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ABSTRACT: Flood risk management in estuaries needs well-validated models to predict morphology. The UK Estuaries Research Programme (ERP) addresses the challenge of predicting longer-term morphological changes. Project FD2107 in ERP aimed to enhance "Hybrid" models combining elements and advantages of "top-down" and process-based "bottom-up" approaches. Developments include:

- An *Analytical Emulator* based on 1-D hydrodynamics;
- A *Hybrid Regime* model combining 1-D hydrodynamics, *regime* relations and evolving cross-sections;
- *Morpho-SandTrack*: 2-D hydrodynamics, sediment dynamics and particle-tracking to change morphology;
- A *Realignment* model with 2-D flow and waves to spread sediment and predict local changes;
- *ASMITA* (pre-existing) now in Matlab, evolving the size of aggregated intertidal areas and channels;
- An *Inverse* model evolving depth in 2-D by a diffusion equation plus "source" based on past changes.

Applications to eight varied UK estuaries and different scenarios identified impacts, sensitivities, respective merits of the models and good practice for morphological predictions.

1 INTRODUCTION

Interest in estuaries and associated flood risks, sediment regimes and morphology is raised by concentrated local populations and economic activities. Estuaries face increasing rates of change: freshwater runoff and MSL, likely increases in flooding events. Outcomes depend on hydrodynamics and sediments, but the sediment regime is challenging to predict.

Methods, hitherto lacking, are needed to predict changes in estuary functioning and improve our ability to manage estuaries sustainably. The UK Estuaries Research Programme (ERP) was formulated.

i. to develop means to predict large-scale, long-term morphological changes and related impacts and
ii. to assess their consequences for estuarine management.

1.1 *Approaches to predicting morphology*

"Bottom-Up" (B-U) process-based models are mathematical (usually numerical), spatially-resolving and predictive. For hydrodynamics, sediment transport and bed evolution, they use fluid-dynamical and related equations, representing 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 relatively small biases.

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

"Hybrid" approaches combine T-D and B-U elements. Typically, an equilibrium state (T-D concept) constrains the form of evolution and is approached with rates and distributions given by B-U models.

ERP Phase 1 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. Accordingly Project FD2107 objectives were to develop models capable of delivering 50-year forecasts of morphology:

- A framework for application of B-U models.
- Development of new Hybrid models via integration of B-U and T-D models (emphasised here).
- Estimates of morphological impacts on potential for flooding.

1.2 *Outline*

The following describes B-U and Hybrid model developments and applications. Outcomes from applications in eight varied UK estuaries are outlined, and impacts of future estuarine morphologies on changes in flood risk and habitats.

2 DEVELOPMENT AND APPLICATION OF NEW HYBRID MODELS

2.1 *Analytical Emulator*

An Analytical Emulator has been developed, the main equations have been coded (Manning, 2007a) and applied to many UK estuaries. The Emulator is largely based on 1-D equations for conservation of water and along-estuary momentum (Prandle, 2006). It assumes that tidal amplitudes are broadly uniform along estuaries. On this basis, estuarine length and depth are derived in terms of time-averaged river flow and estuary side-slope. Thus the Emulator partly explains how estuarine bathymetries have developed in response to tidal and riverine inputs (Prandle et al. 2006). Then estuary length and side slope are assumed constant (baseline conditions were taken from a newly enhanced Future-Coast database of UK estuaries; Manning, 2007b), and morphology responds only to changes of river flow among the scenario changes. MSL rise gives new values for estuary volume and area. The constant side-slope implies that intertidal area remains constant under MSL rise. Mean depth increases by half the MSL rise for the assumed triangular cross-section. A minimum infill time was estimated from flushing time and mean concentration <C> (Prandle, 2004); <C> increases with tidal range but is assumed unchanged with raised MSL.

With constant side slope (zero convexity), the Emulator may not represent consistent high and low water areas and volumes; it is liable to represent channel volume and mean depths poorly. It can only assess changes to intertidal area for changed tidal range. These limitations arise from the triangular cross-section, assumed for simplicity in the analysis. In fact any fixed geometrical form could be used; alternatives could enable a better quantitative match to baseline areas and volumes.

The Emulator was applied to all eight estuaries and is thus generally applicable, needing only gross estuary dimensions, MSL, tidal range and river flow. However, appropriateness is limited to estuaries where volumes and areas are fairly represented by the Emulator's fixed geometry and are not constrained by fixed structures.

2.2 *Shell hybrid regime model*

This model (Wright & Townend, 2006; Fig. 1) allows application of a "regime" relationship with a 1D process-based hydrodynamic model (B-U, e.g. Mike11, ISIS). Ultimately, a new bathymetry is predicted, after some change to the system. Hybrid Regime models were constructed and applied for the Blackwater, Humber, Mersey, Southampton Water, Thames.

Regime theory characterises links between hydrodynamics and estuary form by formulae (here fits to an initial model run) describing an estuary (quasi-) equilibrium, typically in terms of discharge Q:

cross-sectional area $A \propto Q_{max}{}^{p}$,
top width $B \propto Q_{max}{}^{q}$,
mean hydraulic depth $H \propto Q_{max}{}^{r}$.

Then some condition is altered, e.g. water levels, engineering works. The hydrodynamic model runs the altered simulation and regime relationships are reapplied to update the cross-section, subject to

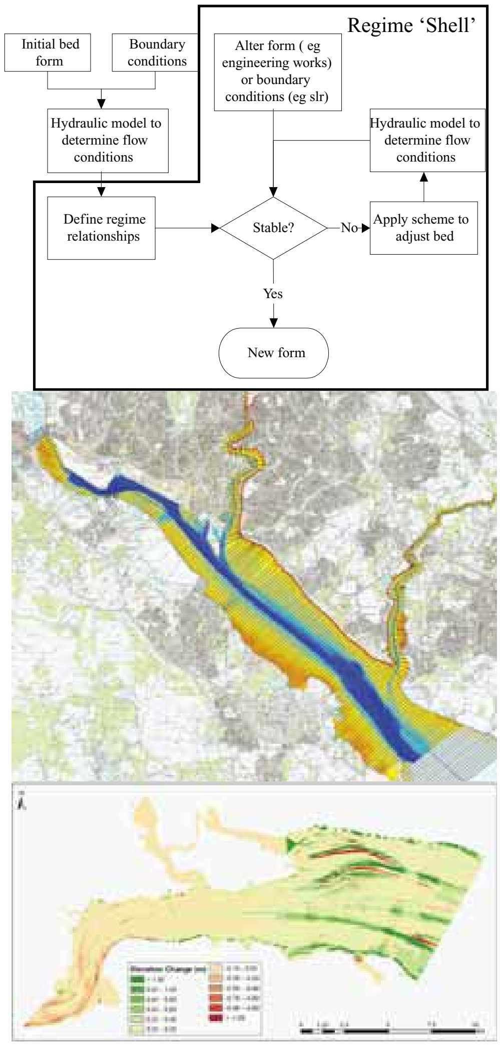


Figure 1. Hybrid Regime flow diagram (top), 1-D Southampton Water model with cross-sections (middle), Thames bathymetry change to 2050 (6 mm/yr MSL rise; bottom).

– no adjustment above the maximum water level,
– linear stretching (vertically and horizontally) to required width and area,
– constraints (e.g. Holocene surface, solid geology, structures).

If individual cross-sections deviate initially from the best-fit regime relationship, relative rather than absolute adjustments can be made. The new cross-sections form the basis of the next hydrodynamic model run. This process is iterative until the cross-sections converge to within a defined tolerance of the regime criteria. Intertidal and plan areas, volumes and hydraulic information are calculated.

With many individual cross-sections, the Hybrid Regime model has flexibility to represent LW and HW areas and volumes accurately. Structures can limit HW area; such sections then tend to deepen and inter-tidal area is lost; 'coastal squeeze'. The model predicts depth increases in most estuaries as MSL rises, but substantial infill for the Mersey. To accommodate greater river flow, the model again predicts a (usually) small decrease in intertidal area.

To moderate initial responses to changes, a later version of the model runs the baseline condition first.

The Hybrid Regime model, applied to five estuaries, is thus widely applicable; it needs MSL, tidal range, river flow and data on estuary form: cross-section areas, breadths and depths at the desired resolution. The approach is most appropriate if there is confidence that a regime condition holds and should persist; if the estuary is subject to rapid change or instability then regime modelling is unsuitable. It predicts changes of individual cross-sections; the allowance for hard constraints is especially useful in heavily modified estuaries (e.g. Thames, Southampton Water). Currently the model does not simulate waves and so lacks their effects; also sediments are not explicit. Interpretation needs care, e.g. forms of morphological change are predicted, but not rates.

2.3 *Morpho-SandTrack*

This is a development of the pre-existing HRW SandTrack model for Lagrangian particle-tracking of sand-grains including bedload, suspended load, incipient motion and burial. SandTrack tracks "tagged" representative grains of sand as they move driven by the flow (predicted by a numerical model; e.g. TELEMAC). The development is to associate a volume of sediment with each tagged grain, and deposit it on the bed as a sediment "lens" with defined and calibrated maximum thickness and extents. The lenses give the morphodynamic development. By iterating at intervals (e.g. 1 year; re-calculating the hydrodynamics), this has become a morphodynamic model (Soulsby et al. 2007).

In areas of deposition (tidal flats, saltmarshes), Morpho-SandTrack thus predicts the source (and potentially other characteristics) of deposited sediment as well as its thickness. Effects of waves could be added (as already in a version of SandTrack).

Morpho-SandTrack was tested in the Thames, predicting morphology over 50 years with annual bed and flow updates (Fig. 2). Landward of Southend, the model resolution was coarse for representing intertidal changes. In the outer estuary the model appears to represent the main features.

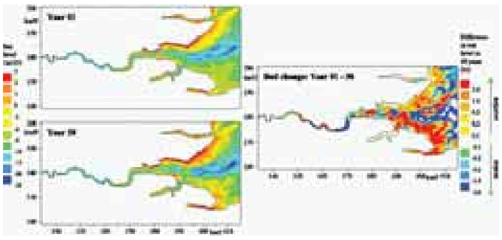


Figure 2. Morpho-SandTrack evolution of the Thames, year 1 to year 50 using yearly bed updates.

In FD2107 Morpho-SandTrack was applied only to the Thames. However, it should be applicable as widely as 2-D B-U models, having the same requirements [MSL, tidal range, river flow; fine enough bathymetry over the whole area, explicit sediment sources]. Continually repeated flow model runs are needed for evolving morphology, and combine with fine resolution to increase computing demand. The approach is appropriate for detail and if there is a lack of historical guidance; the morphological updating allows longer-term prediction.

2.4 *Realignment model*

This model was developed to predict evolving morphology and habitats at managed realignment sites (Spearman, 2007) with significant roles of tides, waves, sediment, vegetation and biology at small scales. The model builds on the approach of di Silvio (1989), di Silvio & Gambolati (1990). A UNIX shell controls the model elements:

a. Set up initial bathymetry;
b. Calculate time-averaged wave heights and periods (Young & Verhagen, 1996);
c. Use model (e.g. TELEMAC-2D) for flow conditions;
d. Derive fields of time-average diffusion coefficient (Dronkers et al. 1982) and equilibrium concentration C_E (q.v.);
e. Run "di Silvio-type" sediment transport model (e.g. SUBIEF-2D): time-averaged, diffusive-only with zero residual currents and calculated diffusion coefficients; net erosion $E = w\ (C_E—C)$ (Galappatti & Vreugdenhil, 1985) where $E < 0$ is deposition, w is settling velocity, C is actual concentration;
f. Update bathymetry, extrapolate bathymetry change over a longer time;
g. Use new bathymetry (f) as basis to iterate again from (b).

The diffusion coefficient is assumed proportional to the mean-square current speed (Dronkers et al. 1982).

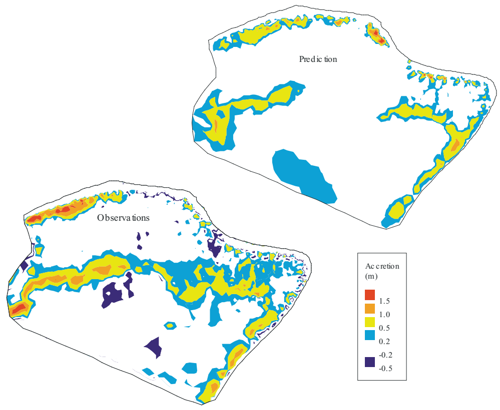


Figure 3. Bed-level change, Tollesbury managed realignment 1995–2002; observed and predicted.

The equilibrium concentration C_E is given by equating deposition during slack water with erosion at other times; C_E depends on currents, waves, friction; erosion, deposition and settling rates; it is subject to their uncertainties.

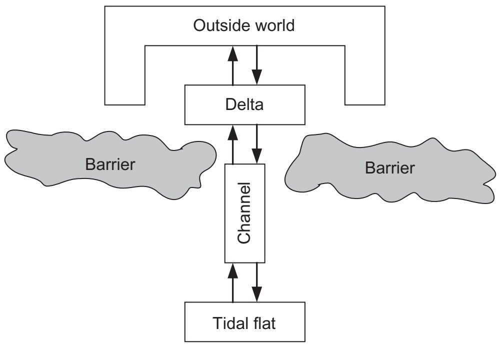
Modelling of a managed realignment at Tollesbury Creek compared well with the observed evolution (Spearman, 2007; Fig. 3) given the uncertain sediment supply. As such the model seems a promising basis for management decisions regarding realignment. Simple vegetation effects have been incorporated; the model can accommodate improved wave, vegetation and biological process modules. As presented, the model lacks erosion of the initial bed or evolution of the breach itself.

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. The approach is most appropriate over a small area requiring detail and lacking historical guidance.

2.5 *ASMITA-type model*

ASMITA (Stive et al. 1998) describes morphological interaction between a tidal basin and its adjacent coastal environment. It schematises a tidal inlet as aggregated elements (delta, channels, intertidal flats; Fig. 4). Under constant hydrodynamic forcing (in particular constant MSL), each element is assumed to tend towards a morphological equilibrium, a function of hydrodynamic forcing and basin properties (van Goor et al. 2003). Empirical relations define elements' equilibrium volumes.

MSL rise creates accommodation space; the estuary becomes a sink for available sediment. ASMITA



Element definitions:
Ebb-tidal Delta: Excess sediment volume above a hypothetical non-inlet shoreface
Channel: Water volume below mean low water
Tidal flat: Sediment volume above mean low water

Figure 4. ASMITA schematisation and element definitions (from van Goor et al. 2003).

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; morphological elements interact by sediment exchange, evolving the whole system and individual elements. Hydrodynamics are represented by (tidal range and prism). In FD2107, ASMITA was coded in Matlab, documented and (graphical) control set up. It was applied to the Thames Estuary with aggregated flats and channels in each of three sections (Rossington & Spearman, 2007). ASMITA was calibrated to historical morphology, using data collated in TE2100.

Under 2 mm/year MSL rise, ASMITA was able to reproduce Thames Estuary evolution reasonably successfully. Its intertidal area loss with faster MSL rise is also intuitively correct.

ASMITA's analytical formulation enables *a priori* evaluation of its predictive uncertainties. Coefficients optimal for representing the period of available data typically relate to timescales of decades to centuries, this being the focus for the application of this type of model.

In FD2107, ASMITA was applied only to the Thames estuary and Tollesbury Creek set-back field. It has been applied elsewhere and is thus widely applicable; it needs MSL, tidal range, river flow and dimensions (volumes, areas) of the aggregated elements. Appropriateness is limited to volumes and areas that are fairly represented by a few aggregated elements; calibration on the past probably implies that scenarios should not diverge far from past experience. There is implicit reliance on continued sediment supply (or by implication information on how the supply is changing).

2.6 *Inverse model*

An Inverse Model for estuarine morphodynamics has been developed and applied to the Humber (Karunarathna et al. 2008). It uses a diffusion-type evolution equation

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

as suggested by combining conservation of sediment with sediment transport having a down-slope bias. "Source" represents non-diffusive phenomena that lead to long term evolution of morphology.

For the Humber, bathymetry data comprised 20 sets since 1851 (15 since 1936). Successive sets allowed "inversion" for the interim time-average source. Structure of the source function was not very sensitive to values K in the diffusion equation.

To predict future morphology, in principle the evolution equation can be used; the future source function has to be estimated. Extrapolation from past behaviour was assessed by EOF (Principal Component) analysis of the sequence of source functions (e.g. Reeve & Horrillo-Caraballo, 2003). In the Humber, 92% of the mean square data was in the first spatial-structure EOF having near-constant time-series (Fig. 5). Hence this first EOF was used as the source function for prediction. Predictions of Humber bathymetry were made for 1, 3 and 10 years ahead. 1-year and 3-year predictions were compared with the most recent measured bathymetries (2002, 2004). This evidence supports using the diffusion equation to predict morphology in the Humber.

The Inverse model is (only) applicable in this way if past bathymetric data are frequent enough to

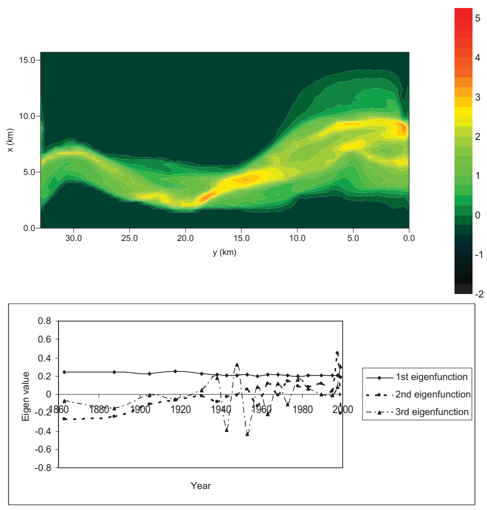


Figure 5. First spatial EOF and time-series of first three EOFs.

resolve past changes without aliasing, fine enough to resolve features of interest (channels, banks). In practice, bathymetry seems to be needed about every 10 years; perhaps more often for a rapidly-changing (e.g. small) estuary. This is rarely available (the Humber is an exception); hence the practical usefulness of the Inverse method may be somewhat diminished. The model depends on past behaviour; it is only appropriate for predicting the morphological response if (i) future changes are within the range of experience; (ii) the EOFs used have an integral time longer than the period predicted and comprise a large majority of the source function hitherto (as for the Humber).

3 ESTUARY SCENARIOS AND RESULTS

The models were applied to eight estuaries as shown in Table 1.

Model predictions were generally inter-compared for 2050. Scenarios to represent possible effects of climate change 50 years hence were:

Mean sea level: present as baseline; rises of 0.3 m (realistic), 1 m (extreme);

Tidal range: present as baseline; an increase of 2 per cent (Flather et al. 2001);

River flow: baseline as at present; an increase of 20 per cent.

The following outlines overall trends.

3.1 *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 (in models that take this into account); 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. in the Hybrid Regime predictions for the Thames, Humber, Mersey, Southampton Water, Blackwater). However, ASMITA predicts a small increase for the present rate of MSL rise, as compared with small losses from an extrapolation based on trend analysis.

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. However, infill reduces the depth increase in the Mersey; in Southampton Water, shallow-water area increases as MSL rises, reducing the average depth increase.

3.2 *Tidal range and river flow*

These effects are proportionally greater in shallow water, i.e. at LW compared with HW. Otherwise, realistic changes in tidal range (e.g. +2 per cent) have likely effects O(2 per cent). Southampton Water gains more intertidal area, apparently related to the position of relatively shallow bed slopes.

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

3.3 *Flushing and infill*

Flushing times as estimated by the Emulator are just a few weeks, and do not correlate with estuary size,

Table 1. Estuaries where models were applied.

Model	Thames	Black-water	Hum ber	Mer sey	Dee ble	Rib Water	S'ton	Tamar
Emulator	Y	Y	Y	Y	Y	Y	Y	Y
Hybrid Regime	Y	Y	Y	Y			Y	
"2.5-D"				Y	Y	Y		
ASMITA -type	Y							
Morpho-SandTrack	Y							
TE2100	Y							
Realign-ment		Tolles-bury						
Inverse			Y					

Entries Y show where each model was run. "2.5-D" refers to a finite-difference B-U hydrodynamic model (mass and momentum equations) with 120-m resolution; vertical structure is derived from the sea surface slope and assumed friction (so controlled by the 2-D solution; Lane, 2004). TE2100 refers to Historical Trend Analysis to 2030 from the TE2100 project.

as they depend also on tidal range and river flow. [The Emulator estimates flushing time as the time to replace by freshwater, half of the salinity content over the saline intrusion length].

Related infill times are some centuries (also from "2.5-D" model predictions), lengthening slightly for rising MSL and shortening slightly for increased mean river flow. Most infill times indicate enough sediment input to enable the morphology to keep up with sea-level rise. However, estuarine dynamics may determine that morphology does not keep up with sea-level rise. In the Mersey, scope for infill is known historically, and the models do suggest infill keeping pace with sea-level rise. For the Thames, a volume increase is predicted before infill keeps pace with faster MSL rise. The Humber Estuary has been surveyed frequently for past trends to give a good guide to development, suggesting that the estuary both responds to the nodal cycle and keeps pace with sea level rise.

4 IMPACTS OF FUTURE MORPHOLOGIES

FD2107 included a discussion (HRW, 2007) of the influences that estuary morphological change can have on flooding. A range of flooding risks, from estuary-wide to the local scale, can be induced by different modes of morphological change. Flood-defence and coastal-protection measures can affect estuary habitat.

As an example, assuming fixed Humber morphology apparently results in over-prediction of peak water levels, relative to changed 2050 morphology. A similar previous result holds in the Severn Estuary (Wright & Townend, 2006). In the Thames, however, historical morphological trends apparently amplify High Water levels. In short estuaries (e.g. Mersey, Dee and Ribble), extreme high levels, i.e. flood risk, should closely follow external levels with little effect of changing morphology.

Other examples (HRW, 2007) indicate that large-scale change resulting from extensive dredging has not been found to cause extensive or significant changes in flood risk. Indeed, where natural siltation is very rapid, such as in the Parrett Estuary, dredging can alleviate flood risk rather than increase it. Flood risks in estuaries with natural flood and coastal protection features commonly entail (often localised) preservation of these features. Defences may be more vulnerable to wave attack as foreshores erode, typically from sea-level rise, saltmarsh-loss and development. A defended shoreline is liable to reduction in mudflat and salt marsh under MSL rise; managed realignment is the main instrument used to mitigate this.

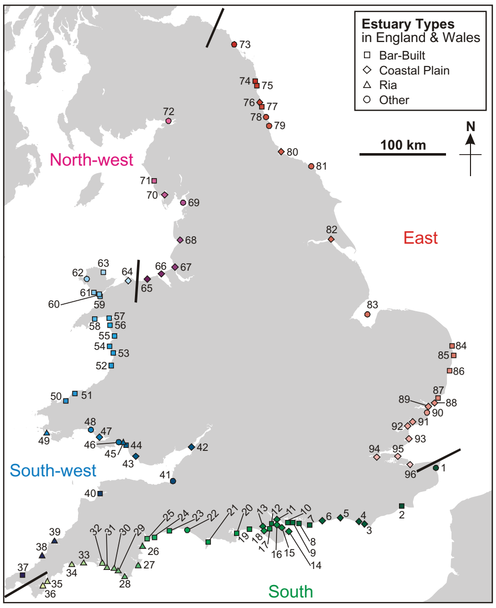


Figure 6. Locations of the 96 England and Wales Future-Coast estuaries. Numbers refer to Future-Coast estuary reference scheme.

5 DATA

The Future-Coast (F-C) database (Burgess et al. 2002) for 96 English and Welsh estuaries includes values of: surface area, intertidal area, saltmarsh area, shoreline perimeter length, channel length, Spring tidal range, mean river flow, mouth width, HW and LW volumes. In FD2107, it was augmented (Manning, 2007b; Fig. 6): more detailed freshwater flows (seasonal statistics), saline intrusion lengths, neap tide equivalent tidal ranges, tidal amplitudes, mean estuary depths and breadths, average side-slopes, LW and HW values depth, breadth and surface area.

6 MODELLING PRACTICE: CONCLUSIONS

6.1 *Factors in model choice*

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

All the models have a *process*-basis, but with limitations: the Emulator assumes uniform tidal range;

the Hybrid Regime model assumes that regime relations hold; ASMITA evolution is according to accommodation space; ASMITA, Realignment and Inverse models assume that diffusive sediment transport prevails. As applied here, none of the models explicitly account for density-driven circulation.

Morphological evolves in the Emulator only for changed river flow, and not at all in the "2.5-D" model; however, both models can indicate infill time. The time-scale of evolution in Hybrid Regime predictions is unclear. ASMITA, Morpho-SandTrack and Realignment models explicitly evolve morphology. Hard structures (geological, man-made) can constrain Hybrid Regime and ASMITA evolution of morphology. The Inverse model may predict morphology under conditions similar to those for valid trend analysis.

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. Beyond this, availability of required data may influence model choice. *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.

6.2 *Gaining assurance*

Estuaries have varied individual responses to climate change scenarios. This puts an onus on modelling the particular estuary studied. Any one model is likely to have uncertainties and not satisfy all requirements. An ensemble can provide scope and validity. 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.

Results in FD2107 are from morphological predictions founded on diverse concepts. All can be valuable: for an ensemble of possible future scenarios; to broaden the range of quantities predicted.

FD2107 and other ERP outputs may be found at www.estuary-guide.net and Defra/Agency (2008).

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