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[1] Different definitions of flushing and related time-scales are possible. If the fresh river inflow is Q and the freshwater volume in the estuary is V_f (the integral $\int f dV$ over the estuary volume of the freshwater fraction $f \equiv (S_O–S)/S_O$ for salinity S and open-sea salinity S_O), then a mean "detention" time is V_f/Q (Fischer et al. 1979); less than an

Infill times are much longer (centuries) because low concentrations of transported sediment are a factor. Emulator estimates range from 182 years (Mersey) to 765 years (Southampton Water). "2.5-D" model predictions of infill times are similar (to baseline HW level; in practice deposition would change before infill is substantial, i.e. before the inferred infill time). Estimated infill times lengthen for raised MSL, and shorten 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. ASMITA predicts that the Thames Estuary will attain a new dynamic equilibrium on a time-scale comparable with the estimated infill time. 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 Humber, the Inverse model indicates accretion in tidal channels, faster than predicted by large-scale diffusion; tidal channels in the outer and middle estuary draw sediment from surrounding mud flats and external sources. This accords with ABPmer (2004); infilling of the estuary was observed during the last 150 years. Localised negative source functions on the south and north banks indicate sediment removal from those areas, either by wave and tidal forcing or by dredging. Localised alternate erosion and accretion is also indicated, on some areas of mud flats in the outer estuary between main channel and north bank. The long-term evolution is nevertheless represented substantially by a large-scale diffusive process.

4.4 Discussion

The selected study area is important. The TE2100 study area included 42 km^2 intertidal area in the Thames Estuary, and the Hybrid Regime 57 km^2; however, the outer estuary between the TE2100 boundary and a line from Margate to Clacton-on-Sea has another 230 km^2 intertidal area. Thus discrepancies between model predictions of estuary volume and area can arise from minor differences in definitions of the estuary limit.

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.

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estimate V/Q using the whole estuary volume V. Another "replacement time" discussed in Fischer et al. (1979) is $0.4L^2/K$ for material initially at one end to be mixed through the estuary. Here L is estuary length and K a dispersion coefficient estimated in Prandle (1984) as $t_D U^2$ where empirically $t_D = 10^3$s, U = tidal current amplitude. For estuaries which nearly dry out at low tide, tidal excursion ~ L, i.e. $U \sim \omega_{M2} L/2$ (ω_{M2} denotes M_2 tidal frequency) and the replacement time $\sim 1.6/(t_D \omega_{M2}^2) \sim 1$ day. An estimate based on flushing by entry and exit of the tidal prism also gives times O(1 day) for estuaries which nearly dry out at low tide. The Emulator estimate of flushing time is conceptually related to the "detention" time V_f/Q, being the time to replace by freshwater, half of the salinity content over the saline intrusion length. For the eight estuaries considered, relationships between the different estimated times are: "tidal prism", "replacement" < Emulator, "detention" V_f/Q < V/Q.

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. However, Section (3.2.1) illustrates that this may be difficult to achieve in practice: historical changes may be influenced by anthropogenic activities; in heavily engineered (e.g. dredged) estuaries, natural trends in estuary behaviour are disguised in historical records.

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.

Results here are from various morphological predictions founded on different concepts. All are important in developing an ensemble of possible future scenarios. Confidence is provided by agreement between results, or if differences can be explained, e.g. by discrepancies in model area or by model limitations (e.g. absence of processes; simplified estuary form); comparison is another means of validation. 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.

The results provided show sensitivities of different estuaries to various climate change scenarios, and that not all estuaries can be expected to respond in the same manner.

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static bathymetry apparently results in over-prediction of peak water levels, relative to the case that includes the 2050 updated bed morphology. For the Humber at least, this suggests that flood studies undertaken with fixed bathymetries should provide a conservative assessment of future flood risk. A similar previous result holds in the Severn Estuary (Wright and Townend, 2006). In apparent contrast, morphological trends in the Thames are found to amplify High Water levels (Appendix H: *Morphological change and estuary management*). However, the distinctions should be noted: 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. For short estuaries (e.g. Mersey, Dee and Ribble, as discussed Section 2.1), extreme high levels, i.e. flood risk, should closely follow external levels with little effect of changing morphology.

The Appendix H examples indicate that large-scale change resulting from extensive capital 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 by eroding foreshores. 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 of land reclamation that has taken place over centuries – originally for agricultural land and more recently for urban housing and industry (Appendix H). 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. The main instrument that is deployed to mitigate this reduction in intertidal area (*coastal squeeze*) is managed realignment. This generally involves deliberate breaching (or permitted decay) of an existing sea wall to allow tidal waters to flow onto the land behind the breach. If the scheme is well-designed, the land (often agricultural in origin) will turn over some years into an intertidal habitat with mudflat and saltmarsh. Through this and other measures, the UK Biodiversity Action Plan targets for offsetting historical and predicted loss of mudflat area are (UK BAP, 2007a):
- to create and restore enough intertidal area over the next 50 years to offset predicted losses to rising sea level in the same period;
- to offset, over the next 10 years, predicted losses in the next 15 years.

The corresponding target for saltmarsh is to restore 140ha/yr (UK BAP, 2007b). The Defra high level targets are to restore at least 100ha/yr (and up to 200ha/yr) of mudflat or saltmarsh (Defra, 2007).

Through the examples considered in Appendix H, and from other studies, the relationship between morphological change and flood risk can be distinguished. This process is likely to emphasise certain key areas where morphodynamic modelling will make a significant contribution to management decisions, and de-emphasise others. In particular the question of whether morphological change has a significant effect on flood risk, which is not definitively espoused by the examples considered here, is pertinent.

6. 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), with the addition of tidal prism volumes. The F-C database includes values of the following quantities for 96 English and Welsh coast estuaries (see figure 6): surface area (ha), intertidal area (ha), saltmarsh area (ha), shoreline perimeter length (km), channel length L (km), spring tidal range (m), mean river flow (cumecs), mouth width (m), and HW & LW volumes (ha.m).

In FD2107, the F-C database has been 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, added for all English and Welsh estuaries.
- tidal amplitudes Z calculated for most estuaries as $Z = Z_R /(2. \times 1.55)$, where Z_R is tidal range between HW and LW
- mean estuary depths D, corresponding to MSL, were calculated for most estuaries, using $D = 0.5(V_H/S_H + V_L/S_L)$, where
  V_H, V_L = HW, LW volume, $\qquad$ S_H, S_L = HW, LW surface area
- mean estuary breadth B was calculated for most estuaries as $B = (S_H + S_L)/2L$
- average side-slopes *a* of most English and Welsh estuaries, determined as $a = 2D/B$
- (dimensional) LW and HW values were added for: D, B, surface area.

Aspects of the expanded database have been applied in the following FD2107 studies: a comparison with estuarine morphological theory and the database of UK estuaries (Prandle *et al.*, 2005); an assessment of dynamical controls on UK estuaries (Prandle, 2006); redefining UK estuary typologies through combined use of estuary morphology theory and FD2107 data (Prandle *et al.*, 2006).

The main Analytical Emulator equations (Section 3.5) have been applied to the database, deriving other characteristics of the estuaries (Manning, 2007a).

In order to provide a more complete UK estuaries database, JNCC data for the main Scottish estuaries were added. This was followed by data for 110 Scottish sea lochs. These data were digitised from a report (Edwards and Sharples, 1986) compiled for the Scottish Marine Biological Association, in collaboration with the Nature Conservancy Council and NERC (.pdf version provided by Richard Whitehouse, HR Wallingford). The Scottish sea loch data include:
- length, depth (maximum), depth (mean LW)
- spring tide range, HW and LW area and volume, tidal prism
- catchment area, annual rainfall, annual freshwater runoff
- ratio of supplies of fresh & tidal water

- ratio freshwater to width (i.e. fjordic circulation theory; Long, 1975)
- flushing time estimate.

The expanded database includes the F-C data, descriptors and some of the Analytical Emulator outputs; it is provided as a Microsoft Excel spreadsheet. For flexibility in use, the JNCC and the F-C estuary reference numbering schemes have been listed. This expanded database will be archived at the British Oceanographic Data Centre (BODC). Persons interested in using the database can contact BODC to obtain a copy of the data for research purposes on CD-ROM or DVD media. Aspects of the FD2107 expanded database will also be incorporated in the *Simulator* developed in FD2117.
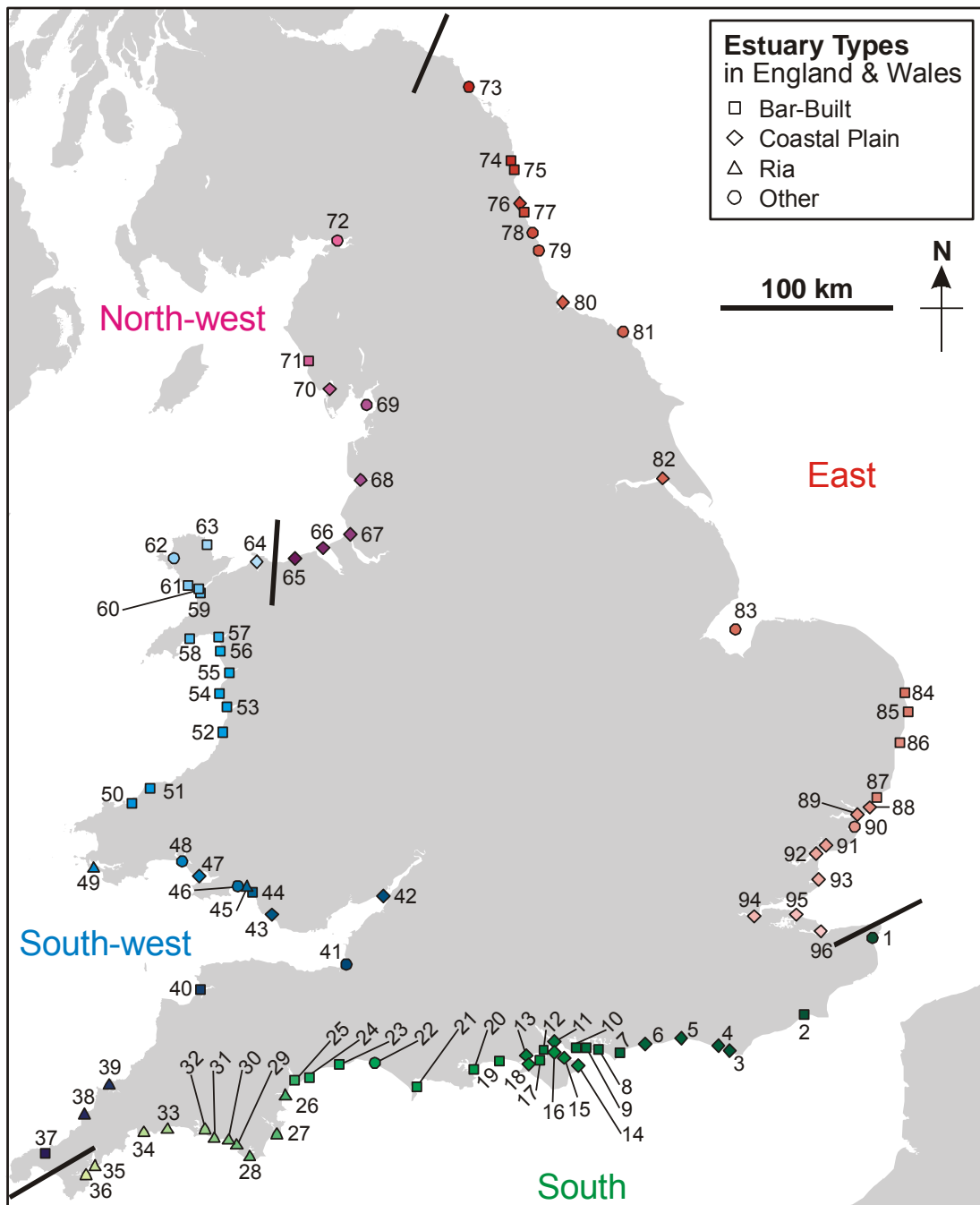

Figure 6 Locations of the 96 England and Wales Future-Coast estuaries. Numbers refer to Future-Coast estuary reference scheme.

7. Discussion, Conclusions and Recommendations

The project FD2107 involved development of a range of models: *Bottom-Up* and *Hybrid* with Bottom-Up and *Top-Down* elements. These and other models have been applied to eight UK estuaries under various scenarios (in some cases using partners' prior developments and other projects); case studies of other estuaries illustrate how morphological change can affect flood risk. We here give an overview of the characteristics (and hence appropriate use) of the models (section 7.1), and of likely estuarine behaviour under the scenarios considered (section 7.2). This is followed by some discussion of approaches to prediction (section 7.3), given that no one model is likely to match fully the constraints of limited validation data and uncertain forcing with the desire for detailed long-term prediction. Sections 7.4, 7.5 describe access to the model developments and give some pointers to future work.

7.1 Overview of model characteristics

We discuss here the "2.5-D" model (Section 2.2) and developments in FD2107: Analytical Emulator, Hybrid Regime, ASMITA, Morpho-SandTrack, Realignment and Inverse models (Sections 3.1-3.5 and 3.7). Detail about the models is in Appendices B for the Hybrid Regime model, C for ASMITA, D for Morpho-SandTrack and E for the Realignment model; Appendix F *Intercomparison of models predicting estuarine morphology* includes a tabulation of their inputs, outputs etc. Table 7.1 summarises model characteristics. The following, ordered by possible characteristics to be modelled (rather than model by model applicability and appropriateness, Section 4.2), may help in model choice.

7.1.1 Estuary shape

The shape of the estuary (as distinct from characteristic scales which all models represent) is not described by the Emulator or by ASMITA; the Emulator may be unable to represent HW and LW volumes and areas consistently. The Hybrid Regime model resolves along the estuary but the shape of any cross-section remains self-similar. The other models ("2.5-D", Morpho-SandTrack, Inverse, Realignment) all describe bathymetry as a function of (2-D) horizontal location.

7.1.2 Process basis

There is a process-basis to all the models (as Hybrids), but with limitations. The Emulator is based only on simplified 1-D hydrodynamic equations (along the estuary) assuming uniform tidal range and a triangular cross-section with uniform side-slope. The Hybrid Regime model uses 1-D hydrodynamics to establish – and monitor adherence to – regime relations between discharge and cross-section parameters; however, the regime relations really determine the evolution. In ASMITA, (rate of) evolution is according to accommodation space into which sediment is transported. ASMITA, Realignment and Inverse models all treat sediment transport as a diffusive process without explicit hydrodynamic advection: exchanges between ASMITA's elements use information about peak flow conditions; Realignment model rates use 2-D flow and wave modelling; the

Inverse model infers a "source" function in a diffusion equation evolving the bed, using past bathymetric change. 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); however, this is an influence on the Emulator formulae and might be a supplement to other models' calculated flow.

7.1.3 Morphological evolution

The Emulator as formulated here only evolves morphology if river flow changes (otherwise changed depths, areas and volumes are strictly related to changes of water level). As applied here, the "2.5-D" model does not evolve morphology. However, both models can indicate infill time-scale, inferred from sediment concentrations and net flows into or out of the estuary. The time-scale of evolution predicted by the Hybrid Regime model is not clear. The ASMITA, Morpho-SandTrack and Realignment models explicitly evolve the morphology (ASMITA only for aggregated volumes and areas). The Inverse model may also predict morphology *if* (i) the predicted scenarios have precedents (c.f. Historical Trend Analysis), (ii) past bathymetry is available with consistent analysed trends and (iii) these trends have an integral time longer than the period predicted. [In practice, bathymetry seems to suffice in the Humber but not usually elsewhere]. Hard structures (geological or man-made) can constrain Hybrid Regime and ASMITA evolution of morphology.

7.1.4 Inputs

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 (or number of elements in ASMITA) 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. River flows, mean sea level and tides enter as boundary conditions in spatially-resolving models (Hybrid Regime, "2.5-D", Morpho-SandTrack, Realignment); ability to do this (availability of data) may influence the choice of boundary. [If the chosen boundaries differ between models, consequent discrepancies between model predictions need to be accounted for].

Table 7.1 Model characteristics

Aspect\Model	Emulator	Hybrid Regime	"2.5-D"	ASMITA-type	SandTrack	Realignment	Inverse
Type	Hybrid	Hybrid	B-U	Hybrid	Hybrid	Process	Hybrid
Source	POL & UoP	ABPmer	POL	WLDelft, HRW, ABPmer	HRW	HRW	UoP
Origins, Functionality *Processes*	Theory for estuary scales related to river flow, tidal range	Regime theory constrains 1-D depth-integral hydrodynamic results to predict new morphology	marine dynamics, wetting & drying, Lagrangian particle transport	Tidal basin morphology in context; "outside" and aggregated channels, flats, delta elements. Accommodation space	marine dynamics, wetting & drying, sand erosion, Lagrangian transport; deposition changes bed	Morphology after realignment. Hydrodynamics, wetting & drying, suspended sediment	To characterise morphology change by 2-D diffusion equation plus "source" (analysed)
Dimensions	Along estuary	Along estuary	3-D grid, t	t; aggregate elements	x. y, t	x, y, t	x, y; t
Limits	Idealised shape. No wind, waves	No wind, waves	Not stratified Non-cohesive single sediment	Coefficients need calibration on past data	Sandy sediment Duration versus resolution	No wind, single sediment, initial bed not eroded	Needs frequent bathymetry over a long period
Morphology(t)?	Depth only	Yes, unclear rate	No	Yes (volumes, areas)	Yes	Yes	Extrapolation only
Inputs:	Mean depth, side slope	Cross sections, hard surfaces	Depth (x,y) on grid	element volumes, areas	Depth (x,y) on grid	Depth (x,y)	Measured depths, gridded
Grid resolution	n/a	Choice O(100m)	Choice ~ 120 m	Choice of elements	Choice, 0.25-5 km	Choice O (100 m)	30m x 30m
Sea level, tides	Y, Y	Y, Y	Y, Y	Y, Y	Y, Y	Y, Y	n/a
River flow	Y	Y	Y	Y	Y (but not here)	n/a	n/a
Sediment sources, type	Implicit, muddy	Implicit to maintain regime	Marine boundary only. Settling w_s	"Outside" concentration	"seeded" + bed erosion	As needed to maintain balance	n/a
Output *fields*	Volumes / Areas C_{sed}	elevation, currents (x); depth (x,y,"t")	elevation, currents (x,y,z, t), Particle fields	Volumes and areas of aggregated elements	elevation, currents, depth (x,y,t), Particle fields	Currents (x,y,t), waves (x,y); C_{sed}, depths (x,y,t)	Grids of source functions, depths (c.f. datum)
Possible (change) Scenarios	MSL Tide range River flow	MSL Tide range River flow	MSL, Tide range River flow Winds, waves	MSL Tide range	MSL, Tide range River flow Winds, waves	MSL Tides Waves	n/a
To use - *range*	Estuary decades	Estuary or reach decades	Estuary or coastal sea; hours - years	Whole estuary decades	Estuary or coastal sea days-decades	Flooded sub-area months-decades	Estuary or reach decades
Documentation	This report	ABPmer R1365	Lane and Prandle (2006) / POL	HRW TR162 ABPmer R1373	HRW TR159	HRW TR157	Karunarathna *et al*. (2008) / UoP
Accessibility	Open	Open; proprietary flow model used	Open	Open as developed	Proprietary; open extension "Morpho"	Open; proprietary flow model used	Open

7.1.5 Outputs

Outputs relate closely to the character of the model, and especially its treatment of space and time. All predict area and volume changes at HW, LW (and hence intertidal). The Emulator and Hybrid Regime model estimates (under changed conditions) are with unchanged and evolved morphology respectively; they do not give a time-scale for changes. [However, infill time can be indicated by sediment concentrations and net flow; also Emulator depth responds to river flow]. The Hybrid Regime model achieves the changes step-wise, resolving area, breadth and depth of each cross-section in the estuary. ASMITA gives time-evolving volumes for each of its aggregated elements; it has also been developed to give time-evolving areas – still to be validated. The "2.5-D", Morpho-SandTrack and Realignment models give mobile particle transports (hence sediment fluxes across sections, for example). These three, and the Inverse model, give deposition or erosion rates as functions of (2-D) location; these rates integrate in time to evolve morphology except in the "2.5-D" model. The Hybrid Regime (1-D), "2.5-D", Morpho-SandTrack and Realignment models include a hydrodynamic model giving flow and elevation in 1D or 2D.

7.1.6 Scenarios

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, albeit this was not always exploited in FD2107. 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.

7.2 Overview of estuarine behaviour

We describe estuarine behaviour as inferred from the models collectively. The following draws largely on the results in Section 4.3 (amplified in Appendix G).

7.2.1 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.

7.2.2 Effects of tidal range and river flow

Likely effects of realistic changes in tidal range (e.g. +2 per cent) are moderate, O(2 per cent). Southampton Water is an exception; its larger gains of intertidal area apparently relate 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].

7.2.3 Flushing and infill

Flushing times as estimated by the Emulator (Section 4.3) are just a few weeks.

Related infill times are some centuries, 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 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.

7.2.4 Morphological influence on flood risk

Case studies (Section 5 and Appendix H) emphasise that morphological change affects flood risk in a manner specific to each estuary. For example, dredging need not change flood risk extensively or significantly; it can alleviate flood risk in the rapidly silting Parrett. The most important factor may be preservation of natural flood and coastal protection features (e.g. saltmarsh, spits or bars; or localised vulnerable / degrading parts thereof). Many flood risks and coastal protection needs are a legacy of land reclamation over the centuries.

7.3 Approaches to prediction

Sections 4.3, 5 and 7.2 emphasise the individuality of estuaries' responses to a range of climate change scenarios, and hence the individuality of morphological change effects on flood risk. This puts an onus on modelling the particular estuary studied. Then Sections 4.2 and 7.1 illustrate that available models are all limited in their own ways regarding: representation of the shape of the

estuary, processes modelled, requirements for input data (that may be unavailable), possible scenarios, what quantities are predicted and whether morphology evolves. No one model is likely to satisfy all these 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 or model limitations (processes, estuary form); it is another means of validation.

Results in Section 4 are from morphological predictions founded on diverse concepts (Section 3). 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.

7.4 Access to model developments and data

The *"2.5-D"* model with particle tracking was not specifically updated for FD2107. Nevertheless, it does not can contain any proprietary code and 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 with this report and is available on the *Estuary Guide* website www.estuary-guide.net.

ASMITA is described most fully in Appendix C with this report and is available on the *Estuary Guide* website www.estuary-guide.net.

The *Inverse model* is published (Karunarathna *et al.*, 2008) and the analysis 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 Appendix I, i.e. 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. These models are geared to use of Telemac (finite element model) flow. Hence the concepts can be used in other models, and in principle the lines of code could be supplied. However, it would probably be easier for a modeller to write their

own lines of code to suit their own model; an existing Lagrangian particle-tracking model is required. The easiest way for others to make use of the new SandTrack model developments is thus to contact HRW directly (Dr. C.T. Mead; ctm@hrwallingford.co.uk). The development and application is described in Appendix D *Development of a Lagrangian morphodynamic model for sandy estuaries and coasts*.

The *Re-alignment Model* and provision of code is described most fully in Appendix E. 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 Appendix J (Manning, 2007b). For further enquiries, contact Dr A.J. Manning (University of Plymouth and HR Wallingford: andymanning@yahoo.com).

7.5 Future work

Recommendations on good practice when predicting long-term morphological changes in estuaries are made in Section 7.3. 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 an ensemble of scenarios. In FD2107, historical changes in bathymetry provided only limited validation or constraint of models predicting future morphology. There is a lack of reliable and suitable historic data which excludes the influence of human intervention (dredging etc.). 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. [An example herein – rather restricted – is the Tollesbury Creek realignment].

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 a rate for the 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 a rate for 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 (Section 2.2).

Lagrangian particle-tracking as in the "2.5-D" model is being implemented in the POL Coastal Ocean Modelling System 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. For example, continuity 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 3.4) 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 within 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.

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