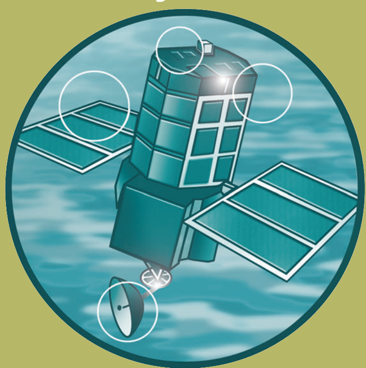
Joint Defra/EA Flood and Coastal Erosion
Risk Management R&D Programme

Development of estuary morphological models

Annex A: Guidelines for application of Bottom-Up estuarine models to assess impacts of Global Climate Change and interventions on flood risks and sediment regimes

R&D Project Record FD2107/PR



Environment Agency

defra
Department for Environment
Food and Rural Affairs

Guidelines for application of Bottom-Up estuarine models to assess impacts of Global Climate Change and interventions on flood risks and sediment regimes

Executive Summary

Climate change and human intervention may have direct impacts in estuaries. They also affect hydrodynamics and hence sediment dynamics, water quality, ecology and human activities. These dynamical consequences are amenable to study by a range of models.

This report synthesises experience into guidelines to aid modelling projects. It is intended primarily for specialists or consultants who may assess impacts of climate change and other human interventions on estuaries. We hope that there may also be useful advice for estuary managers specifying such commissioned studies. The emphasis is on so-called "bottom-up" (B-U) models: process-based, mathematical (probably numerical), spatially-resolving, predictive (probably time-stepping).

The choice of approaches and methods should take account of previous work and "state-of-the art expertise, practice in analogous problems elsewhere, the issues at stake and necessarily the resources, data and expertise available.

We conclude that Bottom-Up models are well-proven for hydrodynamics (including waves) in one or two horizontal dimensions. The vertical dimension is needed to represent many processes: estuarine circulation; bottom stresses, erosion and deposition sensitive thereto; separate paths of near-bed coarse sediment, finer sediments higher up (and dissolved constituents); turbidity maxima associated with river flow; sediment supply in bottom marine inflow. 3-D models hydrodynamic models are increasingly well-proven but require more data and knowledge to run. Confidence decreases along the sequence via sediment transport to morphology. Biases influencing long-term evolution may be inherently hard to predict (aside from their doubtful representation in models).

It is important to estimate uncertainties in models and in future scenarios. This entails use of varied approaches and (i) sensitivity analyses, (ii) investigating causes of differences between approaches to bring understanding, credibility and confidence in results, (iii) data to ascertain past changes and significant processes, and for model calibration and validation. Analysis of historical data for the estuary in question is a vital guide to future prediction. Comparisons with data ultimately provide the basis for all approaches, and so results are only as good as the basis in (all) data used.

In outline, the report has sections describing:
1) *Motivation*: reasons for interest in estuaries (for completeness)
2) *Challenges* for predictive models posed by the complex estuarine environment and processes (should be understood by all concerned with predictions for estuaries)
3) *State of the art*: approaches and progress with models for aspects from hydrodynamics to morphology, ecology and water quality (background for estuary managers)
4) *Outstanding issues* and 5) *Factors in model choice* should be understood by those commissioning model studies

6) *Model characteristics*, 7) *Model application and shell*, 8) *Set up*, 9) *Forcing*, 10) *Cycle of model runs*, 11) *Wider interpretation* and 12) *Case studies*: these sections are likely to be of most interest to specialists or consultants carrying out modelling studies. Sections 9 and 12 emphasise data available to support modelling studies.

Points that may help commissioners of studies, and a Glossary, are collected in Annexes 1, 2.

Glossary

Abscissa. Horizontal axis in a 2-D plot.

Accommodation space. Change in sediment storage capacity (due to rising sea level).

Advection. Carriage of a fluid property with the flow.

Aggregation. As flocculation. Disaggregation – the opposite.

Algorithms. Calculation procedure (in a model).

Analysis (period of forecast model run). The lead-in to the forecast period, the model being run with assimilation of measured data, so providing the best estimate of actual conditions.

Barotropic. Depth-independent part of the flow, related to pressure from surface slope.

Bed-load. Sediment that is mobile to give transport, yet continually touches the bed and is supported thereby (not by water-column turbulence, Brownian motion and collisions).

Biogenic. Formed by plant or animal life.

Bioturbation. Small-scale working or turning-over of the sea bed by animals.

BODC. (NERC) British Oceanographic Data Centre.

"*Bottom-Up*" (B-U approach to morphology). The approach via process-based models: mathematical (probably numerical), spatially-resolving, predictive (probably time-stepping). The processes are represented by fluid-dynamical and related equations for hydrodynamics, sediment transport and evolution of the bed.

Boundary condition. The interior equations in the model do not determine all values on the boundary. There, model variables depend on, e.g., river inflows, ocean tidal elevations, no flow through land boundaries. Boundary conditions express these external conditions and constraints in the mathematically- or numerically-formulated model.

Bulk formulae. Formulae expressing (sea-surface) fluxes of momentum, heat etc. in terms of "bulk" variables that would usually be measured and modelled, e.g. velocity, temperature.

Calibration. The process of determining coefficients in parameterizations for best accuracy.

CASI. Compact Airborne Spectral Imager.

Cefas. (UK) Centre for Environment Fisheries & Aquaculture Science.

CEH. (NERC) Centre for Ecology and Hydrology.

Cohesion. Sticking together of sediments: in the water column (flocculation, so increasing particle size); on the sea bed, so resisting erosion.

Consolidation. Sediments on the bed expelling water (and perhaps also sticking together) so as to become more dense, less fluid overall and more resistant to erosion.

Continuity. Conservation of mass for water or sediment.

Coriolis (force). The inertial force causing currents to tend to turn right as viewed in the northern hemisphere on the rotating earth.

Density current. Flow resulting from lateral differences of water density.

Discretisation. The numerical model grid and time-step.

Dispersion. Separation or spreading of constituents in the water by non-uniform currents.

Divergence. Net outward flux from a unit area or volume.

Dune (or sand wave). A bed-form with length scale related to water depth and intermediate between ripples and banks.

EA. (UK) Environment Agency.

Ebb tide (currents). The phase when the flow is out of the estuary.

ECMWF. European Centre for Medium-Range Weather Forecasts.

Ecosystem. A conceptual view of marine life and non-living constituents emphasising interactions and the flow of materials and energy between functional groups.

Eddy viscosity. Effective coefficient of internal fluid friction as enhanced by turbulence.

EMPHASYS. “Estuarine Morphology and Processes Holistic Assessment SYStem” consortium project FD1401 funded by Defra within the UK Estuaries Research Programme.

Ensemble. A set of model runs for the same context except that parameter values, initial or forcing/boundary conditions may differ. Sometimes (but not here) more tightly defined that the values or conditions differ so little as to be undetectable in reality.

Estuarine circulation. Fresher-water (riverine) outflow above denser sea-water inflow.

FD2107. This project: “Development of Estuary Morphological Models” funded by Defra.

Fetch. The up-wind extent of open water for surface-wave generation by wind.

Finite element (model). The solution is represented as a combination of spatial distribution functions, collectively enabling any spatial distribution. Often the individual functions are defined only over one or a few elements of a grid of simple polygons (e.g. triangles).

Flocculation. Sticking together of particles in the water column, forming larger “flocs”.

Flood tide (currents). The phase when the flow is into the estuary.

Fluid mud. A dense concentration of fine material in the water near the bed, giving a strong vertical gradient of density which reduces turbulence and associated viscosity, so enabling strong shear (which may itself tend to suspend fine material).

Form drag. Enhancement of drag on flow over a rough bottom due to wave generation.

HadCM2. UK Hadley Centre climate model (one of a sequence continued by HadCM3, HadCEM).

Harmonic constituents. Expressions with sinusoidal time-dependence: their sum represents the motion in question. For tides the frequencies are known from astronomy (table 3).

Hybrid (approach to morphology). This combines T-D and B-U elements (*q.v.*). Typically, a T-D equilibrium state is approached with rates and distributions provided by B-U models.

Hydrodynamics. Forces and resulting motion of the water.

Internal waves. Analogues of surface waves, “using” density stratification in the water.

Inter-tidal. Between high and low water levels.

Intra-tidal. Within one tidal period.

JNCC. (UK) Joint Nature Conservancy Committee.

LIDAR. Light Detection and Ranging. Airborne mapping technique using a laser to measure the distance between the aircraft and the ground.

Linearity. Dependence of one variable on another at a uniform rate. Advection and friction terms in the equations are often non-linear because of dependence on e.g. $(\text{current})^2$.

Mixing length (of turbulence). Scale of the energy-containing turbulence eddies, $\alpha\ k^{3/2}/\varepsilon$ where k is turbulence kinetic energy and ε is turbulence dissipation.

Morphodynamics. Forces and resulting changes in the form of the estuary.

NERC. (UK) Natural Environmental Research Council.

Normal (direction). Perpendicular to the boundary in question.

Open boundary. The part of a model boundary that is sea, not land.

Ordinate. Vertical axis in a 2-D plot.

Organic. Bound in long-carbon-chain molecules (as in biogenic material).

Parameter. Coefficient appearing in model equations.

Parameterisation. Representation of a complex process through an algorithm determining the (dependent) variable(s) of interest from variables already calculated by the model.

POL. (NERC) Proudman Oceanographic Laboratory.

Porosity. Proportion of overall bed volume occupied by water between sediment particles.

Probability distribution. For a variable with uncertain value: the range of possible values is subdivided; the chance of the variable being in each sub-range is given; these chances total 1.

Radiational (boundary condition). In the form of a wave progressing out of the model area.

Radiation stress. Force exerted by waves (e.g. when they decay) because they carry mean momentum (e.g. forward velocity forwards and reverse velocity backwards).

Regime relation. Relation of aspects of estuary form (e.g. cross-sectional area, plan area, volume / tidal prism) to “given” quantities (e.g. tidal range, sediment type, river flow).

Regression. Retreat of the sea from land.

Residual currents. Longer-period flow after averaging out (sub-) daily tide components.

Resonance. Natural oscillation in a physical system. Occurrence is more likely in a long estuary, and then probably the amplitude increases from mouth to head, with period near $4L(gH)^{-1/2}$. Here L is estuary length, H is depth, g is gravitational acceleration.

Return period. Inverse of the frequency of occurrence of extremes beyond the stated value. E.g. “A 3m surge has a return period of 50 years” means a 2% chance of a surge exceeding 3 m in any one year.

Ripple. The smallest-scale bed-form, typically a few centimetres in length scale.

Rollover. Vertical and horizontal translation of the whole estuary form to maintain the same relation with changed sea level.

Saline intrusion. The distance up-estuary over which (diluted) salt water is present.

Scenario. The context simulated in a model run, defined by the parameter values, initial and forcing/boundary conditions.

Secondary flow. Flow transverse to the axis of the estuary.

Sediments. Particles that may be deposited on the bed but including their time in suspension.

Sensitivity. The change of model outcome per unit change of input values, parameters (or formulation).

Settling. Falling of particles in the water column, towards the bed under gravity.

Shear. Variation of flow in a direction transverse to the flow.

Significant wave height. Originally: mean height (crest to trough) of the highest third of the waves in a sample. Usually computed as $(4 \times \text{variance of surface-wave elevation})^{1/2}$.

Skin friction. Drag on flow directly by the sea-bed surface (as distinct from form drag).

Spectral analysis. Process of deriving the Spectrum, i.e. the distribution of (usually) energy over frequencies and/or wavenumbers; cross-spectral analysis is an extension for frequency-dependent relations between variables.

Stratification. Vertical variation of fluid properties.

Stratigraphy. Study of the sequence of layers in sediment (or rock).

Surge. Additional sea-surface elevation driven by weather (mainly winds over shallow seas).

Suspension. Particles held up in the water column by turbulence, Brownian motion and collisions. This applies especially to finer particles.

Stability. In the context of numerical models, results remain bounded and of larger scale than the model grid elements and time steps.

Stochastic. Having a random (non-deterministic) component.

Stokes Drift. Difference between net particle transport and measured mean transport of flow past a vertical section, because particle displacements correlate with currents in waves.

Stress. Force per unit area exerted on the flow (especially at the surface or bottom).

SWAN. A wave model for coastal regions, i.e. allowing for shallow water and wave-current interactions (Booij et al., 1999; Ris et al., 1999). It is “third-generation”, representing wave-wave interactions across the spectrum.

Tidal (current) asymmetry. Difference between values (e.g. current speed) on opposite phases of the tidal cycle.

Tidal prism. The volume difference between tidal high and low waters.

Tidal pumping. Net transport of some quantity that correlates with the tidal current (this may include water if the surface elevation correlates with the current).

“*Top-Down*” (T-D approach to morphology). Covers a range of approaches () characterized by emphasising large-scale outcomes in relation to determining factors in context.

Transgression. Gradual submergence of land by rising sea level.

Triad. The three elements, viz. hydrodynamics, sediment transport, bed evolution, that interact for morphology.

Turbidity current. Down-slope flow (analogous to an avalanche) driven by extra density from suspended sediment and strong enough to pick-up further sediment to sustain itself.

Turbidity maximum. A maximum concentration of fine suspended matter, usually in the upper estuary with low salinity, located according to the fluvial and marine inputs, estuarine circulation, salinity and tidally-induced resuspension.

Turbulence. Small-scale fluctuating components of fluid flow. Usually treated as random, but this is not implied by its pragmatic definition as all flow components on time or space scales too small to be resolved by measurements or models.

UKERP. UK Estuaries Research Programme funded by Defra and the Environment Agency.

Validation. The process of establishing a model's applicability in a particular type of context by comparing its outputs with the real counterpart.

Vortex. A small flow-structure with intense fluid rotation.

Wetting and drying. Covering and uncovering of inter-tidal areas during the tidal cycle.

Water Quality. Temperature and contents of the water (dissolved constituents and suspended particulates).

Symbols

Symbol	Meaning	Typical value
C	Coefficient of quadratic bottom drag	0.002
cm	centimetre	
g	Acceleration due to gravity	10 m/s^2
h (H)	Depth (scale)	10 m
K	Effective (pseudo-) diffusivity for bed-form spreading	10^{-6} to 10^{-2} m^2/s
km	kilometre	
L	Length (scale)	10 km
m	metre	
mb	millibar	
mm	millimetre	
p	Porosity of sediment on bed	0.4
s	second	
U	Current speed	0.1 to 1 m/s
α	(Maximum) angle of repose for sediment on bed	35°
2DH	Model with two spatial dimensions, both horizontal	
2DV	Model with two spatial dimensions, one vertical	

1. Motivation

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 (figure 1a). Estuaries support or are affected by transport, renewable energies, cooling water abstraction, aggregate mining, fishing, habitats, agriculture, waste disposal, and leisure. Estuarine environments are facing increasing rates of change: raised temperature, changing freshwater run-off, changes in sea level, likely increases in flooding events.

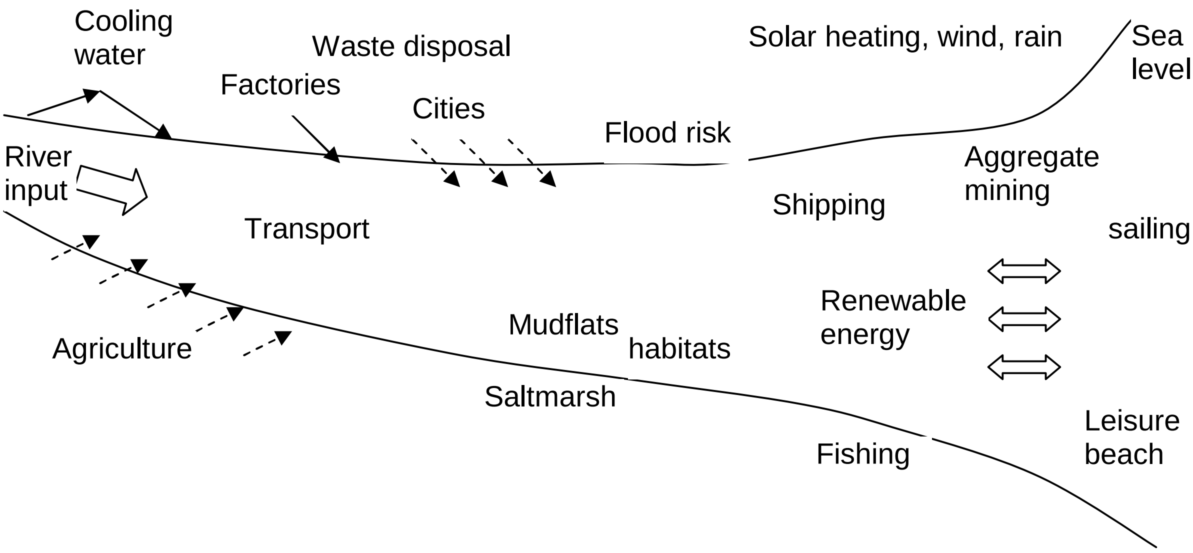


Figure 1a Estuary uses and impacts

Outcomes depend on hydrodynamics and on sediments (figure 1b), which affect the ecosystem (through intertidal / subtidal morphology, shading and the dynamics of biogenic particles) and water quality (as many pollutants adhere to fine sediments or a contaminated bed is eroded). However, the sediment regime is challenging to predict.

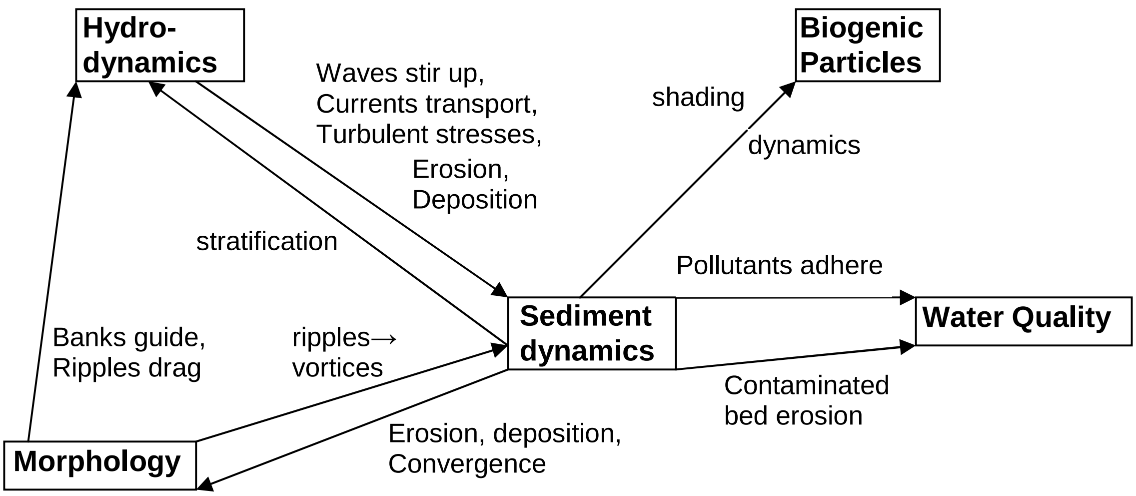


Figure 1b Interaction diagram

Methods are needed to predict changes in estuary functioning and so improve our ability to manage estuaries sustainably (EA & Defra, 2006). Management to minimise flood risk and threats to habitats (from various human activities and climate change scenarios, for example), needs to be informed by accurate, reliable tools. However, we lack well-validated tools (numerical models) to predict estuarine behaviour, especially for long-term morphological changes. The UK Estuaries Research Programme (UKERP) was formulated to develop techniques to predict large scale, long term morphological changes and the resulting sediment related impacts in estuaries (including water quality aspects) and assess their consequences for estuarine management (HRW, 1996; Pye, 2000; EMPHASYS consortium, 2000),

2. Challenges

2.1 Hydrodynamic and morphodynamic background

This is reviewed in HRW (1995), particularly for the background to hydrodynamic forcing and inputs (figure 2.1a), and related ecological and contaminant processes. Typical estuarine circulation has fresher-water (riverine) outflow above denser sea-water inflow, as the different densities "find their own level". Around the UK and for many overseas estuaries, the water volume at low tide is a (possibly small) fraction of that at high tide. Long estuaries may have strong tidal currents to fill this volume difference (the tidal "prism"). Strong currents (whether tidal or wind-and-wave driven) in shallow water are effective in vertical mixing. Mixing reduces the density difference between upper and lower waters in the estuary; correspondingly, the estuarine circulation is increased to maintain a salinity balance. Secondary or transverse flow can result from (i) transverse density differences (e.g. stronger flood currents in a deeper central channel imply higher salinity there, and conversely on the ebb; the result is a transverse "estuarine-type" circulation), (ii) inundation and drainage of lateral salt-marsh or inter-tidal mud flats (or flow through creeks and channels within these areas). Friction tends to reduce the flow near the bed. Hence the flow may be approximately 1D (along-axis), 2D (i.e. adding a transverse or vertical component) or 3D, depending on the scale and form of the estuary and the degree of mixing. More dimensions allow more scope for shear, hence for dispersion and ultimately more extensive mixing.

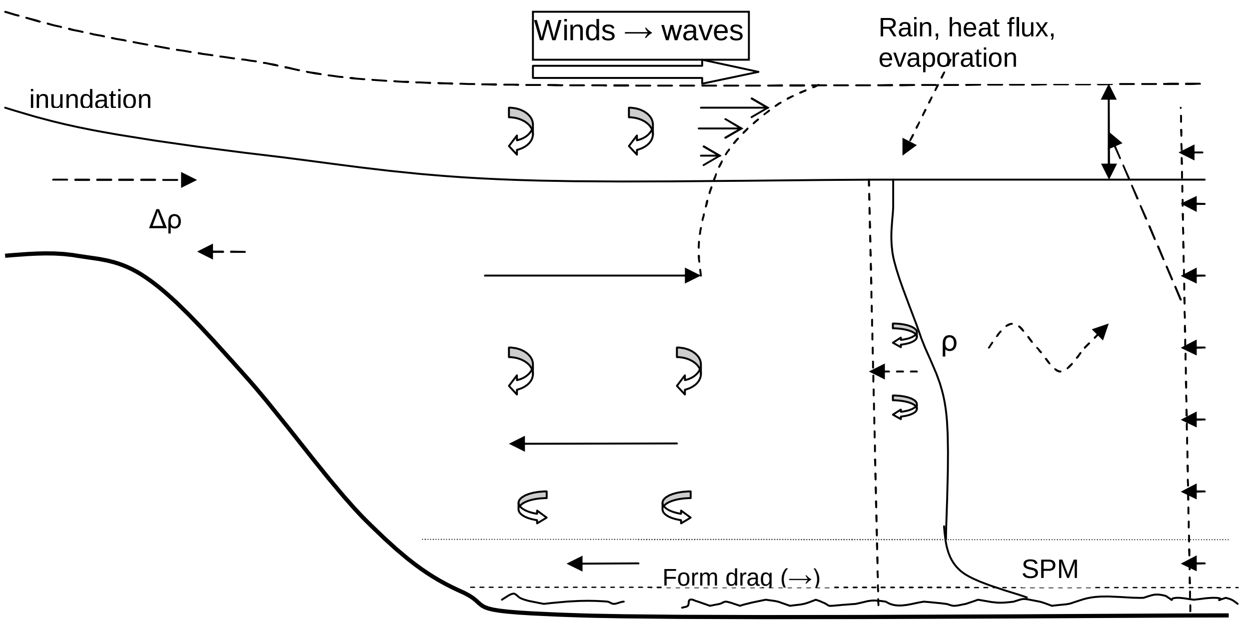


Figure 2.1a Cartoon for hydrodynamic processes

Flow in estuaries (as elsewhere) is governed by well-established fluid-dynamical equations. However, the equations must be simplified to enable tractable solutions because the domain and stochastic turbulent flow are complex. Bed-forms distort the flow and give form drag.

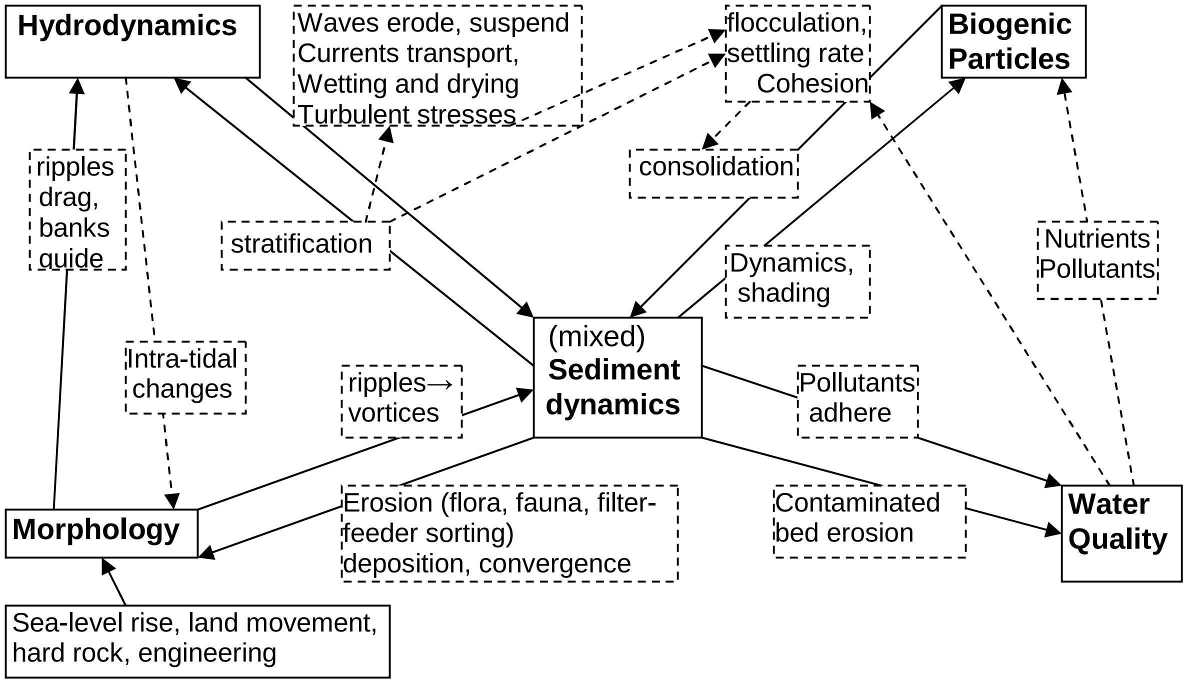


Figure 2.1b Cartoon for sediment-dynamical processes

Fluxes of sediments in estuaries result from many detailed processes governing erosion, suspension and deposition (figure 2.1b). Overall the dynamics form a “triad” of interacting elements: hydrodynamics, sediment transport, bed-forms and evolution (see figure 1 in HRW (1995) for this embedded in a wider set of interactions). Hydrodynamic stresses mobilise sediment and currents transport suspended matter. The balance of erosion and deposition (divergence in sediment transport) fashions the bed. Bed-forms, on all scales from ripples, strongly affect hydrodynamic stresses; on large scales, banks steer tidal, wind- and density-driven flow. Near-bed processes are especially complex, ranging from intra-tidal changes in bed-forms (hence roughness, turbulence, current shear etc.) to long-term mediation by flora and fauna (which may affect erosion, *via* cohesion or bioturbation, flocculation and settling rates). Fine sediments (especially) tend to be cohesive, depending on the water chemistry, the sediment’s physico-chemical properties and biogenic “glue”. Cohesion favours consolidation of the bed with temporally-increasing resistance to erosion; it also favours flocculation, aided by moderate turbulence increasing particle encounters. Floc size affects settling velocity and depends likewise on physico-chemical properties; intense turbulence breaks up flocs. Further complexity arises as settling is hindered and turbulence is damped by dense concentrations of suspended sediment, especially a bed mobilised to fluid mud by strong currents or waves; filter feeders sort sediments; sediments are mixtures of different sizes, shapes, cohesiveness, flocs and particles, organic and inorganic; properties change during wetting and drying in inter-tidal areas. For example: grain size determines the formation of ripples etc.; muddy sand can be separated into sandy shoals, muddy channels and mud accumulation in salt marshes; in some areas bed grain size may be closely correlated with the hydrodynamics, but there can be liquid mud in Bridgewater Bay where the energetic environment would suggest coarser sediment.

Nutrients and pollutants affect the biology and hence sediments indirectly (and conversely). Sea-level rise, land movement, underlying hard rock and engineering work further constrain morphological evolution. Time-scales are seconds for individual waves (effective mobilisers of sediment), decades-centuries for estuary evolution (e.g. Wood, 2000).

Despite the complexity, net sediment transport, erosion–deposition and morphology depend on subtle biases: spatial gradients giving divergence/convergence in net transport, itself the small balance of large opposing fluxes on opposite phases of the tide. Biases (Figure 2.1c) come from:
- tidal current asymmetry,
- river flow (which can strongly affect deposition, e.g. in the Humber, a long, exponential-shape estuary; Norton and Townend, 2000),
- any mean wind- or wave-driven transport or circulation (estuarine circulation tends to give landward transport, especially for coarser sediments concentrated near the bottom),
- a seasonally varying imbalance between fluvial and marine sources of sediment (the finest fluvial sediment is transported seaward; bottom inflow at the sea-ward end may be crucial to the marine supply of sediment, e.g. in the Mersey – Spearman et al., 2000; often these two convergent transports give a mid-estuary turbidity maximum, located according to the fluvial and marine inputs, estuarine circulation, salinity and tidally-induced resuspension),
- tendency for down-slope sediment transport,
- phase lags between currents and sediment mobilisation, slack water and settling.

Ongoing tidal bias and its effects probably differ greatly from effects of storm "events". The bias may be strong in some contexts, e.g. on mud flats: turbid flood waters deposit sediments near slack high water; not all is re-suspended by frictionally-retarded ebb flows; settling lag, cohesion and marsh vegetation all help the bias (Pethick, 1984; Uncles et al., 2000).

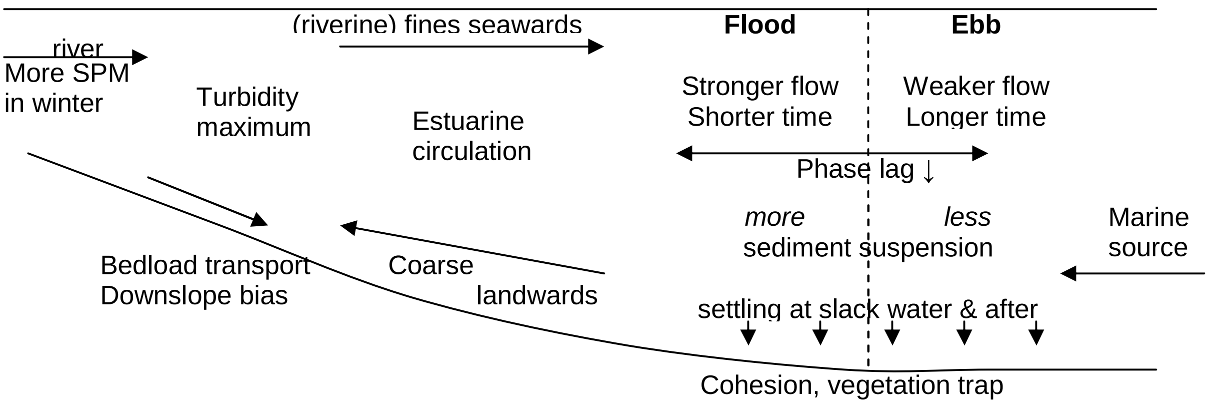


Figure 2.1c Cartoon for sources of bias leading to morphological change

2.2 Predictability

The complexity and wide range of scales (figure 2.2) make model simplifications inevitable. Then inaccuracies and the subtle biases (Section 2.1) render morphological predictions prone to accumulating errors. Errors may arise from the following.

2.2.1 Biases in model representation do not match reality

This applies especially to small residuals of large opposing quantities on opposite phases of the tide. Simulation times are often reduced by accelerating the morphology, e.g. taking change over a spring-neap cycle as a fixed (model-derived) multiple of the change over one spring tide. This assumes a constant relation between springs and spring-neap sedimentation. The net effect may also be sensitive to sediment properties (e.g. settling velocity, effects of biota) and to non-tidal contributions to erosive stresses and transport. Hence outcomes are liable to inaccurate modelling, underlying "chaos" (Section 2.2.2) and the balance of ongoing *versus* episodic processes (Section 2.2.3).

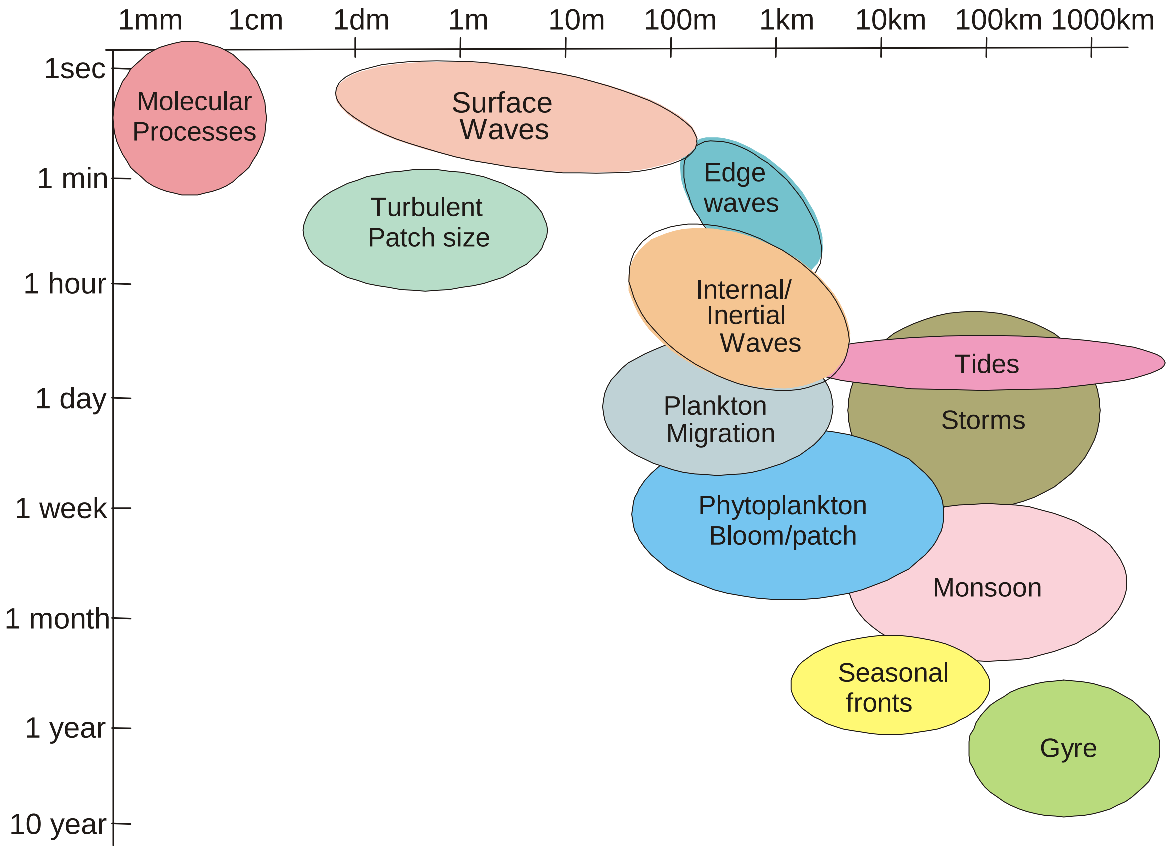


Figure 2.2 Process time-and-space-scale diagram (after Prandle, Dickey)

2.2.2 "Chaotic" system

In some systems, channels and banks migrate; specific patterns vary but overall characteristics (e.g. channel/bank proportions, scales) are retained. Such behaviour exhibits close but not exact repeats of previous patterns after a long period of time, and sensitivity to initial conditions or small imposed changes. Short-term behaviour may then be predictable by a bottom-up (B-U) model. However, longer-term behaviour is not deterministic, and may be predictable only perhaps for some overall characteristics, not for specific patterns. The evolution time-scale for features with scale L in depth H is HL/K. [Here K is an effective diffusivity ~ $2\pi CU^3/[g(1-p)\tan\alpha]$ (e.g. Huthnance, 1982) where typically drag coefficient C ~ 0.002, gravitational acceleration g ~ 10 m/s^2, porosity p ~ 0.4, angle of repose α ~ 35°.] Thus the time scale may be (e.g.) 1 (10^3) year for H = 10 m, L = 10 km and U = 1 (0.1) m/s. There is a tendency for deposition on shoals: flow can by-pass them; speeds are slowed by relatively strong friction over a shoal. So a shoal can approach the surface on a decreasing length-scale (i.e. H, L both decrease); the evolution time scale becomes short. However, waves or limited sediment supply can inhibit rapid shoaling, thereby giving some natural stabilisation and improved predictability. Other factors aiding stability are bias towards down-slope transport (inhibiting short steep bed-forms) and speed-up of flow constrained to go over shoals (so the flow tends to erode shoals).

2.2.3 Balance between ongoing and episodic processes

Typically tides represent an ongoing process and storms drive episodic processes. In some locations, beaches and banks may build up over many (hundreds of) tides; waves in one storm may then erode beaches, banks or cliffs. According to the intensity and path of storms in any given period, the balance between the ongoing and episodic may differ. An intense storm or large engineering works might even cause a change to the long-term form. Hence it can be difficult to identify any period long enough to achieve a stable estimate of the balance between ongoing and episodic processes. Any model "calibration" period may be atypical and introduce biases in longer-term runs. B-U models may be impractical to run for many years with detailed (weather) forcing, even in hindcast mode. For future predictions, the detailed forcing is of course not known, and there is little confidence that any one realisation will force the "correct" ongoing-episodic balance and associated biases.

2.2.4 Probabilistic use of models

Issues of "chaos" and ongoing *versus* episodic are inherent to the real estuary being modelled and not deficiencies of B-U models *per se*. However, they tend to be heightened in B-U model application by the usual need to provide deterministic and detailed initial conditions and boundary forcing. This information is rarely available in all detail and to sufficient accuracy; obviously not in the case of future scenarios.

These limits to predictability raise the need for an ensemble of calculations. An ensemble can cover a wide variety of future possibilities. It can also be used to estimate the sensitivity of outcomes to context (boundary forcing), sediment properties and model formulation using a wide variety of simulated characteristics. Such sensitivities and outcomes can be used to guide where more effort should be put in the study (*viz*. aspects of context and model for which outputs are sensitive to the current range of uncertainty). If probabilities can be attached to the future scenarios, then a corresponding probability distribution of outcomes is obtained; such probability distributions (of scenario and outcome) enable natural use of the model results for management purposes relating to expected socio-economic benefit.

Such probabilistic use of B-U models may be desirable for these reasons, but is not generally practised. [Process models tend to be used to inform expert judgement based on a sound understanding of physical process.] Some discussion of means to facilitate multiple runs as implied by probabilistic use is given in Sections 7 and 10.

3. State of the Art

3.1 "Top-Down" and "Bottom-Up" approaches

The expression "Top-Down" (T-D) covers a range of approaches to sediment regimes emphasising morphology. These approaches, outlined in EMPHASYS consortium (2000), include: Holocene analysis (e.g. for sea-level changes, regression and transgression); concept of accommodation space; Historical trend analysis; sediment budgeting; characterising estuary form; regime relationships between aspects of form and (e.g.) tidal prism and sediment properties; tidal asymmetry; concepts of equilibrium along-axis profile and of translation (onshore and upward) or "rollover" with rising sea level.

The "Bottom-Up" (B-U) approach is *via* process-based models: mathematical (probably numerical), spatially-resolving, predictive (probably time-stepping), as expounded below. The processes are represented by fluid-dynamical and related equations for hydrodynamics, sediment transport, evolution of the bed (as required).

Phase 1 of the UKERP included detailed assessments of the capabilities and limitations of B-U and T-D approaches; see EMPHASYS consortium (2000).

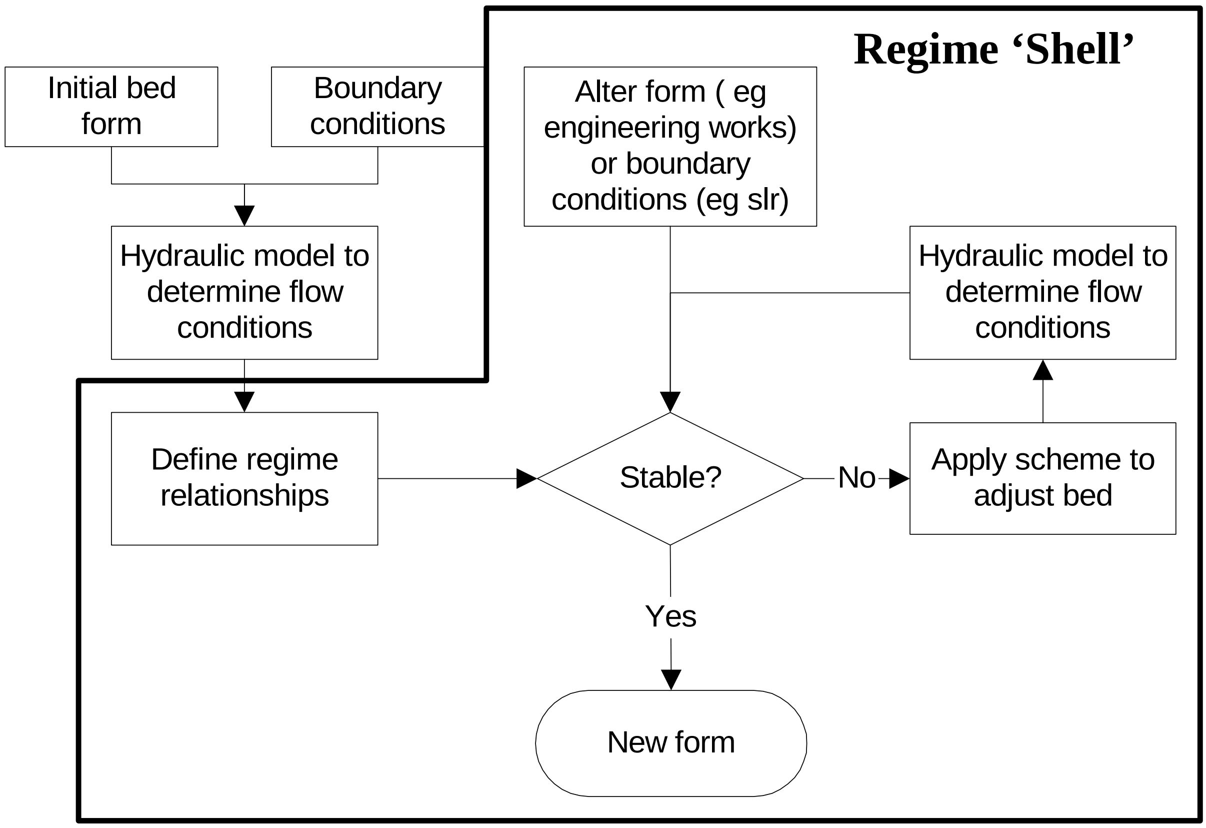


Figure 3.1 Conceptual diagram for hybrid linking of B-U and T-D approaches

B-U and other approaches are converging. "Hybrid" approaches combine T-D and B-U elements (figure 3.1). [Typically, a T-D-concept equilibrium state is approached with rates and distributions provided by B-U models. Phase 2 of the UKERP has included development of Hybrid models, aiming to combine dynamics with observational experience.] B-U bed-evolution can be integrated over any desired area to correspond to the closely analogous T-D sediment budget. Advances are being made in types and possibilities of parameterisation at varied scales, e.g. vortex shedding and sediment suspension over a ripple is a process with recent improved understanding (Davies and Thorne, 2005) but typically parameterised even in B-U models. Sand waves might be parameterised or explicit, depending on model resolution.

3.2 "Bottom-Up" approach and models

We consider the "triad" elements in turn: hydrodynamics, sediment transport, bed evolution.

3.2.1 Hydrodynamics

This covers prediction of water levels, current speed and direction (hence discharge, density currents and secondary circulation).   Predictions use well-established fluid-dynamical equations for continuity and momentum (figure 3.2.1a). The domain may be fixed or use a prediction of bed evolution (within the triad). Typically, models' spatial and temporal resolutions are too coarse for individual turbulent structures and surface waves, and possibly too coarse also for fine-scale features of the domain, e.g. salt-marsh or inter-tidal flats with small creeks and channels. For these aspects, parameterisations are needed. Otherwise, the flow is supposed to be resolved in time and space (in the dimensions modelled), including distortion around bed-forms of scale O(0.1 - 1 km) as resolved in the model. [Regular grids are not well suited to complex topography. Some models use an irregular grid, e.g. with triangular elements in the horizontal, for locally-finer resolution where needed and better adaptation to curved boundaries and channels, for example].

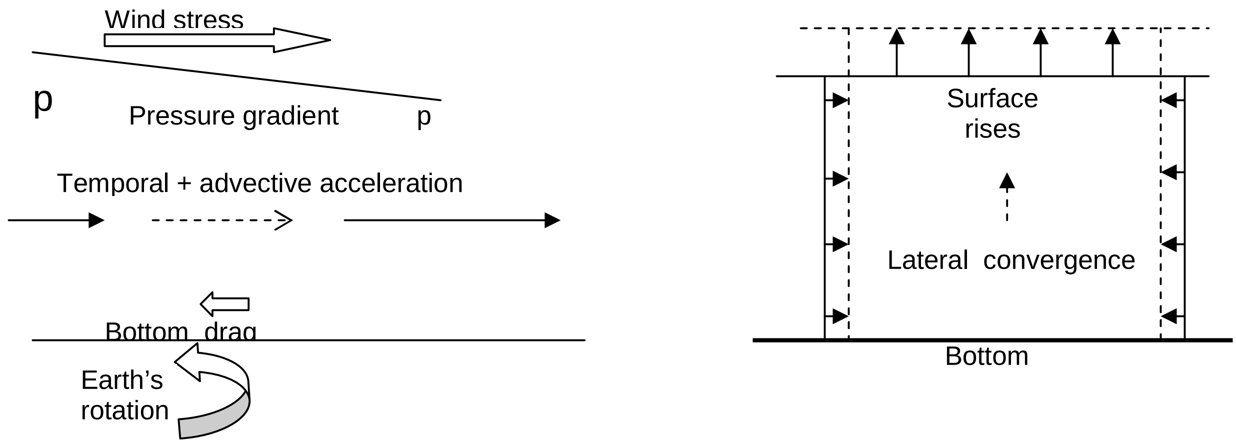


Figure 3.2.1a Forces in momentum equations; concept of continuity equation

Elevations and flow rates are well-described by depth-integrated non-linear equations (figure 3.2.1b), if the water is well-mixed in depth (and friction-controlled vertical profile and bed stress properly allowed for). Bottom friction is usually related to flow speed; an empirical coefficient implicitly represents a typical bed roughness with contributions from ripples and perhaps larger bed-forms. This is the typical limit to resolving intra-tidal changes in bed-forms and roughness affecting flow stresses, turbulence, current shear etc. Established models generally work well, even for tidal flow asymmetries causing net sediment transport. [Asymmetries are more subtle if the estuary is wide (kms) and residual circulations are steered around large bed forms by a pressure-Coriolis balance (Huthnance, 1981). Then accurate modelled residual currents depend on good representation of non-linear (momentum and continuity) terms and friction. Even so, relatively strong friction in shallow water enables models to work well].

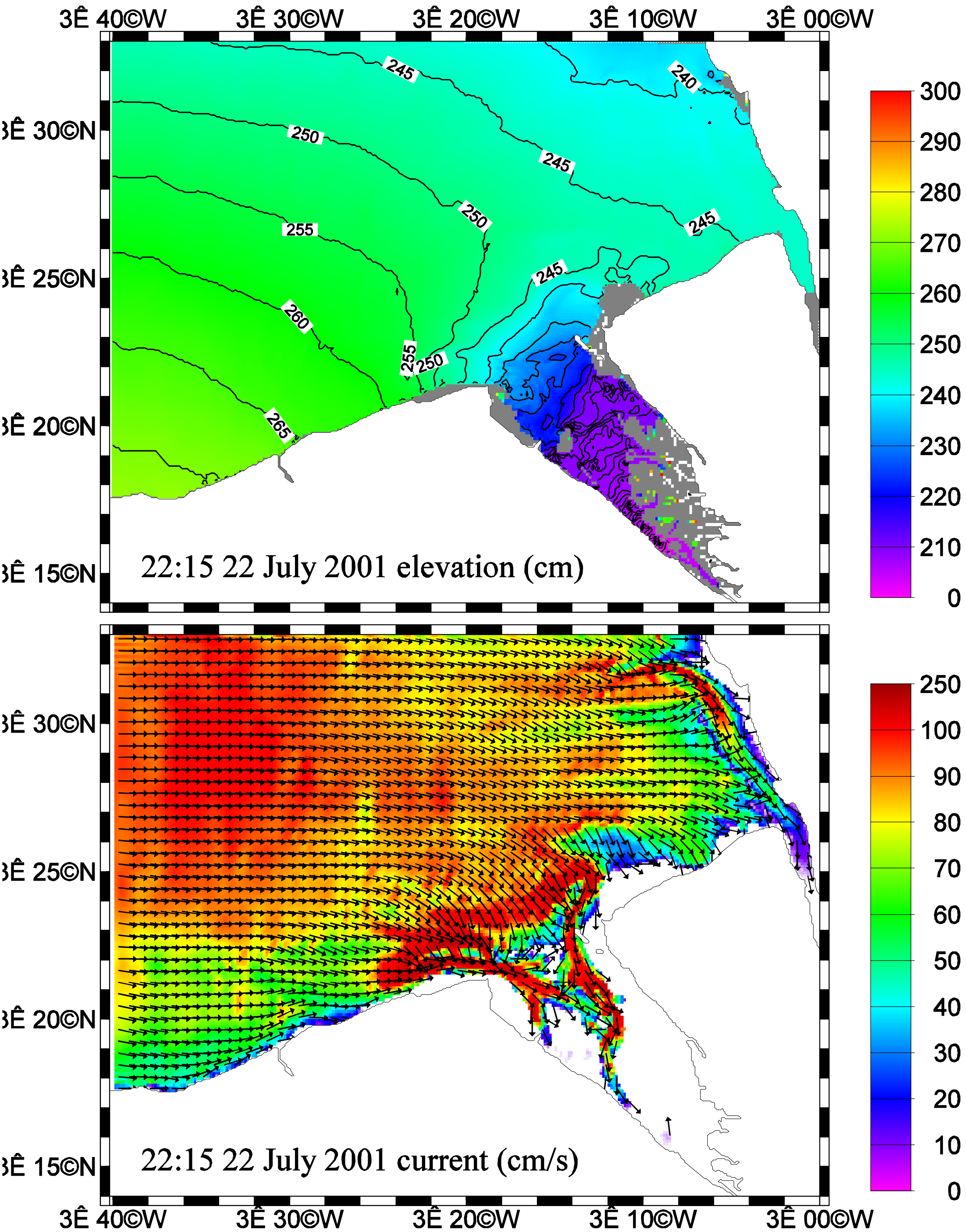


Figure 3.2.1b Illustrative output of 2DH hydrodynamics model, e.g. colour-contoured elevation and instantaneous current vectors on grid of actual estuary.

Variations of density and flow through depth depend on turbulent friction and mixing. Modelling of turbulence has been the subject of much study and is still an active area of research (Baumert et al., 2005). Whilst stratification tends to reduce turbulence and shear increases it, these effects may not be direct and local; internal waves on the stratification carry energy from place to place. Density stratification by suspended sediment (q.v.) equally tends to reduce turbulence, and can be similarly modelled – but rarely is. Unless the model has finer resolution than is normally practicable over a whole estuary, turbulence is usually wholly parameterised by two variables: (i) its total kinetic energy and (ii) a mixing length or dissipation. One or both of these may be evolved by a transport-type equation, but non-local effects of internal waves are not properly allowed for. Hence accurate modelling of vertical structure and mixing is still difficult.

3.2.2 Surface waves

Waves are usually the subject of a specific model for their spectrum (figures 3.2.2a, b). [Simpler representation as significant wave height and period effectively assumes a particular form of wave spectrum]. Such models are well established; they can include appropriate interaction with currents in shallow water, dissipation and input to water-column turbulence. However, these latter aspects are still research topics and would particularly benefit from dedicated validation data. Regular practice tends to use less complex models.

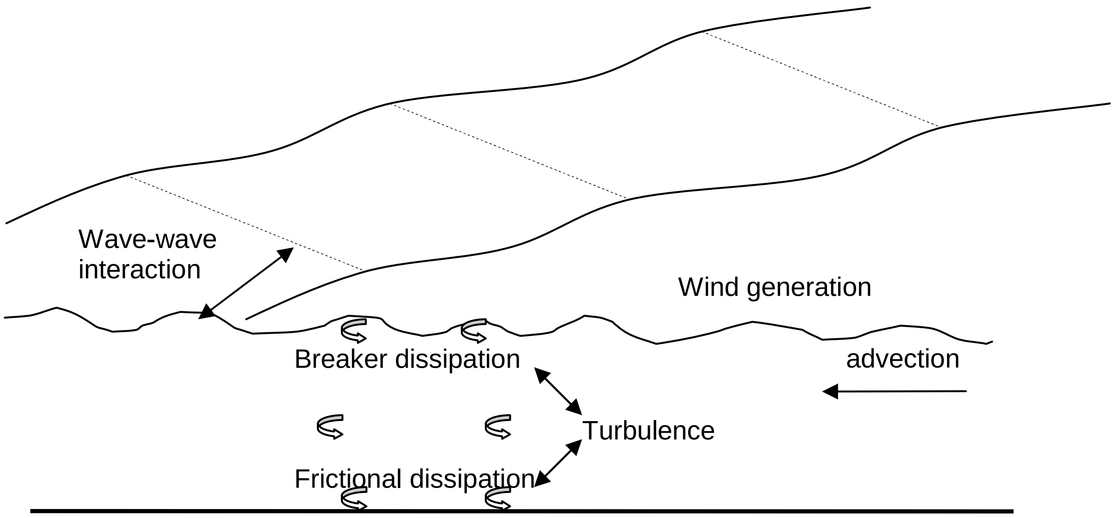


Figure 3.2.2a Elements of wave action equation

Winds drive flow in an estuary *via* their momentum input (as well as indirectly *via* waves generated). This is well represented in models if the wind stress is known. However, wind stress depends on wind velocity and the wave spectrum; to this extent the wind forcing is subject to the same *caveats* as the wave field. Research continues to seek full consistency between wind inputs to waves and to non-wave momentum in the water.

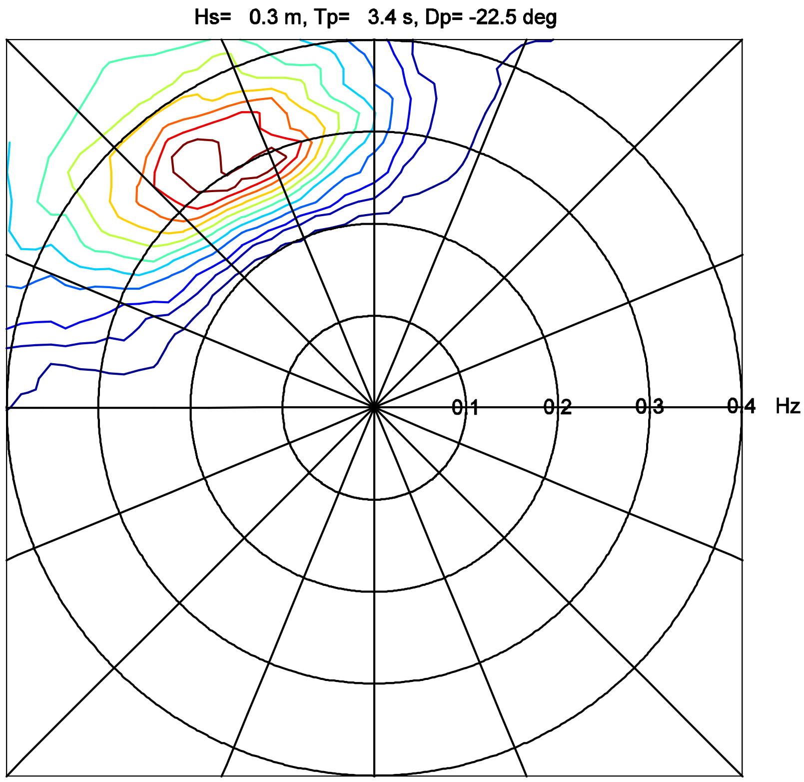


Figure 3.2.2b Example of Liverpool Bay model wave spectrum
for NW wind 5 m/s.

3.2.3 Sediment transport

This comprises bed-load and suspended load (figure 3.2.3). Along with patterns of erosion and deposition, these are predicted from the hydrodynamics. In the "triad", this is usually one-way coupling: hydrodynamics drives sediment transport. However, large sediment concentrations increase the water's effective density and stratification, typically damping turbulence or even (rarely) driving a turbidity current (obliquely) down a slope.

Bed-load sediment transport is typically calculated as a direct function of flow speed, sediment type and perhaps broader-scale bottom slope. Ripples and dunes are not spatially resolved but might be allowed for (effectively parameterised) in the calculation. Soulsby (1997) quotes alternative formulae for bed-load transport under steady currents, under waves (only) and under waves and currents combined. In the latter case, alternative values range over a factor of nine overall (the recommended procedure being in the middle).

Suspended load concentration may be estimated from an analytic form of profile and near-bed reference concentration, under steady currents or under waves and currents combined. Under waves alone, the suspended load is confined to a thin layer near the bed. Soulsby (1997) gives a calculation for waves and currents (close to an alternative on a similar basis). Another approach uses a transport equation analogous to the hydrodynamic momentum equation, with the same discretisation. Bottom boundary conditions change the suspended load through erosion rates and settling, related to flow-induced stress and critical stresses for the sediments. Davies et al. (1997) compare four such transport formulations; results are comparable with observations for waves and currents, within a factor of about three. In all approaches, fluxes are obtained by combining concentration and flow velocity.

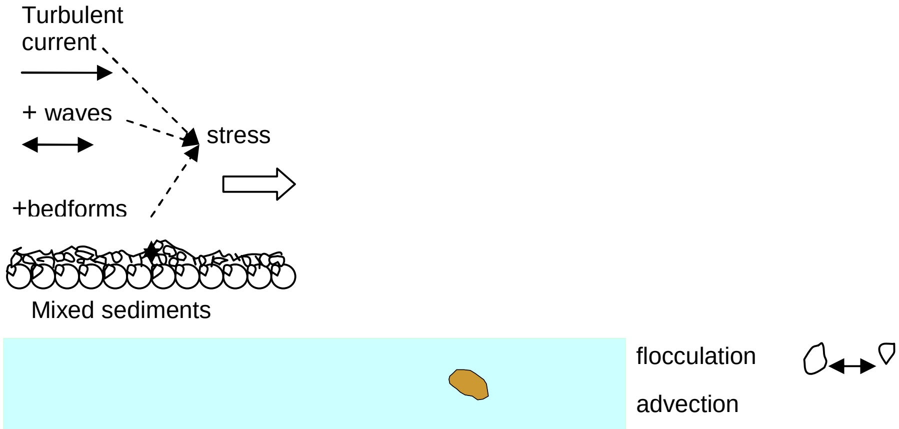
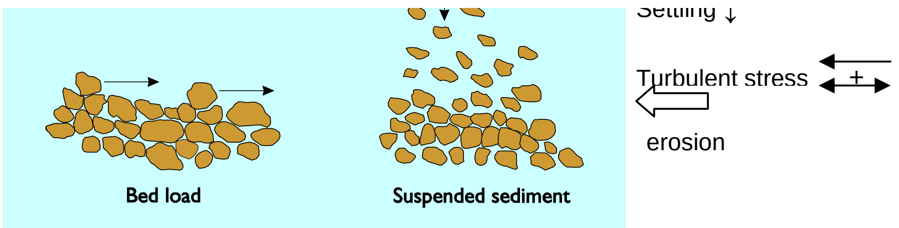


Figure 3.2.3 Bed load, suspended load and influences on them. Critical stress to move bed is a function of: bioturbation, sorting, organic%, cohesion, consolidation, wet or dry. Settling depends on flocculation and is retarded by upward-diplaced water at high concentrations.



The cited calculations are for bed- and suspended load of non-cohesive material. Cohesion can increase the critical stress for erosion, especially if the sediment has been on the bottom for some time. Flora and fauna can enhance this effect; however, bioturbation can reduce the critical stress for erosion. Wetting and drying can change bed properties in inter-tidal areas. In the water column, particles may flocculate [more if concentrated; turbulence encourages particle encounters, but too much breaks up flocs]. Flocculation means larger particles and hence faster settling velocities. Most of these complications are not so well formulated for model simulations, albeit formulations for floc formation and corresponding settling (e.g. Winterwerp et al., 2006) have recently been implemented. Typically, parameterisations of erosion and (dis)aggregation are simplifications, especially for mud or sand-mud mixtures; fluxes may be in error by a factor of three or more. Thus models can represent transport of non-cohesive material (sand, if supply is plentiful), along-shore drift of sand given the incident wave “climate”, and suspended transport of fines (possibly cohesive – mud; EMPHASYS consortium, 2000). It is harder to model limited sand supply, mixtures, fluid mud, erosion and consolidation of a cohesive bed.

Sediment parameterisations in models need calibrating for the particle properties in any particular estuary studied. [Data required for such calibration are discussed in Section 4.1].

An alternative approach for suspended material, viz. tracking particles advected by the model hydrodynamics, is now quite well developed by several groups (e.g. Lane, 2005; see Section 6.4).

3.2.4 Evolution of the bed

This is modelled *via* continuity of sediment: the bed level is updated for any divergence of modelled suspended-load and bed-load transports. [Divergence lowers the bed. Divergence of suspended transport = erosion – settling]. Porosity *p* can be taken into account (bed-level changes are simply increased by a factor $(1\text{-}p)^{-1}$ relative to the volume of sediment transport). Evidently the hydrodynamics (maybe indirectly) and sediment transport models provide the basis for this modelling of bed evolution. As part of the equation set, resolution would most simply be the same as for momentum and sediment transport. However, evolution on this spatial scale is relatively slow (compared with current reversals over a tide, say). Hence an acceleration factor is often used to reduce the total time of integration (but probably at the expense of the range of conditions integrated over, Section 2.2.1).

Formation of bed-forms of shorter scale than the model resolution has to be parameterised.

3.2.5 Water Quality and/or Ecology

These are typically modelled within the B-U hydrodynamic discretisation by means of transport equations for the various constituents. Advection and dispersion are in common with suspended sediment concentration, but water-quality and ecosystem constituents have particular sources and sinks (figures 3.2.5a, b). Pollutants may adhere to particles and possibly undergo chemical reactions. Plankton can grow (taking up nutrients and CO_2), respire and suffer grazing by other species. The ecosystem depends on light and temperature, giving a strong seasonal cycle in UK estuaries. There are models for these processes, many based firmly on laboratory experiment. However, ecosystem modelling of all individual species is impractical, yet there is no theoretical basis for partitioning to a feasible number of functional groups. In practice, models use empirical groupings; for each group, the models for growth, respiration and grazing can only be approximate; model-to-model variations are large. Primary production is necessarily modelled, sometimes for a few functional groups with different nutrient requirements; often secondary production (zoo-plankton) is modelled. Quantities higher up the food chain are less (often much less) predictable.

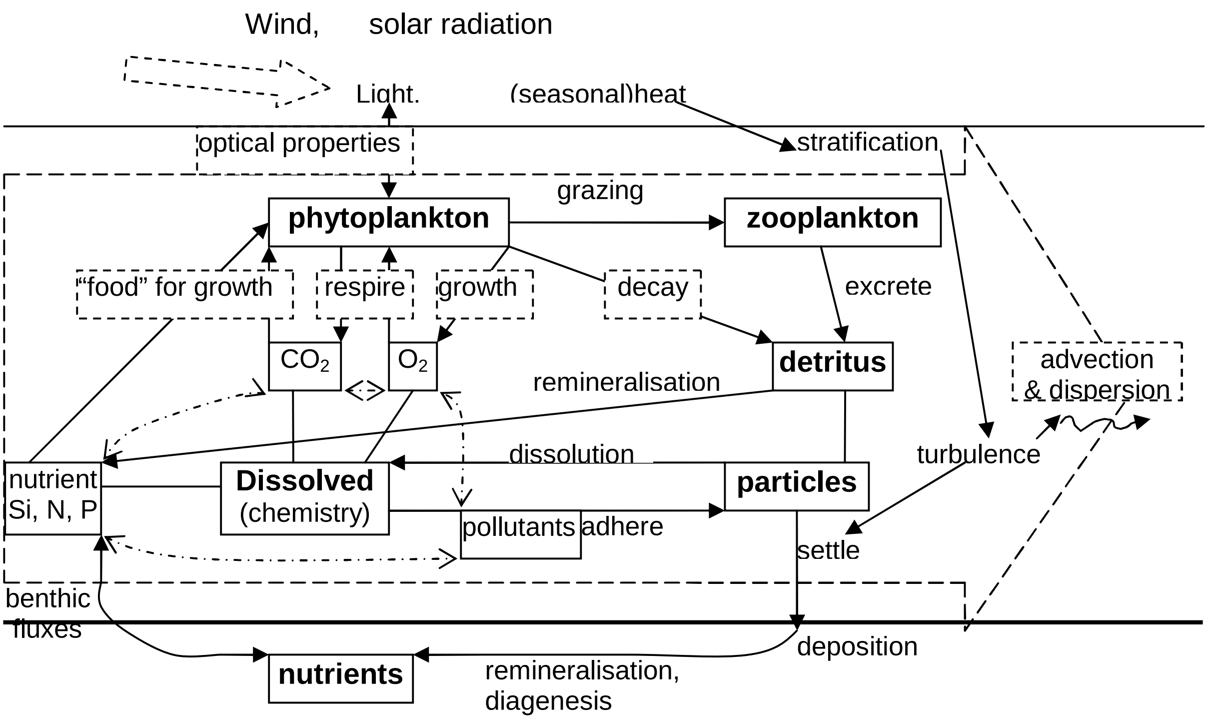


Figure 3.2.5a Sediment-water-quality-ecosystem processes

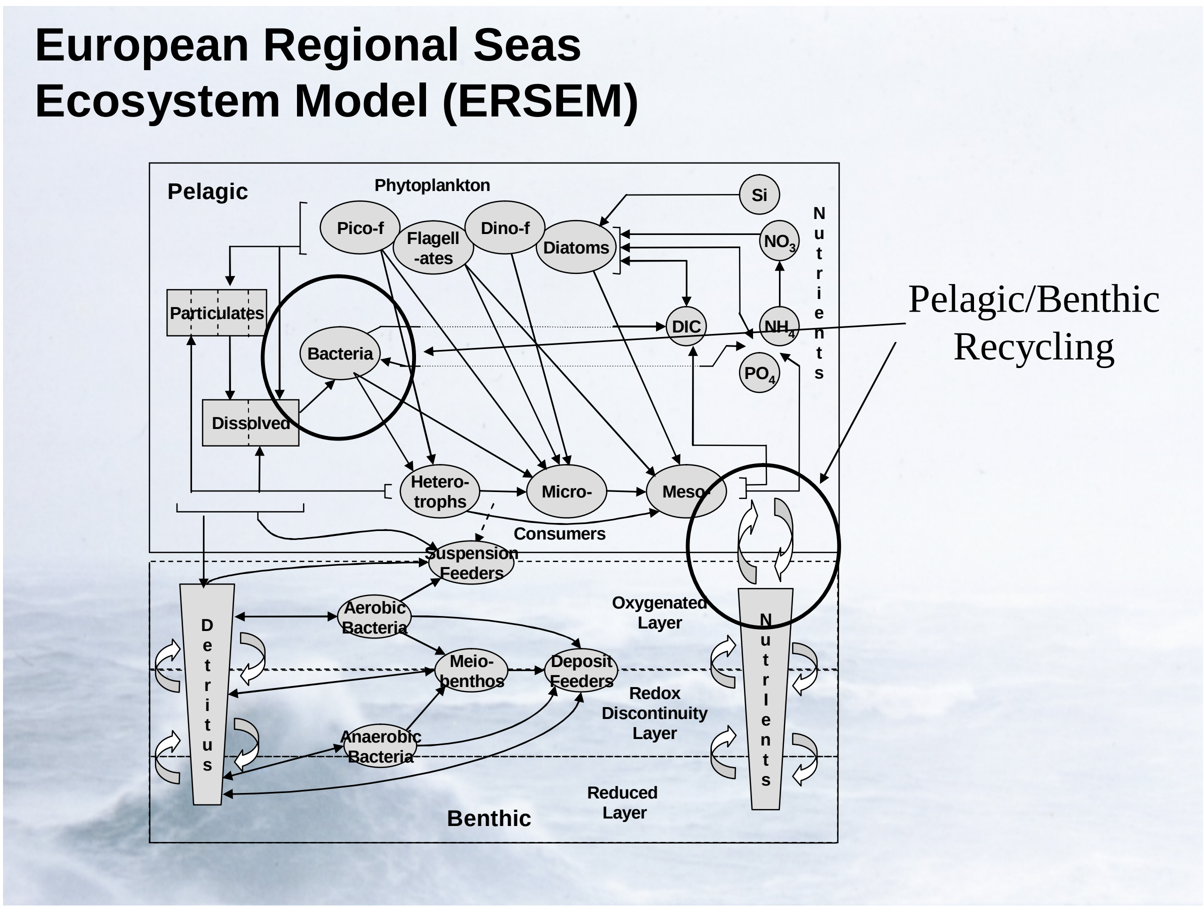


Figure 3.2.5b Diagram for processes in ERSEM

4. Outstanding issues

Progress is still needed in several respects to achieve validated numerical models predicting estuarine behaviour, especially for long-term changes in bathymetry.

4.1 Data and model testing

B-U models need data (figure 4.1a):
- for their formulation (especially, calibration of sediment-related parameters using sediment properties in the estuary studied),
- as forcing (particularly *via* boundary conditions),
- for testing and validation by comparing model outputs with measurements.

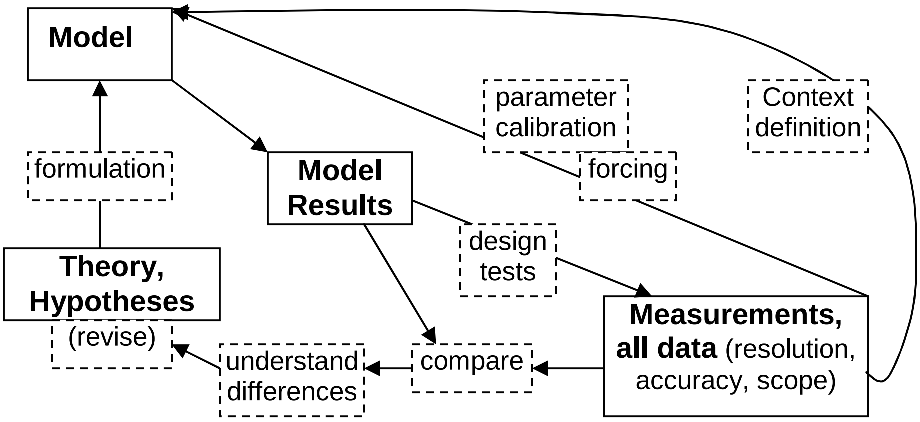


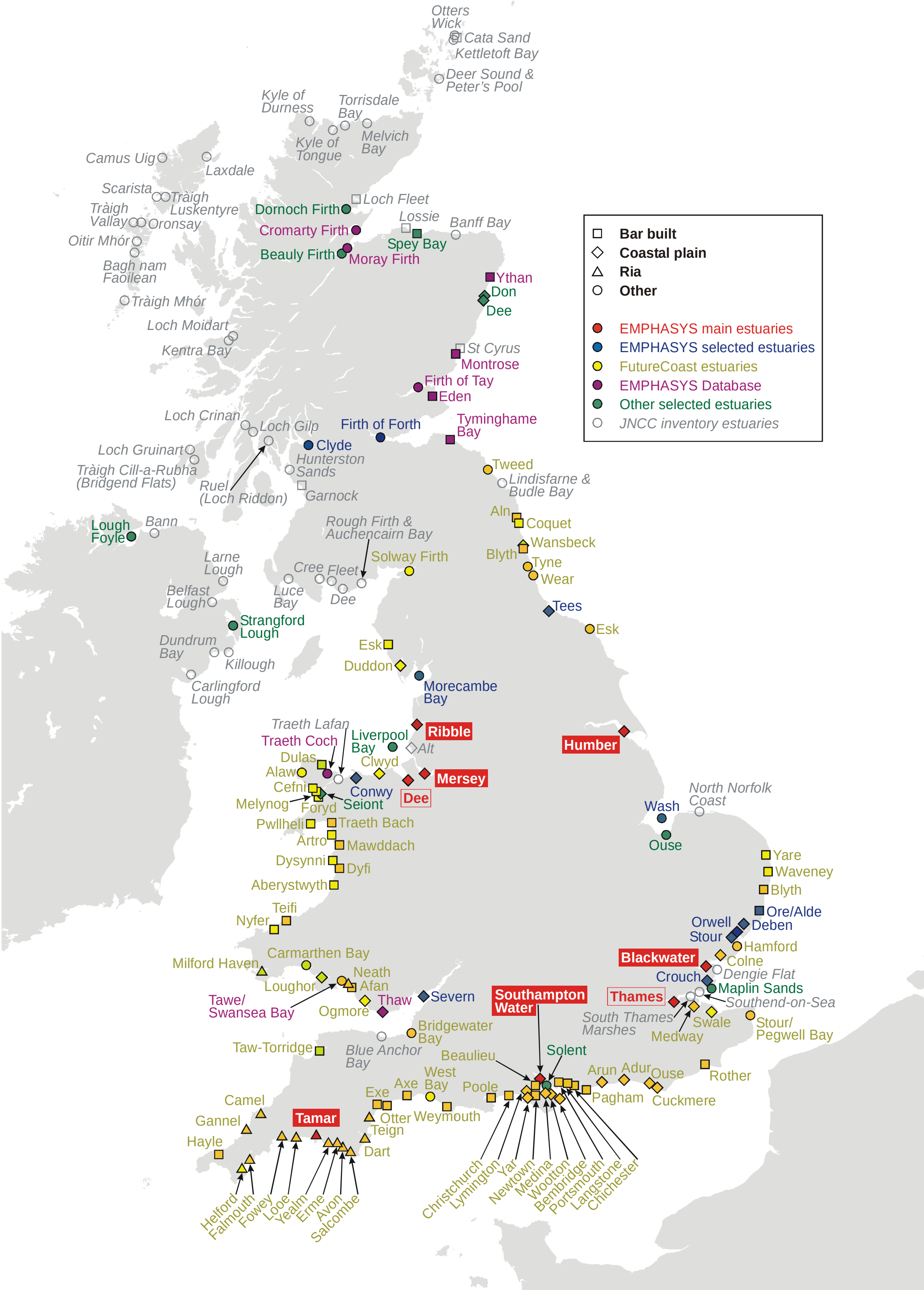
Figure 4.1a Diagram for model – data relations and scientific cycle

Here we consider testing. Model validation and confidence tend to decrease through the hydrodynamic, sediment-transport, bed-evolution sequence, because errors in the former affect the latter. For confidence in models of sediment, water quality and the ecosystem, validation of the hydrodynamic and sediment-transport elements is important. Moreover, test comparisons should involve all modelled variables that are critical to overall results, ultimately testing against sediment transport patterns as specific as possible to the location modelled. Good simulation of any one variable is not sufficient. For example, net transport depends on hydrodynamic biases and probably-uncertain sediment properties; corresponding validation needs data sufficient to resolve these biases and such uncertainties – and to define the context closely so that the model simulation should reproduce the biases; no “room for excuses”. Thus confidence in model predictions is best built up by testing them against all available observations in the specific estuary(s) studied – and by understanding differences between model results and measurements. Limited data may be partly offset by model sensitivity tests, but there is no substitute for data to test model performance.

Considerations for data sufficiency are resolution in time and space, accuracy (calibration of the measurements), variables measured, location(s) and time(s) of year to be representative. B-U model calibration certainly needs profiles of current (speed and direction), salinity and suspended sediment concentration through a spring and a neap tidal period. Direct measures of sediment properties should be obtained. [Compared with currents and elevations, sediment-concentration measurements remain imprecise, infrequent and localised, despite significant recent advances: acoustic, optical and laser instruments *in situ*; CASI and LIDAR remote sensing. The need to use concentration measurements in estimating fluxes adds uncertainty, especially for net residual values.]

At least two bathymetric surveys are needed to test any trend suggested by a model. The surveys need to be separated in time, enough to define their trend given their resolution and accuracy, yet close enough for the B-U model to be deterministic. [Increasing accuracy of bathymetric surveys is encouraging, and LIDAR gives the prospect of repeat surveys, but clear evidence is rare for spring-neap, seasonal, inter-annual or post-event changes]. Surveys used in this way require knowledge of any activities, e.g. dredging or reclamation, that may have affected the trend. In a complex estuary, or one with multiple users, proper interpretation of trends may be difficult.

To test models when data from the estuary in question are inadequate, it may be necessary to test the model on another estuary (as analogous as possible). EMPHASYS formed a data base (Townend, 2000; ABPmer, 2003) with detailed data for two coastal-plain estuaries with moderate tides (Blackwater, Southampton Water), three with large tides (Humber, Mersey, Ribble) and one ria with large tides (Tamar). There are summary data for 18 estuaries and contemporary bathymetry for 79 estuaries. Project FD2107 has extended the FutureCoast (Burgess et al., 2002) data for 65 UK estuaries (figure 4.1b; ??BODC ref later when done??). Some other studies with data in UK estuaries are given in Section 12 (as a route into a wider range of estuary types and relevant data; however, there is no reason to suppose that data from a previous study will satisfy the requirements of the case in hand).



EMPHASYS main estuaries, EMPHASYS selected estuaries (not the main estuaries), FutureCoast estuaries (not included above), EMPHASYS Database estuaries (not included above), Other selected estuaries, *JNCC inventory estuaries* (not included above).

4.1b. *UK map marking estuaries with data from the various sources mentioned*.

4.2 Instability

Individual model components forming the “triad” are usually well-tried; for them, instability need not be a problem. However, (bedload) sediment transport and bed evolution may form a diffusion-type equation $\partial h/\partial t - K\partial^2 h/\partial x^2$ = “source” (1D form). Numerical stability limits the time-step to $\Delta t < (\Delta x)^2/(2K)$ which is very restrictive for fine grid resolution Δx. Here

$K \sim 2\pi C U^3/[g(1-p)\tan\alpha]$ (e.g. Huthnance, 1982)

$\sim 3.10^{-3}$ (3.10^{-6}) m^2/s for total current U = 1 (0.1) m/s

[where quadratic bottom drag coefficient $C \sim 0.002$, gravitational acceleration $g \sim 10$ m^2/s, porosity $p \sim 0.4$, angle of repose $\alpha \sim 35°$. The term in $\tan\alpha$ (hence K) derives from assuming a down-slope component of sediment transport.] So bathymetric updates every few hours may be necessary for 10m model resolution.

4.3 Cost

Computational costs of long B-U models runs may seem prohibitive. However, this cost can be reduced by using an acceleration factor for the morphological evolution (e.g. Price and Norton, 2000). In effect this extrapolates to long times the particular sediment properties and biases (from tidal residuals, storms etc.) sampled in the runs as carried out. Sampling a wider range of conditions (i.e. more scenarios, perhaps of changed conditions in future) necessarily involves more modelling, B-U or otherwise.

Computational cost is decreasing as computer power increases. However, interpretation of ever-increasing model outputs is a growing cost in experts’ time. This consideration urges careful design of model experiments and ensembles.

5. Factors in model choice

The approach to any study, and the choice of models used, depends on the following (EMPHASYS consortium, 2000):
- the issues of concern (e.g., flood risk, morphology, water quality, ecology) in context
- character of the context
- the location's designated status (importance), hence level of confidence required in predictions
- scale of any proposed intervention
- previous studies (which should be reviewed in any case, and made use of as appropriate)
- best practice for the type of study or issues involved
- data availability; information needed to set up the model, data to calibrate and test it
- justifiable basis for model parameter values and ability to assess sensitivity thereto
- investigator's experience; hydrodynamic and morphodynamic complexity (Section 2.1) favours the use of previously-acquired skill to guide applications, so as to minimise uncertainty and errors due to stochastic processes and model simplifications
- study budget and duration. [A balance is needed. Sophisticated models tend to need more – and hence new – data; the demands on study budget and duration could be prohibitive. On the other hand, too simplistic a model may be no help].

"Model choice" may appropriately mean several simple models and inter-comparisons. Estuaries respond to varied natural forcing factors and human activities, hence processes and dependencies involved in the functioning of an estuary need to be understood. The aim to understand and predict argues for various analysis and modelling approaches and their interpretation, to give a convincing basis through inter-comparison and understanding of differences, and to assess the sensitivity of outcomes to model formulation. This aim also favours using models that are simple enough to understand and run quickly; then multiple runs (ensembles, not too hindered by costs) can sample a wide range of conditions (i.e. scenarios, perhaps of changed conditions in future). We now discuss how issues of concern may bear on model choice. The other factors in this section are specific to particular studies and hence are treated (sometimes implicitly) in the Section 6 discussion of models' appropriateness.

5.1 Issues of concern

The questions at issue in any particular project (flood risk, sediment regime, water quality, ecosystem and/or morphology; figure 5.1) should guide the balance of observational, analysis and modelling approaches. No one (modelling) approach is likely to be adequate. Possible questions (e.g. EMPHASYS consortium, 2000) include:
- direct impacts of intervention (e.g. broad-scale flood defence strategy or habitat management; local dredging, reclamation, construction or outfall siting);
- impacts on morphology, of sea-level rise, climate change, tidal processes, waves, fluvial processes, sediment supply and dynamics, geology; associated ecology, water quality;
- how present morphology arose.

The latter questions (underlying geology, ecology, water quality, how present morphology arose) require a wider perspective in time or scope (discipline) than the others, which are largely physical and decadal or shorter-term.

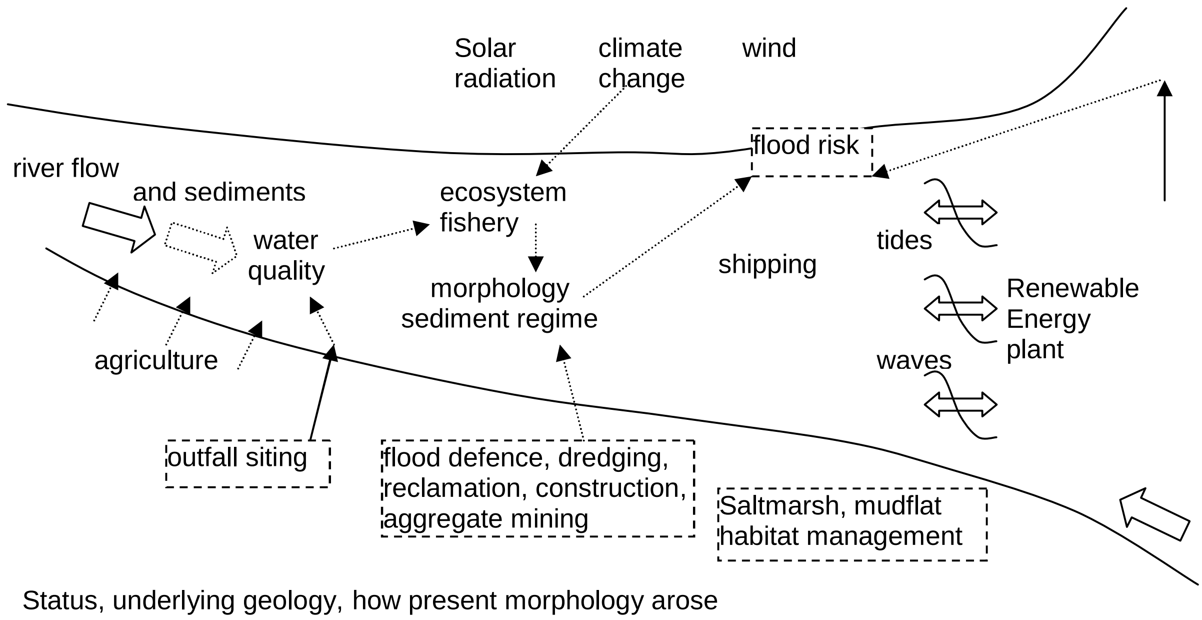


Figure 5.1 Possible influences on an estuary and impacts

Shorter-term prediction is widely regarded as most suitable for (fine-resolution) B-U model application. However, B-U models embody physical conservation laws which may provide important long-term large-scale constraints, and time-scales are short for "chaotic" growth of small-scale bed-forms. [Larger scales are predictable for longer, Section 2.2]. Thus B-U models may predict overall patterns or trends better than small-scale channel alignment, for example (Price and Norton, 2000).

B-U models are necessary for water-quality modelling. For morphology, complementary studies should help to understand estuarine function and give confidence to interpret model outcomes. Such complementary studies – "expert geomorphological assessment" (e.g. Pye and van der Wal, 2000) – may include T-D approaches (Section 3.1) and information about current processes, sediment properties, bed forms and geological constraints.

In parallel with morphological, water-quality or ecosystem questions, there may be a socio-economic management goal. Typically, this envisages various possible future scenarios (for the context and possible management action). If probabilities can be attached to the future scenarios, then model predictions give a corresponding probability distribution of outcomes, a natural basis for management decisions to optimise expected benefit.

6. Model characteristics (relative to factors in choice)

We consider in turn: hydrodynamics, sediment transport, bed evolution and water quality (see also EMPHASYS consortium, 2000).

6.1 Hydrodynamics: larger-scale currents, mixing

Here we discuss water levels, current speed and direction integrating to transport, density currents and secondary circulation. These aspects underpin all others. Waves are discussed in Section 6.2. The domain depends on the prediction of bed evolution (Section 6.5).

1D models can represent tidal surface elevations and up/down-stream transports of water quite well (figure 6.1: 1D), as found in the Humber after detailed calibration (Wright and Norton, 2000) and in the Mersey (Prandle and Lane, 2000). Even for elevations and transports, non-linear (momentum and continuity) terms and friction need good formulations. Wright and Norton (2000) ascribe poorer modelling of Humber neap tides to increased non-linear and frictional effects as compared with springs.

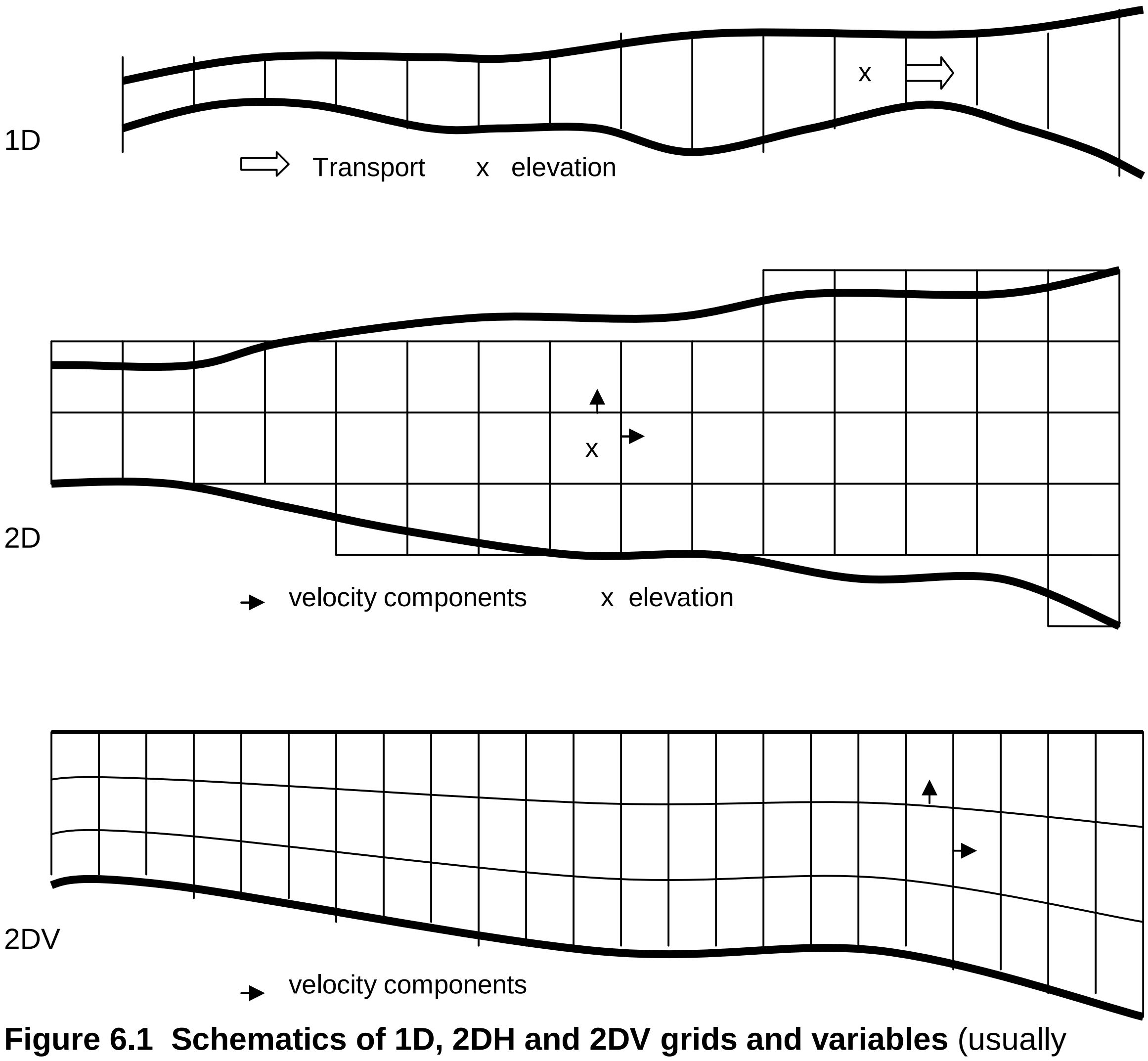


Figure 6.1 Schematics of 1D, 2DH and 2DV grids and variables (usually evaluated at centre of grid cell or face).

However, 1D models cannot represent vertical shear or transverse components of flow. For arbitrary cross-sections, they have no means to represent realistic friction, flow or sediment distribution. They are probably at their best for fine sediments (suspended through the water column) in narrow, short estuaries (little Coriolis effect; continuity rather than dynamics constrains the flow). If an estuary is long (near-resonant) or large (volume comparable with an adjacent coastal sea), then the estuary dynamics probably affect the adjacent coastal sea significantly; then the coastal sea should be modelled, certainly in two horizontal dimensions. Such an extended area complicates the application of open boundary conditions (Sections 8.1, 9.1).

Among important terms contributing to suspended sediment flux, a 1D model can represent mean advection, Stokes drift and tidal pumping [from temporal correlation of ebb and flood with suspended concentration; as found in a case study of the Humber (Dyer, 2000)]. With strong assumptions for water levels and associated flow continuity, lateral flow to and from inter-tidal or "storage" areas per model segment might be estimated (Uncles et al., 2000).

1D models are relatively quick and easy to run, an advantage if many scenarios are to be run.

2D (depth-averaged; 2DH) models can usefully represent the shape (plan and 2D bathymetry) of the estuary (Figure 6.1: 2D); a curvilinear or "unstructured" grid may also give finer resolution locally. In particular, 2D models can represent an adjacent (open) coastal-sea area; this generally forms the offshore boundary (Thomas, 2000) and is often an important source of sediment in the estuary. 2DH models can represent the Coriolis effect, transverse components of flow, realistic friction and non-linearity *via* the distribution of flow through an arbitrary cross-section (shallow water lends importance to friction and non-linearity). Many features and distributions of estuarine flows can thus be represented: tidal current speed and direction, and waves sensitive to depth and fetch, leading to areas of potential net erosion, deposition and sediment transport. 2DH models cannot *per se* represent secondary circulation, whether transverse and vertically sheared as at bends, or driven by lateral differences in salinity due to differential ebb or flood currents. Nor can 2DH models represent estuarine circulation (surface outflow to the sea, and bottom inflow); however, an analytical representation might be added, e.g. (Prandle, 1985)

$$\text{down-estuary } U = g\, S_x\, D^3/\upsilon\, (-z^3/6 + 0.2687z^2 - 0.0373z - 0.0293).$$

[Here the current U has zero depth-mean to represent shear, g is gravitational acceleration, S_x is down-estuary salinity gradient, D is water depth, z is height above bed relative to D, υ is depth-mean eddy viscosity]. Friction needs to be represented well because it can strongly retard tidal currents (Prandle, 2000), especially over shoals. Form drag over a rippled bed can be an important frictional effect. Soulsby (1997) gives procedures for calculating the total bottom stress (skin friction and form drag) under currents and/or waves. Friction and non-linear momentum and continuity terms need to be accurate to simulate residual currents (hence tidal asymmetry; Huthnance, 1981).

If the density or flow varies through depth, the vertical dimension should normally be resolved in the model (thus 3D – or 2DV, see below). Then the (turbulent) frictional forces and mixing that control the variations through depth need to be well represented. Thereby many processes having or depending on vertical structure can be properly represented:

- estuarine circulation; river inflow at the land-ward end and bottom inflow from the sea

- bottom stresses, erosion and deposition sensitive to the estuarine circulation
- separate paths of coarse sediments near the bed, finer sediments ranging higher in the water column (Prandle & Lane, 2000) and (non-settling) dissolved constituents
- estuarine turbidity maxima and deposition associated with the river flow
- marine supply of sediment associated with bottom inflow at the sea-ward end.

Thus 3D (or 2DV, see below) is needed to model the important terms in suspended sediment flux not handled in 1D: vertical shear correlating with depth-dependence of suspended sediment concentration (Dyer, 2000). 3D is needed to represent all contributions to shear, hence dispersion and extensive mixing, probably important for water-quality modelling. If the vertical eddy viscosity is prescribed, then the model is simpler and quicker to run, but in effect the vertical profile is controlled by the bottom-frictional boundary condition and 2D dynamics. Estuaries where stratification significantly affects the flow need a more responsive vertical eddy viscosity, usually by evolving the turbulence through time; in turn, turbulence is affected by vertical gradients of density (a function of salinity, also of temperature and of suspended sediment concentration if these vary strongly). A factor countering resolution of the vertical is the dependence of stratification on precipitation, evaporation and heat flux data; they are less generally available and possibly less accurate than winds (for example, judged by relative error in derived fluxes).

As in 2DH, an irregular grid, e.g. with triangular elements in the horizontal, can give locally-finer resolution and better adaptation to curved boundaries and channels.

Salinity can be a significant factor even in improving modelled tidal elevations, e.g. in 2DH or 3D models of the Humber (Wright and Norton, 2000; by inference, in 1D models also).

2D (transverse-average; 2DV; Figure 6.1: 2DV) models may be useful if the estuary is stratified but relatively uniform from one side to the other. They have the limitations of 1D models, relative to 2DH, but share an important capability with 3D-models: to represent the vertical structure of flow – hence estuarine circulation, bottom stresses, suspended sediment flux resulting from vertical shear correlating with the depth-dependence of suspended sediment concentration.

Sparsity of information may reduce the usefulness of more dimensions in the model. For example, limited accuracy and availability of precipitation, evaporation and heat flux data for stratification effects may reduce the benefit of resolving the vertical in the model (Section 9.2). Lack of bathymetric data is often a limit on model resolution; furthermore, there is little merit in a cross-channel dimension if there is only one depth measurement across the channel. On the other hand, human constructions, inputs and extractions are on typical scales 1-100 m or so. These need either local resolution (possibly too fine to extend to the whole estuary) or parameterisation with its inherent assumptions, e.g. discharge becomes a source homogenised through a whole grid cell. Such pressure for fine resolution may favour a 2D over a 3D model for feasibility of computation, especially if many scenarios are to be run.

Some examples of hydrodynamics models in use are given in table 6a.

Table 6a Some B-U Models used by ERP participants

Type / Name	Dimensions	Description	Reference or Web site
Hydrodynamics			
POL "2.5D"	2DH	C-grid, depth-integrated, prescribed friction→**u**(z)	Lane and Prandle (2006)
Telemac	usually	Unstructured grid	See note[HT]

	2DH		
MIKE	1, 2 or 3D	Free surface flow	http://www.dhi.dk/Produkter.aspx
POLCOMS	3D	B-grid, predicts current, turbulence and density	Holt *et al.* (2005)
Waves			
Pro-WAM	2DH	Spectrum (frequency, direction); WAM adapted for fine spatial resolution	Monbaliu *et al.* (2000)
ECMWF operational (ECWAM)	2DH	Spectrum (frequency, direction) WAM version at ECMWF, coupled with atmosphere; assimilation	http://www.ecmwf.int/research[WE]
K-model	2DH	Spectrum (wavenumber, direction); source functions differ	See note[WK]
SWAN / TOMOWAC	2DH	Spectrum (frequency, direction); implicit solution for propagation; for limited areas of fine resolution	Booij *et al.* (1999), Ris *et al.* (1999)[WS]
WaveWatch III	2DH	Spectrum (wavenumber, direction)	See note[WW]
Sediment Transport			
POLCOMS	3D	Suspended concentration equation with erosion, settling	Holt and James (1999)
SUBIEF	usually 2DH	suspended sediment (mud) transport module of Telemac	See note[SS]
MIKE	2D	With MIKE hydrodynamics	http://www.dhi.dk/Produkter.aspx
Particle-tracking			
POL Lagrangian	"2.5D"	Suspended fines advected with "2.5D" flow plus settling, random vertical displacements proportional to vertical diffusivity	Lane and Prandle (2006)
SandTrack	2DH	Sand erosion, Lagrangian transport, deposition, burial	Soulsby *et al.*, 2007
Bed Evolution			
SandTrack	2DH	Aggregates deposited "lenses" of tracked particles	Soulsby *et al.*, 2007
Ecosystem			
ERSEM	3D	Coupled to hydrodynamic model (e.g. POLCOMS). All trophic levels and several compartments in each. Also Benthic ecosystem component.	Lewis *et al.*, 2006

[HT]Web site http://www.telemacsystem.com/gb/info/comm/telemac2d/telemac2d.html
[SS]Web site http://www.telemacsystem.com/gb/info/divers/prtx-gb.pdf
[WE] Specific Web site http://www.ecmwf.int/research/ifsdocs/WAVES/index.html
[WK]Web site http://www.baw.de/vip/en/departments/department_k/methods/hnm/kmodel/
[WS]Web site http://vlm089.citg.tudelft.nl/swan/index.htm
[WW]Web site http://polar.ncep.noaa.gov/waves/wavewatch/wavewatch.html

6.2 Hydrodynamics: waves

Waves have important roles. They mobilise sediment effectively because rapidly-varying bottom currents induce a thin boundary layer with large stresses. Thereby waves inhibit rapid shoaling of bed forms, provide some natural stabilisation and improve predictability (particularly in models with two horizontal dimensions). Wave breaking is a source of turbulence and helps to mix the upper water column (perhaps mixing right through shallow estuarine waters). Energetic waves can also influence the longer-period, larger-scale flow through enhanced surface and bottom stresses and radiation stresses from waves' mean momentum.

However, wave heights and periods depend on the particular estuary. Except for a small range of directions nearly aligned with the (outer) estuary, incident waves often fail to travel far into an estuary, because (i) the estuary may be in the "shadow" of adjacent land, (ii) long waves are damped rapidly in shallow water, (iii) near an estuary mouth, ebb and flood shoals often effectively dissipate much incident wave energy. Hence local wind-generated short waves may dominate except near the mouth. In some contexts, ship waves may be significant. [As an approximate calculation, energy input from wind speed w into the water is stress $\rho_a C_w w^2$ times w, if the stress is supposed to act primarily to generate waves moving approximately with the wind speed; here ρ_a is the density of air, near 1 kg/m^3, and C_w is the drag coefficient of order 0.001. Energy input from a ship is $\rho_w C_s a^2 u^3$ where ρ_w is the density of sea water, near 1000 kg/m^3, C_s is the ship's drag coefficient of order 0.1, a^2 is the cross-sectional area of the ship of order (0.1 tonnage)$^{2/3}$ and u is ship speed. The ratio is

$$(\rho_w/\rho_a)(C_s/C_w)\,(0.1\ \text{tonnage})^{2/3}\ (10^{-6}\ \text{number of ships / km}^2)$$

if ship and wind speeds are comparable. Thus ship and wind-wave inputs may be comparable for one 10^4tonne ship per 10 km^2 unless winds are strong.]

Wave modelling can be a challenge. Wave-current interactions are typically strong and varied: depths vary spatially and tidally, and currents distort slowly-propagating short waves. The computational cost for a full wave model (including nonlinear interactions) may be several times that of a 3D hydrodynamic currents model. However, the only extra data needed to set up and run a wave model are waves at the outer boundary. To reduce the cost of computing, a "library" of scenarios might be run: a range of incident waves at the outer boundary, high and low water as well as peak flood and peak ebb, combined with a range of wind directions. "Parametric" models that predict only a few wave statistics can be run more economically, preferably after calibration, and may be preferable if many scenarios are run.

Simulating the larger-scale effects of waves requires two-way coupling of wave and current models throughout model runs (as distinct from the "off-line library" approach).

Some examples of hydrodynamic-waves models in use are given in table 1.

6.3 Sediment transport

According to context, models may need to predict bed-load (especially for sands and larger particles), transports of suspended particles (fine sands and smaller) and patterns of erosion and deposition. If concentrations of sediment are dense, effective density and stratification may need to feed back to the hydrodynamic model to dampen turbulence or drive a turbidity current. More often, varied sediments may need to be modelled. Because larger particles settle fast, they may be carried shorter distances after mobilisation and have varied concentration reflecting immediate local conditions. By contrast, fine sediments can be held in suspension for days with a larger-scale distribution (and greater concentrations according to the supply). Typically simplified and inaccurate parameterisations for mixed sediments imply a need for calibration (see Section 4.1). At least settling velocities, erosion threshold (possibly varying with depth into the bed), particle size distribution and consolidation rates are needed for typical models. Calibration is complicated for detailed models with many parameters (e.g. Price and Norton, 2000) which may be difficult to distinguish in comparing models with validation data.

Commercially-available models can typically represent transport of non-cohesive material (sand) if supply is plentiful, transport of cohesive material (mud) in suspension (EMPHASYS consortium, 2000) and along-shore drift of sand in a given incident wave "climate". Other aspects of sediment transport are more difficult and tend to need specialist attention: supply-limited sand transport, mixtures, flocculation, fluid mud, erosion and consolidation of a cohesive or biologically mediated bed. Care should be taken for good representation of sediment supply, which can be an important factor in predictability.

Some examples of sediment transport models in use are given in table 1.

6.4 Particle tracking

This is an alternative approach to modelling sediment transport. Again, the hydrodynamics are the main input. Many thousands of notional particles are advected with the local flow (usually plus a random displacement at each time step to represent dispersion). This approach enables individual particles to have a "history", especially useful if they are biogenic and for modelling cohesive behaviour, consolidation on the bed with increasing resistance to erosion, etc. Concentrations and emergent properties are recovered from the number and character of particles in any chosen volume and time.

In comparison with a concentration equation, advantages of particle tracking can be:

- retention of information about each particle, e.g. age, size, origin, position (history)
- less prone to numerical dispersion
- more accurate advection
- efficiency where confined to part of the model domain – with more scope in 3D.

Possible disadvantages of particle tracking are

- spurious accumulation in low-diffusivity regions (can be overcome: Hunter et al., 1993)
- computational effort: accuracy improves slowly, as $(\text{effort})^{1/2}$.

Accuracy depends on a combination of model resolution and number of particles chosen to represent the whole mass.

Some examples of particle-tracking models in use are given in table 1.

6.5 Bed evolution

This is necessarily modelled with the same number of horizontal dimensions as the models of hydrodynamics and sediment transport which are the input; the horizontal grid should also be the same. Porosity should be taken into account. However, temporal resolution is a matter for choice. For short durations of model run, it needs to be fine enough to resolve accurately the biases through one tidal cycle or a storm (say). However, little change of bed is likely through one tide. An acceleration factor can reduce the number of tidal cycles integrated explicitly. A choice has to be made, balancing this saving against the need to cover a sufficient range of conditions: spring and neap tides, various storm tracks and intensities, waves from other storms and combinations of these factors.

Bed-forms (dunes, ripples) with scales O(metres or less) are not practicable for explicit model resolution. In any case their precise location is random. Only parameterisation by amplitude, wave-length and orientation may be predictable.

6.6 Water Quality and/or Ecology

Some applications need the sediment regime for its role in water quality or ecology. These are well-suited to a B-U approach, for ecological variables up to secondary production (zoo-plankton). Present practice is increasingly to model water quality and the ecosystem within the B-U hydrodynamic space-time framework. [Formerly, computation of many ecosystem variables with complex sources and sinks was only practicable for a relatively small number of sea areas; increased computer power has greatly reduced this problem]. The main choice is of the sub-set of water quality and/or ecosystem variables to be modelled, e.g. figure 3.2.5b. Water quality variables should be chosen according to the constituents of concern. For the ecosystem, if succession is an issue as one or other nutrient becomes depleted, primary production should comprise several functional groups. Secondary production (zoo-plankton) needs to be modelled if its variability precludes a fixed grazing rate on primary-production variables. Quantities higher up the food chain are less (often much less) predictable.

Some examples of water-quality and ecosystem models in use are given in table 1.

A summary of the forms of models relative to factors in their choice is given in table 2.

Table 6b Models relative to factors in choice; entries refer to (requirement for) *model* qualities.

Model	Hydrodynamics (flow)				Waves (+ 2DH minimally)	Sediment: use flow grid	Bed evolution: use flow grid (x,y)	Water quality / ecology
	1D	2DH	2DV	3D				
Issues:								
Flood risk	Can be OK	For complex domain	Little extra benefit		Needed if energetic			
morphology		minimal			mobilise sediment, mix water column	Essential	Essential	
water quality, ecology	minimal	For complex domain	For estuarine circulation (river flow, salt wedge)					Essential
Context:								
Vertical shear	Only by formula		minimal					
Transverse flow		minimal						
Secondary circulation				minimal				
Broad estuary		minimal						
Coastal sea		minimal						
Long estuary	Good friction needed							
Varying cross section		minimal						
Complex topography		Irregular grid?						
Mixed sediment			Need for coarse vs. fine			Need bedload for coarse		
Cohesive / biogenic sediment, flocs, consolidation						Particle tracking?		
Turbidity max; marine sediment			minimal					
Confidence decreases with scale of change; previous studies help	High within scope		Medium	Medium	High	Medium	Short-term: medium, Long-term: low	Medium
Need for data	Low	Medium	Medium	High	Flow model → Low	High	Low	High
Parameters:								
justifiable	Medium	Medium	Good	Good	Medium	Medium	Good	Medium / Poor
Assess sensitivities?	Good	Good	Good	Medium	Good	Medium	Good	Medium / Poor
Resource need	Small	Small	Small	Medium	Medium	Medium	Small	Medium / Large

7. Model Application and Shell

Multiple runs of a B-U model will probably be needed for reasons given in Sections 2.2, 5:
- to cover a wide variety of scenarios and future possibilities;
- to estimate the sensitivity of outcomes to context (boundary forcing);
- to treat uncertainties, e.g. sediment properties and model formulation, by using a wide variety of simulated characteristics;
- so to put error bars on simulations;
- to develop understanding by comparing results from different models.

Some form of easy-use interface (“shell”) is desirable,
- to aid multiple runs of different models and scenarios,
- to minimise user involvement with the “machinery” of model runs,
- to help focus on contextual variables.

FD2107 has developed an application shell (Figure 3.1): a standardised tool especially for coupling bottom-up hydrodynamic models (presently 1-D) and top-down morphological models. The shell is described in more detail in a separate report (ABPmer, 2006). In outline, the shell provides a basic framework within which hybrid morphological prediction tools can be configured and applied as part of an estuarine study. The hydrodynamic model component is pre-configured using the respective proprietary software, eg. MIKE11, ISIS (as adapted). The shell interface provides a link to standard top-down modelling concepts, such as the application of regime theory (Dennis et al, 2000). The shell handles the transfer of information between the separate models allowing long-term simulations to be undertaken. Using this approach a hybrid model can produce estuary morphologies for 50 years ahead, based on specified forcing conditions and constraints within the system.

8. Set up

8.1 Model boundaries

The estuary shape itself defines most of the model boundary. Decisions are needed about (i) upstream limits for rivers (ii) the outer boundary along adjacent coasts and offshore.

The river can participate in the estuarine dynamics along all reaches where the bed is below the highest adjacent sea-surface elevation; indeed further upstream than this if high waters "back-up" river flow and if high water levels increase up-estuary (through "funnelling"; figure 8.1). Such river-estuary interaction makes an upstream limit difficult to define. It should preferably be at the upstream limit of tidal influence or back-up (in fresh water) rather than the limit of saline intrusion further downstream. Then a boundary condition specifying river inflow to the estuary causes minimal distortion to the modelled estuarine dynamics. Often a weir defines the upstream tidal limit and forms a natural location for this boundary.

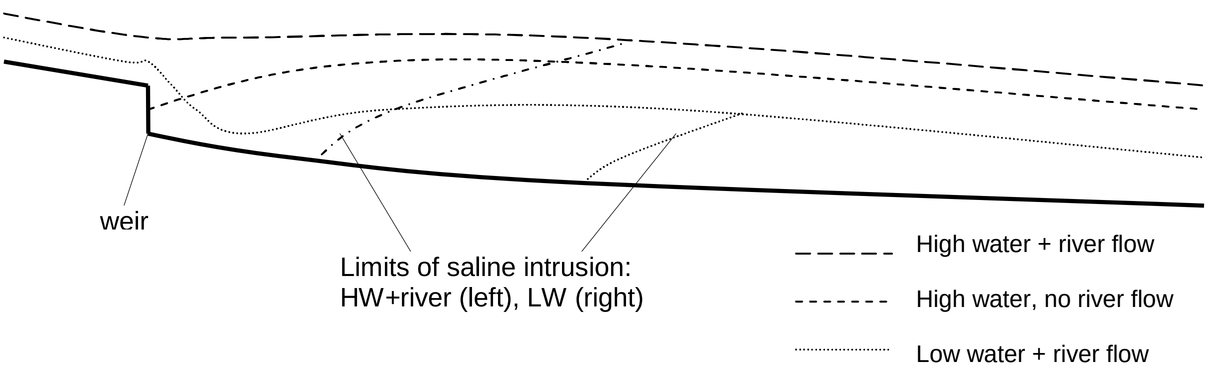


Figure 8.1 Different reaches in upper tidal estuary and location of river boundary

At the outer boundary, open boundary conditions will be applied to the B-U estuary model; probably these conditions allow little scope for amendment by modelled estuarine behaviour. Therefore the outer boundary should be taken outside the estuary beyond the influence of changes in estuary behaviour under the different scenarios modelled. Fortunately, most estuaries are small enough for this to hold true directly at the estuary mouth if the boundary condition prescribes elevation. Here "small enough" means
estuary volume << volume of adjacent sea supposedly controlling the prescribed elevation
and *estuary length << ¼ [g × estuary depth]*$^{1/2}$ *× time scale* to avoid resonance.
For example, estuaries of depth 10 m are "small enough" if much shorter than 100 km, taking gravitational acceleration g ~ 10 ms^{-2}, time-scale ~ tidal period ~ 4.2×10^4s. The Bristol Channel is a notable counter-example: to study effects of a tidal barrage there, the whole of the continental shelf west of the UK needs to be modelled (Proctor, 1981). A corollary is that 1D or 2DV models (i.e. only 1D horizontally) should not be applied to long estuaries for which an extensive adjacent sea should also be covered.

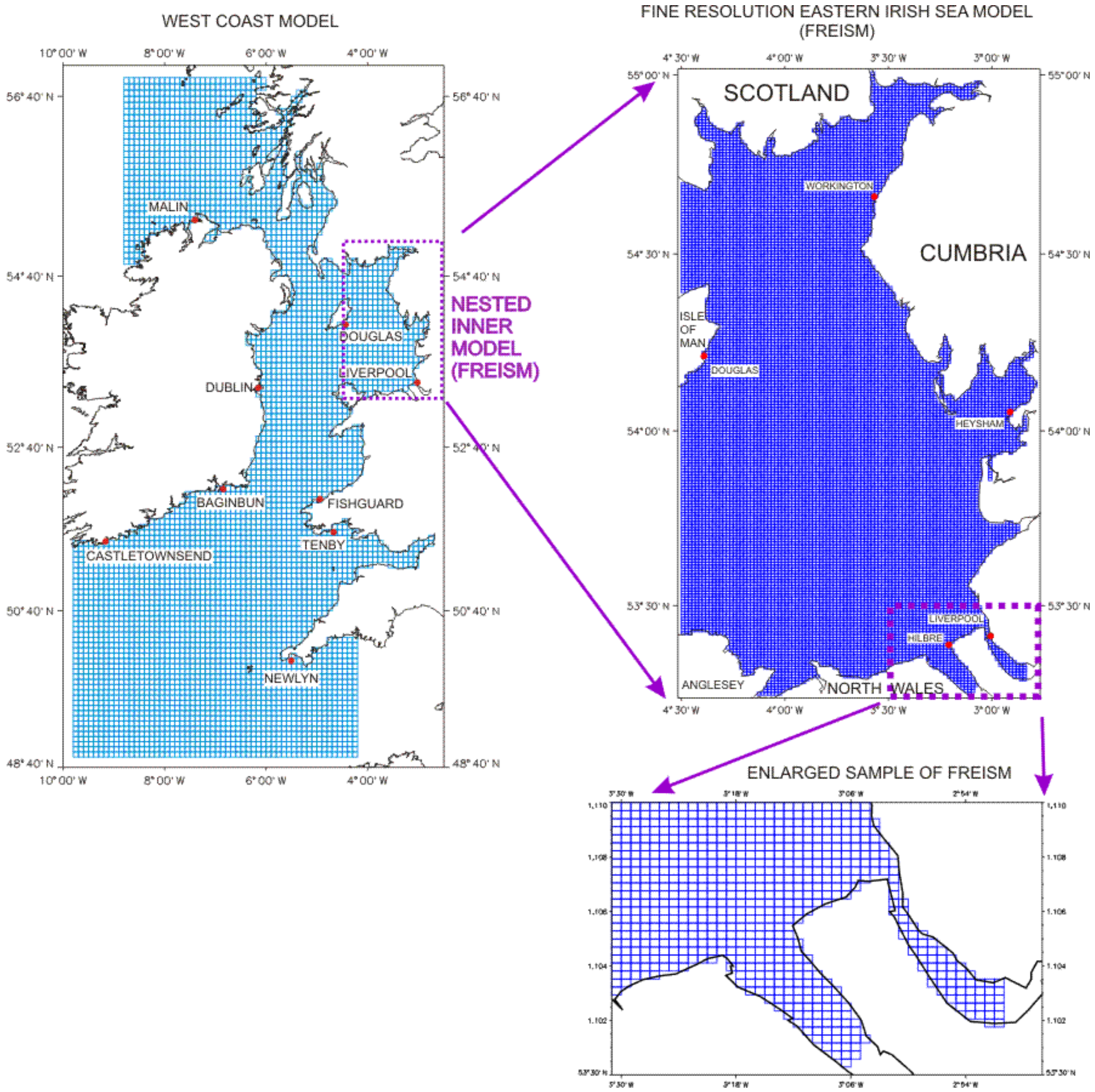
The discussion of model forcing (Section 9) shows that boundary conditions for the estuary mouth are often simpler and certainly need less information than for an extensive open boundary. Tides, surges and waves are cases in point: (i) the condition for a long open boundary may need to be radiational, or even require iteration over model runs, whereas simple specification of boundary values suffices at the estuary mouth; (ii) the quantity of information on a long boundary probably entails output from a wider-area model.

8.2 Grid

The general form of grid is necessarily determined by the choice of model, especially its dimensionality. Hence desirable aspects of the grid, as determined by the estuary studied, may be a factor in the choice of model. An irregular or curvilinear grid can give locally-finer resolution or better adaptation to curved boundaries and channels (figure 8.2). If the estuary is fairly regular, good alignment of a regular grid can help. In any case, the grid resolution should be fine enough to give a good representation of the estuary's shape in all (modelled) dimensions. [Model stability may also need fine-enough resolution]. This implies:

- several grid cells across the width of the estuary, across any main topographic features (for 2DH and 3D) and through depth (for 2DV and 3D)
- grid cells much smaller than the radius of curvature of the estuary's axis and shores
- small fractional changes of depth between grid cells.

"Several" is often subjectively of order 5 and "small" of order 20%.



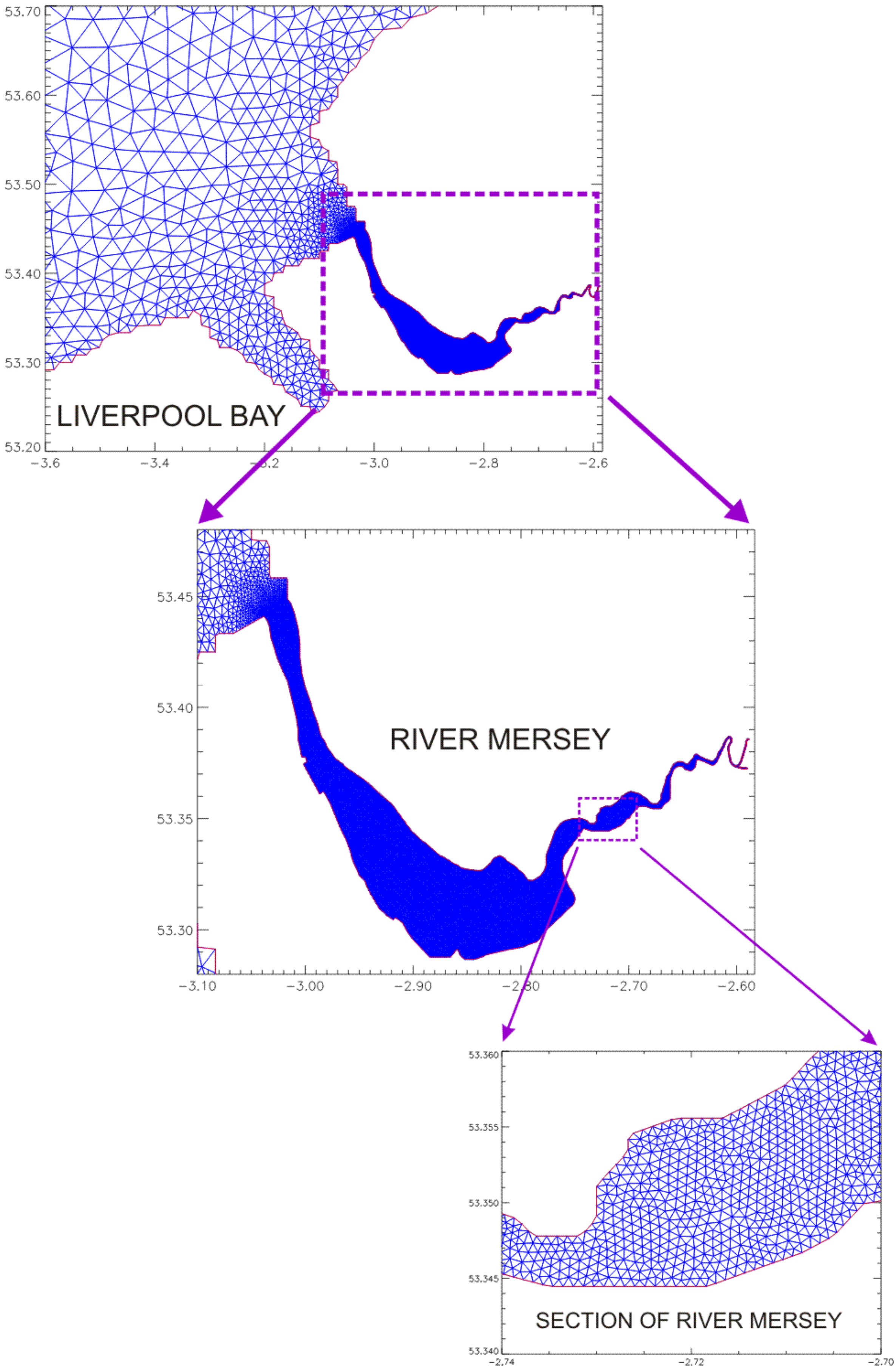


Figure 8.2 Regular and unstructured grids in Liverpool Bay

Grid refinement entails increased computation and output "data" visualisation etc. For an n-dimensional model, the number of grid cells (scale L) varies as L^{-n}; the number of time-steps for a given integration period varies as L^{-1}. Ideally, grid refinement should be varied initially to find a good balance between practicality (for the study) and convergence to fine-grid results. Available bathymetry's coarse resolution or poor quality may also limit useful grid refinement (or even model dimensionality).

8.3 Bathymetry

Bathymetry often lacks resolution and accuracy, limiting B-U model accuracy. Some sources may be (EMPHASYS consortium, 2000):

- a dedicated bathymetric survey, typically limited to ≥ 2 m below mean high-water springs
- (Admiralty) charts, typically lacking shallow-water and inter-tidal detail, and biased to shoals by their use for safe navigation
- Ordnance Survey maps showing mean high and low waters and flood-plain features
- local topographic surveys, which may cover inter-tidal and flood-plain areas
- LIDAR.

8.4 Surficial sediments

A sediment distribution must be specified for model initialisation; this is part of the supply available to change the estuary. If marine sediments enter the estuary, then their availability from outside the estuary is needed. The choice of model(s) for sediment erosion, dynamics in suspension, settling and deposition will determine the required sediment characteristics (e.g. particle size, settling velocity, cohesiveness, biogenic content affecting flocculation, effective density in flocs, erosion and deposition thresholds) needed to model. If bed consolidation and bioturbation are modelled, then information on flora and fauna at the bed is needed.

Bed roughness depends on the estuary's long-term regime; ripples vary within a tidal cycle. To this extent bed roughness is part of the model output rather than set up. Ripples are typically allowed for in calculating bottom stresses under currents and/or waves (Soulsby, 1997). However, initial "roughness" as in sub-grid scale dunes or sand waves may survive for a while rather than relating to the current regime. Bed roughness then needs to be part of the model set up.

Information on sediments and roughness over inter-tidal and flood-plain areas may come from aerial photographs and remote sensing (e.g. LIDAR, CASI; EMPHASYS consortium, 2000). Sources of information on bed sediment properties, for or around particular estuaries, are any local port authorities, the NERC British Geological Survey, the JNCC Review of Marine Nature Conservation and sea-bed mapping. Remote-sensed distributions typically need some "ground truthing" for corresponding sediment properties (especially critical stress for erosion).

8.5 Model parameters

All values of parameters in the model (suite) must be chosen. Parameters may
(i) represent the context, e.g. sediment grain size, and should be chosen accordingly;

(ii) result from a parameterisation simplifying reality, e.g. a coefficient for bottom drag. In principle, as for the drag coefficient, values should relate to a previous model validation which enabled the calibration.

9. Forcing

A general description of the contemporary state of the seas around the UK is given by IACMST (2005) with references to more detailed sources of information on processes forcing estuaries. Here we describe the forcing processes in turn; their method of application in a B-U model, present information and possible ranges for scenarios.

9.1 Tides

For small enough estuaries, it suffices to apply tidal forcing through a boundary condition on elevation at the estuary mouth. An open boundary involving elevation is still applicable if the modelled area extends over 100s km, e.g. a long estuary requires the model to include much adjacent coastal sea. These outer boundary conditions may simply be of the form

Model elevation at boundary point ζ_M = specified tidal elevation ζ_T.

At an extensive open boundary (depth h, outward normal $\mathbf{n}$), however, a preferable condition allows model-generated motion (current $\mathbf{u}_M$) to radiate away (e.g. Flather, 1976):

$$(\mathbf{u}_M - \mathbf{u}_T).\mathbf{n} \;=\; (g/h)^{1/2}\,(\zeta_M - \zeta_T).$$

The model may need to be run iteratively if ζ_T and $\mathbf{u}_T$ are initially uncertain. Such difficulties are often a factor in choosing a reduced model area (or even 1D within the estuary), even if ideally an extensive area is wanted for the reasons in Section 8.1.

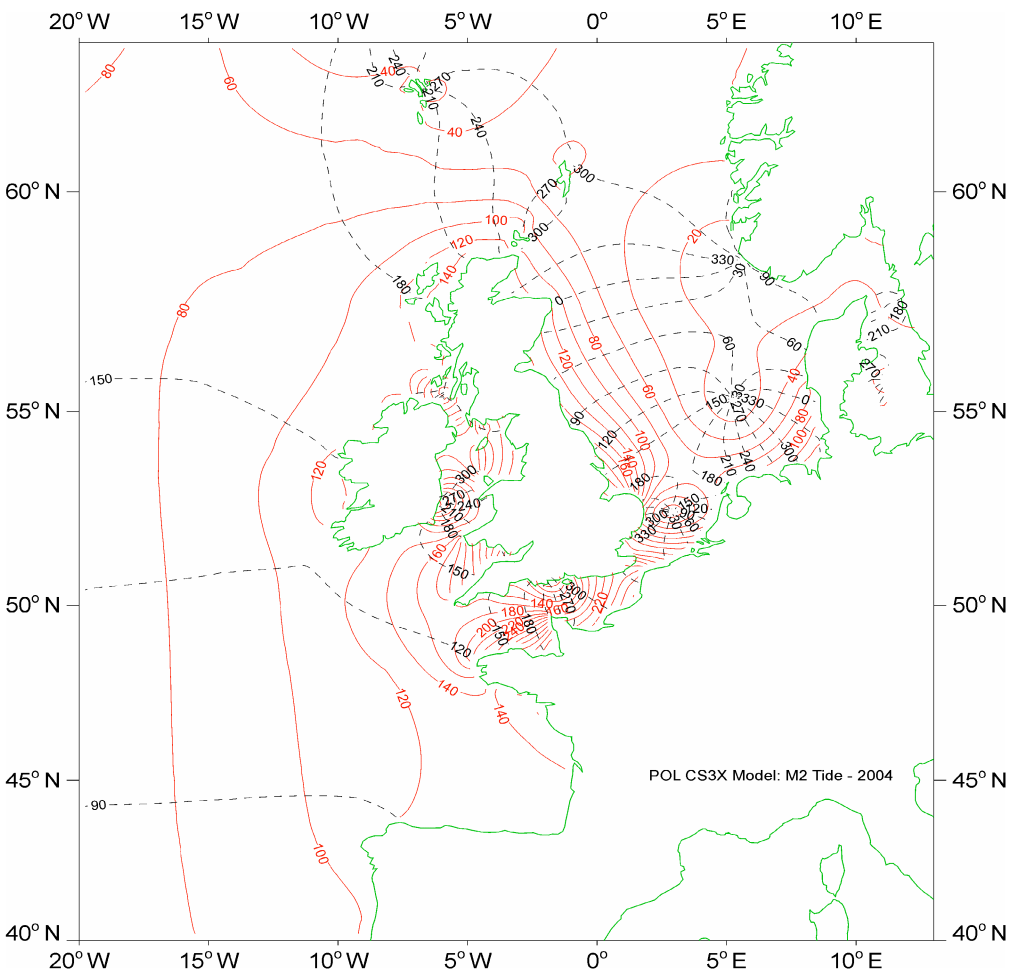


Figure 9.1 Tidal amplitudes and phases in UK shelf seas

Extensive models also need forcing by the tide-generating potential within the model area. The pressure gradient term $-g\rho(\zeta_x, \zeta_y)$ in the momentum equation can be replaced by

$$g\rho(Z_x-\zeta_x, Z_y-\zeta_y).$$

Here Z is the equilibrium tide (e.g. Pugh, 1987) with a reduction factor $(1 + k_2 - h_2) \approx 0.69$ (to allow for the elastic earth's yielding to the astronomical tidal potential and the consequent change in gravitational potential; e.g. Farrell, 1973).

Tidal data to be applied at the estuary mouth should be derived from measurements nearby. Such data exist at quite short intervals around the UK coast (usually in the form of tidal harmonics convenient for re-forming the tide in a model). POL, the EA, the Hydrographic Office and local port authorities are likely sources of data. Tidal amplitudes for many estuaries have been assembled in the FutureCoast (Burgess et al., 2002) and present FD2107 projects. At extensive open boundaries, model data are needed. Particularly relevant are the extended NW European tide-and-surge model (POL; figure 9.1a), a regional north east Atlantic barotropic model (Flather, 1981; as used by POL), the TPXO6.2 1/4^{o} global model, with assimilated TOPEX/Poseidon satellite altimetry data in -66^{o} to +66^{o} latitude (Egbert and Erofeeva, 2002), and the MOG2D barotropic finite-element model of Laboratoire d'Etudes en Géophysique et Oceanographie Spatiales (LEGOS/POC).

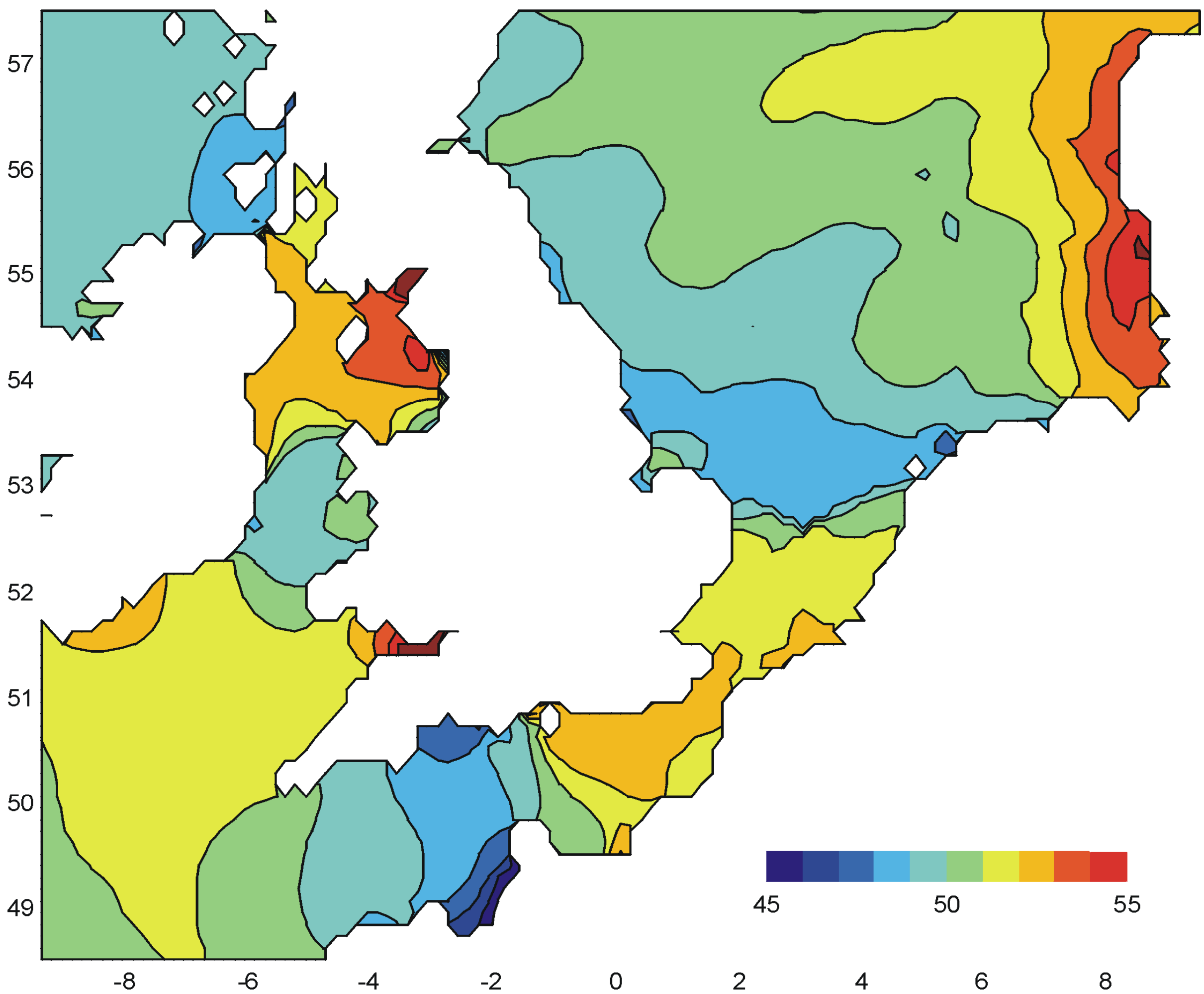


Figure 9.1b Change in tidal amplitudes in UK shelf seas after sea-level rise (Flather, 2001). Change in Mean High Water is shown due to an assumed 50cm rise in Mean Sea Level. Changes at the coast are 45 - 55cm (-5 to +5 cm relative to Mean Sea Level).

In future scenarios or modified estuaries, the tidal forcing might differ slightly. The actual difference is predictable only by running a shelf-wide model for the full scenario of raised sea level etc. as in e.g. Flather et al. (2001; figure 9.1b). Rough estimates of typical magnitudes of change can be inferred from the fractional change in depth due to relative sea-level rise. Sea-level rise 0.5 m over the next century (IPCC, 2001 estimate) corresponds to about 2% in shallow areas, ½% in typical depths of 100 m. Similar fractional changes in typical tidal amplitudes may then result from changes in O(1) frictional effects. Changes due to faster propagation (increase in wavelength) as $(gh)^{1/2}$ are generally less because of the weaker $h^{1/2}$ dependence. Exceptions are locations of near-resonance, e.g. the Bristol Channel (Fong and Heaps, 1978) and eastern Irish Sea. Here, the change depends sensitively on present proximity to resonance and whether the natural period is greater or less than M_2. Flather et al. (2001) found amplitude increases up to 10 cm in the Bristol Channel and Eastern Irish Sea; ± 2 cm was typical elsewhere.

9.2 Meteorology

Atmospheric pressure and winds are applied as stresses at the surface. Precipitation and evaporation at the surface, and the various components of heat flux, may also be needed: density affects surface level and stratification affects estuarine circulation. [Latent and sensible heat fluxes apply at the surface; radiational components are distributed through the upper water column]. Most of these factors are more important in large estuaries.

Within a small estuary, differences of atmospheric pressure have relatively little dynamical effect; gradients of 2 mb / 100 km (corresponding to winds exceeding 10 m/s) convert to a quasi-static surface slope of only 2mm/10km. However, there must be consistent use of pressure or surface level as dynamical variables in the estuary and boundary conditions; they differ by atmospheric pressure. Wind stress has more dynamical effect, generating waves and causing set-up of order $10^{-6}U^2L/(gh)$, e.g. 10 cm for an estuary depth h = 1 m, length L = 10 m and wind speed U = 10 m/s.

Density effects on surface level could be significant if *in extremis* the estuary were entirely filled with fresh water, affecting the surface-level / depth-mean-pressure relation by more than 1 cm per 1 m of water depth for typical coastal-sea salinities 30-35. Around the UK this is unlikely even due to river inputs after heavy rain, let alone from rain on the estuary itself. [UK precipitation amounts are only O(0.1 m) over periods of days-weeks, during which exchange with the adjacent coastal sea takes place. Over a year, precipitation and evaporation are comparable]. Summer heating can expand estuarine waters of depth 10 m by more than 1 cm, but the estuary level adjusts to greater changes in the deeper adjacent coastal sea. Hence precipitation, evaporation and heat flux are wanted primarily for stratification effects on estuarine circulation, i.e. for 2DV and 3D models, and especially for any model of the adjacent coastal sea. These data are less generally available than pressure and winds, and possibly less accurate (judged by relative error in derived fluxes), reducing the benefits from resolving the vertical in the model.

Meteorological variables are usually obtained (at regular time intervals on a regular grid) as analyses and forecasts from numerical weather prediction models; see http://www.metoffice.gov.uk/research/nwp/index.html. The UK Met. Office Unified mesoscale model gives hourly fields on a 0.11^o by 0.11^o grid centred on the UK. Six-hourly archived fields are available from the global model run by ECMWF (~ 1^o by 1^o) who have also carried out re-analysis back to 1958 (ERA-40; http://www.ecmwf.int/research/era). Data are available *via* the British Atmospheric Data Centre. Variables are 10-m wind, surface pressure, temperature and relative humidity, precipitation, cloud cover and radiation (long-wave and short-wave, downwards and upwards). Fluxes may need to be derived from these and (modelled) sea-surface temperature using bulk formulae, e.g. as recently updated by Fairall et al. (2003); ftp://ftp.etl.noaa.gov/et7/anonymous/cfairall/bulkalg/.

Climate change implies changes in these variables. Sensitivity tests are recommended: to a 10% increase in wind speeds; to wind direction; to a 20% increase in high or extreme rainfall (Defra, 2003). For an extensive (coastal-sea) model, sensitivity to changes in storm track should be tested. Projections of future climate have been run by the UK Met. Office Hadley Centre; results for some variables are published in Hulme et al. (2002); http://www.ukcip.org.uk/scenarios/ukcip02/documentation/ukcip02_scientific_report.asp

9.3 Surges and mean sea level

Surge generation within the estuary model will result from the meteorological forcing. Forcing by surges and mean sea level outside the model area needs to be introduced through the open boundary condition, in the same way as the tide (Section 9.1; add the specified external surge to the specified external tide).

Surge data for application at the mouth of an estuary may come from measurements nearby. Time-series (tide+surge) data from the 44 locations of the UK National Tide Gauge Network (Figure 9.3a) are available at http://www.pol.ac.uk/ntslf/. Data from some other locations may be available from POL, the EA, the Hydrographic Office or local port authorities. Otherwise, model data are needed (certainly at extensive open boundaries). For areas around the UK, POL holds an archive of output from the operational storm surge model, run routinely from September to April each year at the UK Met. Office Storm Tide Forecasting Service (POL Applications: http://www.pol.ac.uk/appl/downloads/POL_Model_Details-CS3.pdf). These predictions are on a 1/6° by 1/9° grid (about 12 km); some interpolation or extrapolation to the estuary mouth may be needed; alternatively, the estuary model's offshore boundary may be taken further out from the estuary mouth to match the surge model grid. Mean sea level data come from the UK Tide Gauge Network (http://www.pol.ac.uk/ntslf/), other south-coast locations (http://www.channelcoast.org) and *via* the Permanent Service for Mean Sea Level (http://www.pol.ac.uk/psmsl/datainfo; figure 9.3b).

Future surges may be affected by raised sea level and by changes in future weather, e.g. more intense storms. Lowe et al. (2001) found that the interaction between surges and mean sea level (raised by 0.5 m) was very small. However, weather predicted by HadCM2 for 2080-2100 (as compared with "the present") caused an increase in extreme surge heights around much of the UK. Typical increases in extreme surges were 0.1-0.2 m (5-year return period), 0.2-0.3 m (50-year return). However, there was no increase along the English coast of the southern North Sea. Other climate models have given different results. For total sea-surface elevation, surges have to be added to mean sea level and tide.

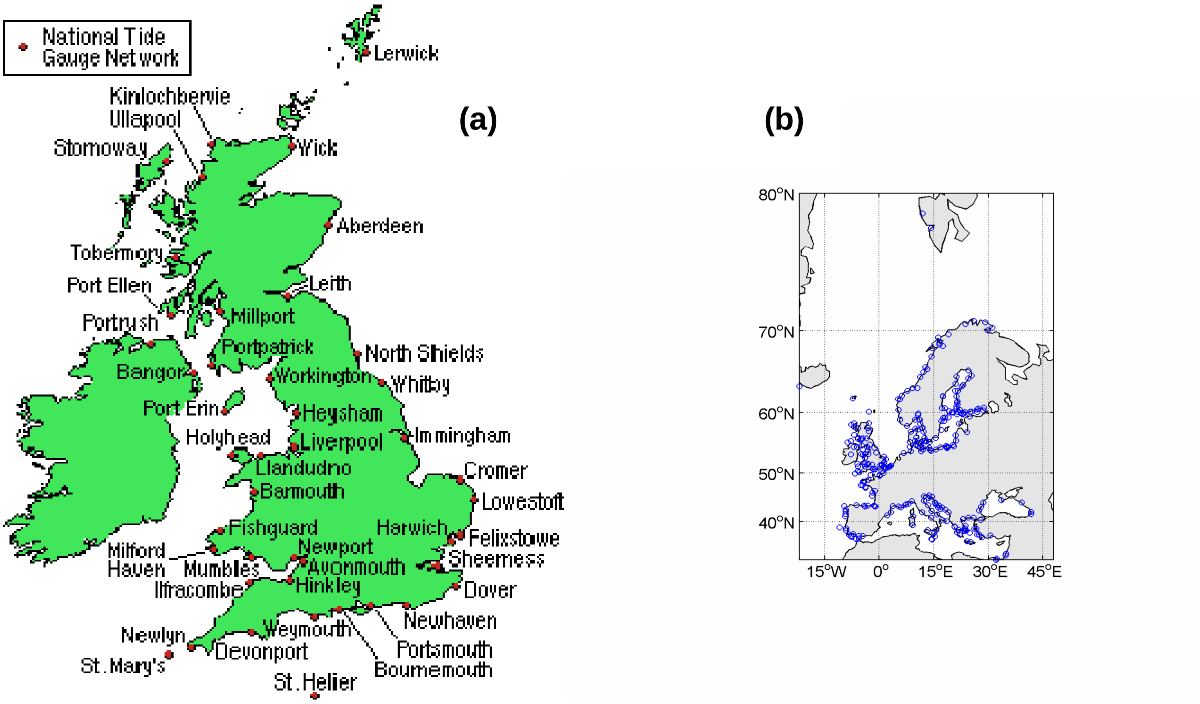


Figure 9.3 (a) UK tide gauge network, (b) European sources of data to the Permanent Service for Mean Sea Level.

9.4 Waves

Wave generation in an estuary wave model results from the wind forcing. However, the model needs waves to be specified at its open boundary. Often the information available (or scenarios to be simulated) are significant wave height, period and spread about a principal wave direction. If the model has wave-spectrum variables, it is necessary to assume a spectral form (e.g. JONSWAP; Hasselmann et al., 1973; figure 9.4a) determined by the available parameters. Then the SWAN model, for example, treats only incident wave energy; waves propagating in other directions are ignored at the boundary – the effective wave spectrum just inside the model boundary does not exactly correspond to that specified. All model energy is absorbed at land boundaries; reflection is not usually included (e.g. at vertical sea walls), although SWAN can treat transmission and reflection by obstacles.

Wave data are available from several sources. BODC hold series from many locations around the UK, in particular off eastern and southern England and in the Bristol Channel. Data from many UK Wavenet locations, coordinated by Cefas (figure 9.4b), are available *via* http://www.cefas.co.uk/wavenet/default.htm. The UK Met. Office holds wave “data” from prediction models, some from 1986 and constrained by measurements.

Climate change implies changes in wave spectra. Sensitivity tests are recommended: to a 10% increase in wave height and 5% increase in wave period; to changes in near-shore depth, to which wave propagation is very sensitive (Defra, 2003). For an extensive (coastal-sea) model, sensitivity to changes in storm track should be tested.

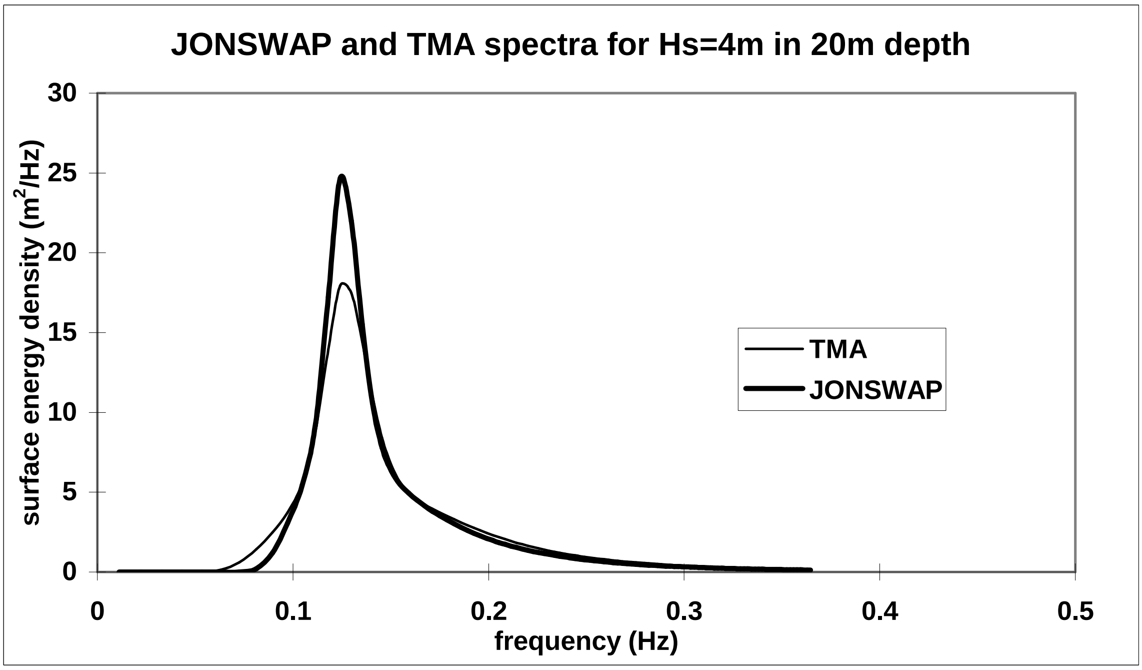


Figure 9.4a Typical form of the shallow water wave spectrum
(Young and Babanin, 2006)

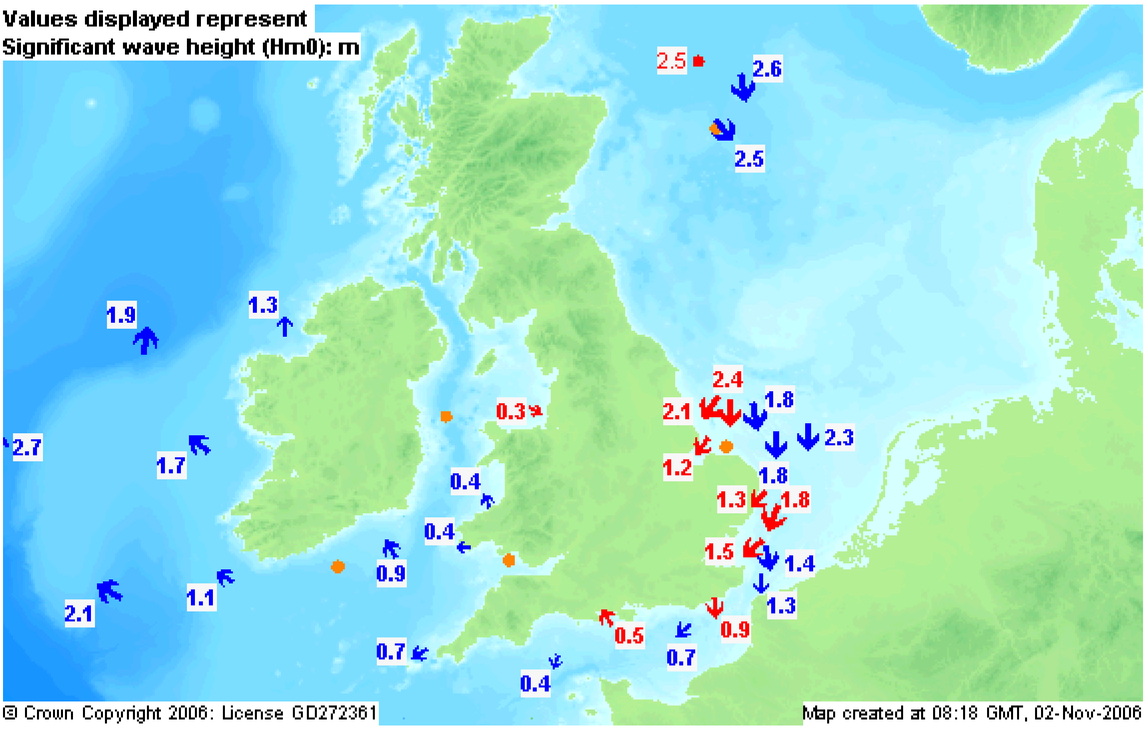


Figure 9.4b WaveNet data locations
Red arrow: wave direction; blue arrow: wind direction; red dot: active buoy, no directional data; orange dot: inactive buoy.

9.5 River flows

River discharge should be a specified influx (volume of fresh water) at the estuary model's upstream boundary. This assumes that the boundary is taken far enough upstream (Section 8.1).

For the north-west European shelf, a 50-year dataset of daily-mean river fluxes has been constructed, combining data from the Global Runoff Data Center (GRDC) and the UK Centre for Ecology and Hydrology (CEH). CEH maintains the UK National River Flow Archive, see http://www.ceh.ac.uk/data/nrfa/index.html. The Environment Agency (at HiFlows-UK) provides annual maxima and peaks-over-threshold at ~ 1000 UK river flow gauging stations. For 65 UK estuaries, seasonal statistics from long records have been assembled in projects FutureCoast (Burgess et al., 2002) and FD2107. The EA is the source for any near-real-time river-flow data.

Climate change is likely to increase summer droughts (with low flows) and winter river flows and flooding events, as a result of trends in precipitation and temperature (Hulme et al. 2002, at http://www.ukcip.org.uk/scenarios/ukcip02/documentation/ukcip02_scientific_report.asp). Current practice is to test sensitivity to an additional 20% in peak flow (Defra, 2003). This "20%" may have to be increased. Clearly behaviour with low flows needs to be studied.

9.6 Sediment supply

Bed-load is supplied locally according to sediment properties and flow speed (usually using a formula). Hence sediment properties need to be specified over the model grid. If a model run alters the sediment distribution, only uniform properties remain valid. Otherwise, the model should follow sediments' provenance (by particle tracking). However, consolidation of the bed could be modelled by updating elapsed (Eulerian) time since the last sediment movement. Supply could be limited by setting a base to mobile sediments; at grid cells where the bed has lowered to this base, out-going bed-load transport could be capped at the sum of in-coming transports. Bed-load transport formulae inherently assume supply across model boundaries, unless an explicit extra condition is applied (e.g. that the bed is above some base level).

Suspended load is supplied by erosion and by inflow across boundaries. Supply by erosion can be constrained, by specifying erosion parameters (e.g. critical shear stress) as a function of depth through the bed. For inflows from rivers or the open offshore boundary, suspended load must be specified (as a vertical profile for 2DV and 3D models). Zero normal gradient of suspended sediment concentration can be specified in the absence of other information. This is "neutral" but implicitly assumes an unlimited source. The condition only applies to incoming flows; the model determines concentrations in out-going flows. If there is an external limit to incoming sediment, then an explicit extra condition is needed.

Information on the bed for bed-load and erosion is discussed in Section 8.4. There is little systematic information on suspended concentrations. Some rivers and near-shore areas are monitored by the EA. Data for six estuaries have been assembled in project FD2107. See also Section 12 case studies. Data for some sea areas are available *via* BODC, notably from the North Sea Project (south of 57°N; UK-NERC, 1988-89) and from Liverpool Bay (Coastal

Observatory; POL since 2002). Suspended sediment models are not operational to the point of giving systematic reliable input on concentrations.

Scenarios for future sediment supply may be based on hydrodynamic extrapolations of the present regime, but in some contexts might be significantly changed by human activities, e.g. dredging or beach nourishment (or cessation thereof).

9.7 Ecology and water quality

Inflow boundary concentrations may be needed for the variables that are modelled (and not immediately calculated by local formula from other modelled variables).

Values around the UK coast are monitored by Defra, the EA, Cefas, Fisheries Research Services (Scotland), a consortium (Northern Ireland) and others, see Figure 9.7 and
http://www.defra.gov.uk/environment/water/marine/uk/science/merman.htm
http://www.cefas.co.uk
http://cobs.pol.ac.uk (Liverpool Bay)
http://www.northseanet.co.uk (Humber)
http://www.marlab.ac.uk/ (Fisheries Research Services)
http://www.afsni.ac.uk/services/coastalmonitoring
These are liable to change with the advent of a Marine Bill and the proposed Marine Management Organisation.

Scenarios for future changes in ecological and water quality variables have little *a priori* basis at present.

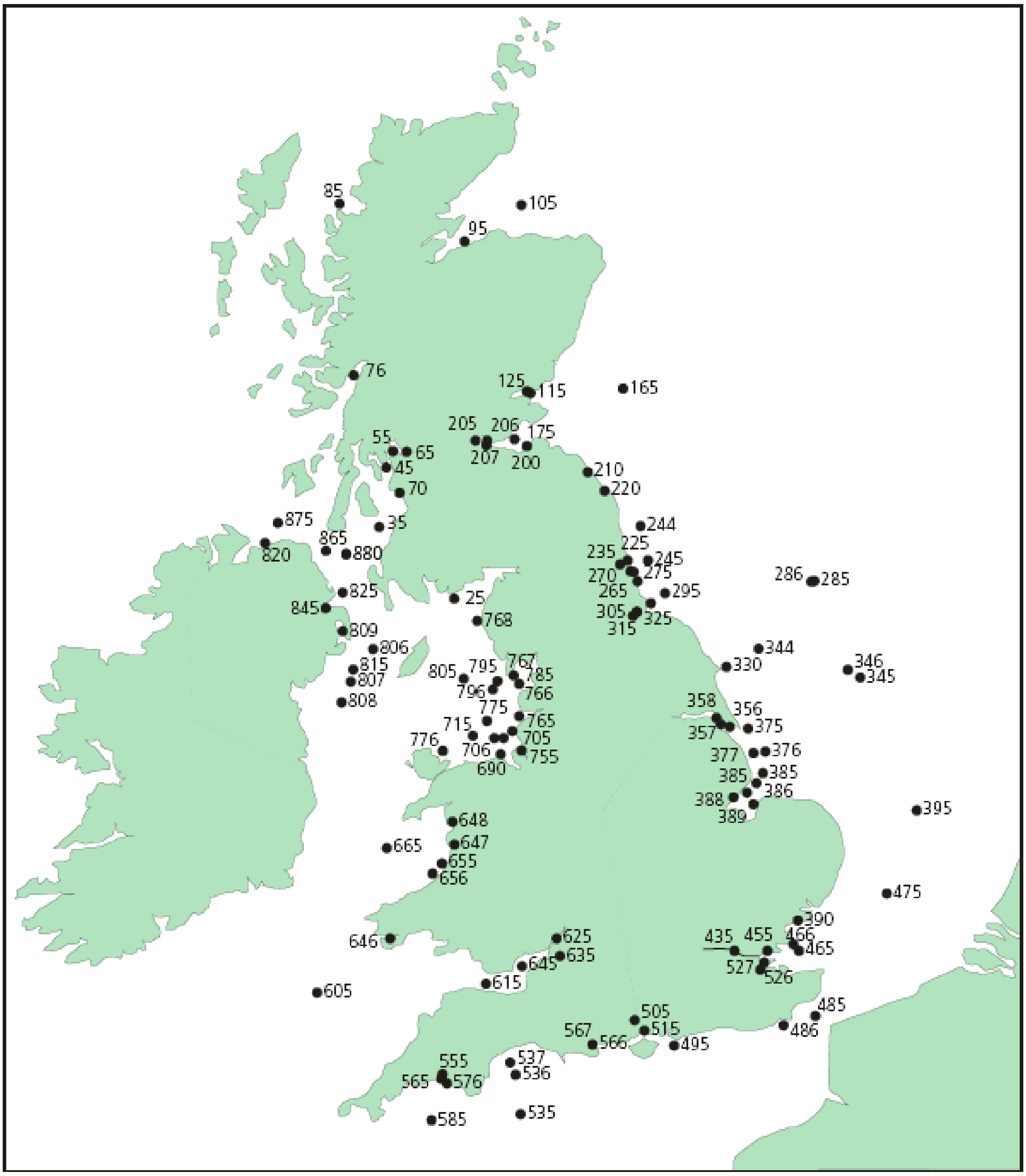


Figure 9.7 Map of Marine Monitoring locations

From UK National Marine Monitoring Plan second report (CEFAS, 2004).

10. Cycle of Model Runs

After specifying the model and forcing, there is typically a cycle of actions as many runs are carried out under different conditions (for reasons summarised in Section 7). Such a cycle is also part of the scientific method: hypotheses form a conceptual model which forms the basis for the (probably numerical) model implementation; model outcomes are consequences of these hypotheses (and the forcing); comparison with data or experiments may cause revision of the hypotheses. This cycle involves model initialisation, simulation (one run), treatment of output, assessment (comparison with independent evidence), consequent choices for further runs (scenarios) – and hence a return to the initialisation stage, forming an iterative loop.

10.1 Initialisation

This is closely related to data assimilation. Specified fields probably do not satisfy the model equations (dynamical balances). At best there is evolution to a dynamically-balanced state, on a time-scale set by (i) friction and radiation of energy for the hydrodynamics, (ii) vertical "diffusion" and settling through the water column for suspended sediment. These time-scales are not shortened by a good initial approximation, but integration to a specified tolerable error may be shorter if the initial state is good.

Common practice is to run the model for a period leading into the period studied. This lead-in period should be several times the time-scale for evolution to dynamical balance. The lead-in period can be as repeat tidal cycles, if results for a tidal cycle are to be examined. [If an annual cycle is to be examined, a lead-in period might be a repeat of the first fortnight, say; hydrodynamic and suspension time-scales are typically less than a fortnight. The lead-in period should represent the initial season and stage / all of the spring-neap cycle].

Evolution over months to centuries characterises bathymetry, sediment distribution in the horizontal dimensions, many ecological and water-quality variables. Hence initial dynamical balance should not be expected. Indeed, change in these variables is often the object of study (following a changed context and hence initial imbalance). Care is needed to initialise the appropriate variables according to the study aims.

If the model has already been run for a "close" scenario (similar values of model parameters, context and forcing), then the output satisfies the model equations and may form a good start. [A lead-in period is still needed to achieve balance for the case in hand]. Thus archiving runs may be useful, and ordering runs so that "close" scenarios are run in succession.

10.2 Simulation

Start and end times need to be decided. The following are factors in the choice.

Time-scale of evolution of the variables of interest. As in Section 10.1 this may range from hours (hydrodynamical variables) to centuries (large-scale morphology, buried pollutants).

The spring-neap tidal cycle. Net sediment movement averaged over the spring-neap cycle almost certainly differs from that with an average tide. Differences between springs and neaps may also be a concern.

Season affects stratification, the intensity of winds and waves, river inflows and what they carry, biota and water quality, even tides (diurnal tides are almost zero near equinoxes). Season also affects the intensity of concern, e.g. impacts on or effects of summer recreation.

The range of conditions to be simulated especially concerns storms (winds and waves) and variable freshwater inflows from rivers. Varied conditions might be represented by many short runs for systematic ranges of scenario parameters. However, reference to a long period of real data is necessary to represent the correct probability distribution of varied conditions and extreme statistics. Especially, input variables may be statistically dependent, e.g. surges and river flow (Svensson and Jones, 2002)

10.3 Output

Models produce much output. Rather than storing all output for possible later use, it is often easier to re-run a model for a desired sub-set of results. Nevertheless, either the results must be stored, or the initial conditions, forcing and model configuration must be stored. In either case, the output's relation to the scenario generating it must be documented unambiguously.

Large quantities of output imply a need for reduction or visualization to help comparison and interpretation. Prior thought as to what exactly is to be compared can reduce the output to be processed and guide analyses. For example, there may be most interest in fluxes (transport integrated across a few critical sections), i.e. scalar time-series, although a 3D model may have been used to represent processes properly.

Tides form a large part of the motion in most UK estuaries, hence tidal analysis to a relatively small number of harmonic constituents is efficient data reduction. To represent the main variations and asymmetries, it is desirable to analyse for the following constituents:

- M_2, S_2, N_2 and K_2 semi-diurnal (springs-neaps; distance to moon; equinoctial maximum)
- K_1, O_1 and P_1 diurnal (diurnal inequality on a fortnightly cycle; small total near equinoxes)
- Z_0 mean, M_4 quarter-diurnal and M_6 sixth-diurnal (non-linearity, frictional asymmetry).

The frequencies of these constituents are shown in table 10.3.

Table 10.3 Principal tidal constituent frequencies (°/hr)

Constituent	Z_0	O_1	P_1	K_1	N_2	M_2	S_2	K_2	M_4	M_6
Frequency	0	13.943	14.959	15.041	28.440	28.984	30.000	30.082	57.968	86.952

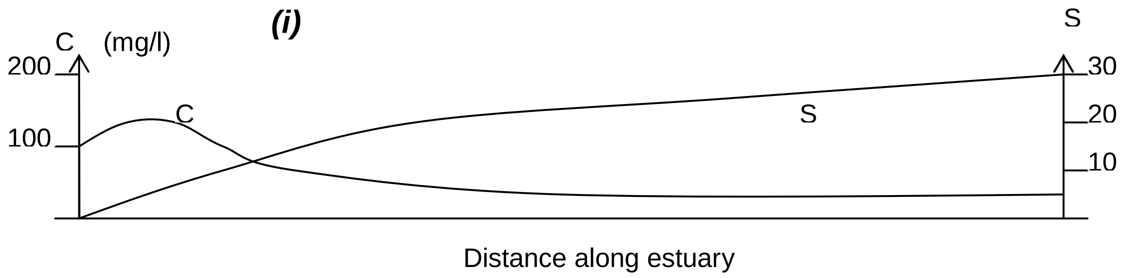
To clearly distinguish between O_1 and K_1, and between M_2 and S_2, needs about 15 days' time series. N_2 is clearly separable from M_2 over a month. P_1 and K_2 need a half-year time series for clear separation from K_1 and S_2 respectively. However, short time series may be analysed if a tidal analysis already exists for same variable nearby, by assuming the same relations between constituents. Alternatively, the relation in the equilibrium tide might be used. More details and least-squares analysis are discussed by Pugh (1987).

Where tides are substantial, interpretation may be helped if any further analysis uses "de-tided" time-series with the analysed tide removed. Then, according to interest, mean values, spring-neap or seasonal variability may be the focus of analysis. For the character of the largest actual variations, visual inspection of time-series plots is always useful, and probably spectral analysis as well. Correlations between variables may be sought by regression or cross-correlation of time-series; coherence is correlation analysed according to frequency (from cross-spectral analysis, e.g. Båth, 1974). Correlation and regression coefficients are data reductions; coherence, amplitude and phase relations by frequency band also represent reductions and offer useful data interpretation.

Statistics of extreme values are important in assessing flood risk, and in estimating sediment transport and morphological change, which are strongly dependent on extremes of current. Estimates of extremes are sensitive to the length of time-series on which they are based, and especially to any biases or unusual characteristic of the period analysed. [If a one-in-100-year event occurs in a one-year record, it is likely to be ascribed a return period of only a few years]. There is a considerable literature on extremes, especially of sea level in relation to flood risk. See Pugh (2004) for an introductory discussion and further reading.

Visualisation is an important aid to interpretation. Model outputs are well-suited to plotting, being regular in space and time. Common forms (corresponding Figures 10.3i, ii, iv) are:
(i) values of any chosen variable(s) as the ordinate, as a function of time or of distance along the estuary (abscissa). Variables can be easily compared in this way;
(ii) distribution of any one variable as a function of two independent variables (e.g. x,y; x,z; y,z; x,t) shown as contours or by colour-coding values. (Here x is distance along the estuary, y is across the estuary and z the vertical coordinate). Sometimes the horizontal components of current (two variables in principle) are represented as scaled arrows on a grid;
(iii) time-evolution shown as a sequence or "animation" of plots of form (ii);
(iv) regime diagrams for estuary character. Axes may be for two characterising variables, e.g. estuary length, depth, river inflow, tidal range, bed slope, current strength, scaled friction, suspended sediment concentration (not all independent). Modelled values of a third variable might be shown as contours, and/or different estuaries compared by plotting their position according to their values of the two characterising variables.

Tables can display systematic information, juxtaposing values and statistics for quantitative comparison. This works best if model output and data are reduced to just a few comparators.



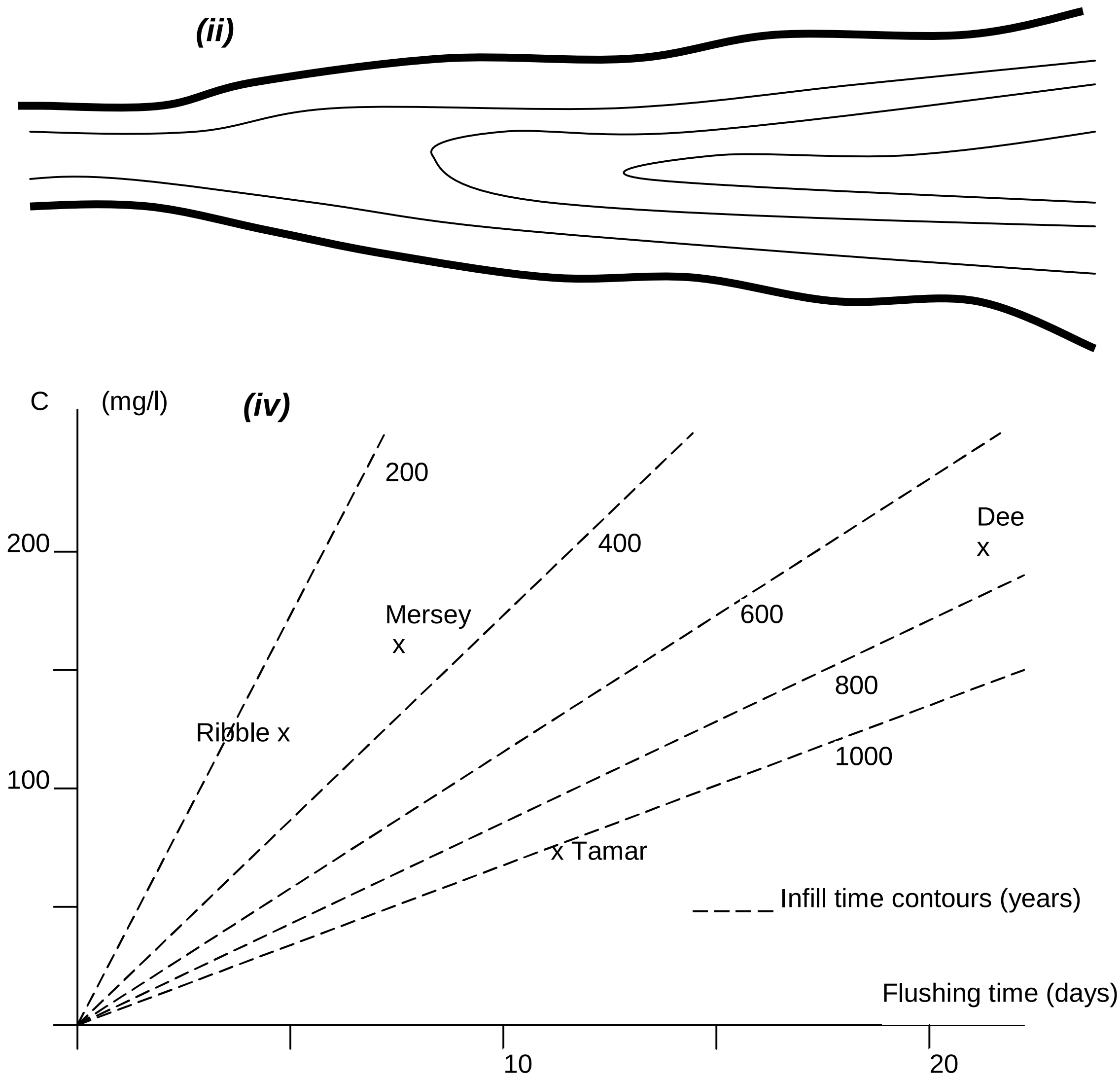


Figure 10.3 Examples of different types of plots

10.4 Model assessment

Comparisons are the essence of assessment. Ideally, compared quantities should be strictly comparable, i.e. have the same location, time and variable definition so that they “ought” to agree. Moreover, (i) the assessment should be demanding – comparators should be derived independently with no in-built tendency to agree, (ii) there should be traceability – if the independent comparators disagree, diagnosis is possible using variables with intermediate derivations. Especially, (ii) can be helped by a sequence of models with varying complexity but compatible in their common attributes. Much can be learned from how well different models simulate various aspects of observed data. However, (i) and (ii) are ultimately incompatible for the model sequence.

The choice of comparison variables will be guided by the study interests and data availability (especially for observation – model comparisons). Variables for comparison might include:

- Surface elevations
- Fluxes of water at a few particular cross-sections – tidal, and net over a tidal cycle,
- Concentrations – tidal variation; vertical, axial, transverse distributions

- Fluxes of constituents and suspended matter at a few cross-sections – tidal and tidal-mean
- Deposition – rates, spring-neap variation, locations (inter-tidal / sub-tidal)
- For morphological interests:
  change in proportions of inter-tidal and channel areas or volumes
  change in overall cross- or along-estuary convexity of the depth profiles
  change in area of salt-marsh
  time-scale of evolution (e-folding time).

Independent measurements are the most demanding for assessing models. Some issues for the sufficiency of data for testing models are discussed in Section 4.1.

Sources of measured data are discussed in Section 8, 9. Comparison data may come from work in analogous UK estuaries (Section 12) or form part of the study in question. Accessible holdings include: surface elevation data (POL; http://www.pol.ac.uk/ntslf/); currents, concentrations in some experimental locations (BODC; http://www.bodc.ac.uk/data/where_to_find_data/); constituents and suspended matter (EA monitoring locations). Constituent fluxes usually have to be derived from measured concentrations and currents. Typical deposition rates, mm to cm/yr, are too slow to measure directly in the short term; the character of suspended sediment and of surficial sediment in cores may provide evidence. For the long-term (rates of accumulation, morphological change, position relative to sea-level and former shorelines), "point" information may come from boreholes, short cores and perhaps archaeological data.

B-U model results may also be assessed by comparison with findings from theory, and from T-D approaches in the case of morphology (EMPHASYS consortium, 2000; also Section 3.1).

Model assessment can utilise comparisons between model runs, testing sensitivity to set up, algorithms, model parameters and forcing. Such tests should seek traceability through a sequence of runs with just one aspect varying at a time. Sensitivity tests may partly offset lack of knowledge or data, by identifying ranges of parameters or forcing where results are relatively insensitive. Bed friction and sediment properties merit a sensitivity analysis; they are needed in models but may be uncertain in context.

10.5 Scenarios

Simulations may aim to cover various future climate-related and anthropogenic scenarios, using varied boundary forcing and context properties, e.g. sediment characteristics. [As well as the interest in different scenarios *per se*, the different simulations may help to estimate errors and sensitivities of results, and to develop understanding].

In relation to climate, Sections 9.1-9.5 suggest ranges of some forcing parameters.
- *Mean sea level*: a 0.30 m rise may be realistic for the next 50-75 years; 0.5 m is the IPCC (2001) "central" estimate for the next century – see also Defra (2003). However, future rises remain uncertain; some suggest smaller values while correlations with increased temperature suggest a metre rise over the next century (S. Rahmstorf, personal communication).
- *Tidal range*: typical amplitude increases (for a 0.5 m rise in mean sea level) are ± 2 cm but up to 10 cm in the Bristol Channel and Eastern Irish Sea (Flather et al. 2001).
- *Surges*: typical increases in extremes of 0.1-0.2 m (5-year return), 0.2-0.3 m (50-year return). Results of different climate models vary; distributions of the increases are uncertain.

- *Winds*: sensitivity to a 10% increase in speeds, and to wind direction (Defra, 2003). For an extensive (coastal-sea) model, sensitivity to changes in storm track should be tested.
- *Waves*: sensitivity to a 10% increase in wave height, to a 5% increase in wave period, to changes in near-shore depth (Defra, 2003); to changes in storm track for a coastal-sea model.
- *Rivers*: sensitivity to 20% increase in peak flow (Defra, 2003); behaviour with small flow.

For many interests, responses to extreme events may be important; they may counteract the cumulative effect of on-going tidal and other biases. Typically, a representative long period of meteorological forcing is chosen and effects of strong events therein are simulated. Then sensitivities should be tested: to wind speeds +10%, wind direction and storm track.

Effects of varied sediment properties and supply are of wide interest; scenarios should cover an appropriate range of sediment types and interactions through consolidation, flocculation, bed roughness etc. Effects of different former bathymetries are of morphological interest. These scenarios for sediment properties and bathymetry are case-specific.

10.6 Iterative loops

Evidence of the estuary's likely state comes from various sources; observations, theory, T-D approaches – as well as B-U modelling. All these approaches have associated errors which diminish the weight given to their evidence. If these errors can be estimated, then a cost function can be defined from the differences of any predicted state from all the lines of evidence. [A sum of squared numerical differences is often used, with appropriate weights].

The aim is then to minimise the cost function by choice of uncertain parameters and forcing in the B-U model. Iterative simulations, for different values of parameters and forcing, estimate the slope of the cost function (as it depends on the parameters and forcing), so going "down-slope" to a minimum.

This approach can be made more formal. The B-U model equations (incorporating the model parameters) are added to the cost function as constraints with (initially arbitrary) Lagrange multipliers. Minimisation of the cost function implies zero derivatives with respect to the model parameters and the consequent values of modelled state variables. The solution involves solving the adjoint of the B-U equations (and determines the Lagrange multipliers). Annan (2001; and references therein) discusses issues in formulating and integrating the adjoint equations for a surge model. This formalism entails more computation than any one direct solution of the "forward" B-U model problem.

Care is needed, to find an overall minimum of the cost function, rather than a merely local minimum. This implies initial trials with wide ranges of parameters and forcing.

11. Wider Interpretation

There are benefits from setting findings in a wider context, even if the study only concerns specific aspects of just one estuary. Analogues can help to give confidence in the findings. Comparisons develop scientific understanding, especially by relating contrasts to differences in context, and so inform future studies.

In the spirit of B-U modelling, interpretation is naturally through processes: tides, wind- and density-driven flow, waves, turbulence, sediment dynamics. Comparisons with data, and between models representing different processes, can help to diagnose the relative importance of various processes. A different balance of processes is likely in different estuary types: fjord, fjard, ria, coastal plain, bar-built, complex, barrier beach, linear shore, embayment (Buck and Davidson, 1993). Process rates (especially sediment flux), estuary type and T-D approaches can suggest if the estuary is approaching an equilibrium form; or if the estuary form may be "externally" imposed and not a result of the internal processes; or if regime relationships hold.

12. Case studies

Studies of the Mersey, Ribble, Humber, Blackwater, Crouch/Roach, Thames, Southampton Water and Tamar are described by papers in EMPHASYS (2000b). The ABPmer (2003) estuaries data base includes the Mersey, Ribble, Humber, Blackwater, Southampton Water and Tamar. These six, the Thames and the Dee (west of the Mersey) are modelled also in the present project FD2107. The Joint Nutrient Study (JoNuS) and Southern Nutrient Study (SoNuS) included Liverpool Bay, Tyne, Tees, Humber, Wash and Thames (Kelly-Gerreyn et al., 2001; and Dundalk Bay). The Ribble is a current focus of catchment to coast studies by the Environment Agency and collaborators. However, these are all *coastal-plain* estuaries except for the Tamar (a *ria*), Tyne and Wash (an *embayment*); stretches of the outer Thames estuary may also be considered as *linear shore*. Table 12 gives a variety of fairly recent references to other case studies. It is not exhaustive but is intended to provide a route into a wider range of estuary types and relevant data.

Table 12 UK Estuary case studies

Estuary	**Type**[1]	**Character of studies**	**References**
Camel	Ria	circulation	Sherwin (1992)
Taw	Bar-built	sediment dynamical processes	Rose and Thorne (2001)
Severn	Coastal Plain	recent local morphodynamics long-term stratigraphy	Haslett et al. (2001) Carling et al. (2005), Allen (2003)
Tawe	Canalised	water-quality post-barrage	Lamping et al. (2005)
Swansea Bay	Embayment	coastal defence	Sutherland and Wolf (2002)
Loughor	Coastal Plain	evolution	Bristow and Pile (2003)
Carmarthen Bay	Embayment	Evolution wave modelling	Bristow and Pile (2003) Wolf et al. (2002)
Milford Haven	Ria	modelling salt intrusion	Das and Nassehi (2004)
Dyfi	Bar-built	Evolution, salt marsh morphology	Shi and Lamb (1991) Shi et al (1995)
Mawddach	Bar-built	sediment dynamical processes	Larcombe and Jago (1996)
Conwy & Seiont, Dulas	Coastal Plain	tidal asymmetry, non-linearity, salinity, salt fluxes, suspended sediments	Bowers and Al-Barakati (1997), Münchow and Garvine (1991), (Pelegri, 1988), Simpson et al. (2001), West and Sangodoyin (1991)
Dee	Coastal Plain	sediment dynamical processes, salt-marsh development, turbulence	POL, Huckle et al. (2005), Simpson et al. (2004)
Mersey	Coastal Plain	bathymetric evolution, sediment transport model and measured fluxes	Thomas et al. (2002), Lane (2004, 2005)
Liverpool Bay	Embayment	Coastal Observatory	http://cobs.pol.ac.uk/
Ribble	Coastal Plain	Morphology, modelling	van der Wal and Pye (2003), Gleizon et al. (2003)
Morecambe Bay	Embayment	sediment transport	Mason and Garg (2001), Aldridge (1997)
Clyde	Fjord	Modelling, salinity distributions	Crowther et al. (2001), Wallis et al. (1996), Thomason et al. (1997)

Beauly Firth, Cromarty Firth, Dornoch Firth	Complex	nutrients	Balls (1994)
Spey Bay	Bar-built	geomorphology	Riddell and Fuller (1995)
Ythan	Bar-built	salinity and nutrient distributions	Gillibrand and Balls (1998), Balls (1994)
Dee, Don	Coastal Plain	nutrients	Balls (1994)
Tay	Complex	salinity, suspended matter, dynamical modelling, nutrients	McManus (2005), Neill et al. (2004), Balls (1994)
Eden	Bar-built	tracking variability	Consalvey et al. (2004)
Firth of Forth	Complex	tidal currents, suspended sediments, nutrients	Clarke and Elliott (1998), Elliott and Clarke (1998), Balls (1994)
Tweed	Complex	seasonal variability and modeling, nutrients	Uncles et al. (2000), Punt et al. (2003), Balls (1994)
Wansbeck	Coastal Plain	effects of barrage	Worrall and McIntyre (1998)
Tyne	Complex	water and salt fluxes	Park and James (1988, 1990)
Tees	Coastal Plain	internal waves and mixing, sedimentation history, salinity distribution and flux	New and Dyer (1988), Plater and Appleby (2004), Lewis and Uncles (2003)
Esk (N. Yorks.)	Complex	hydrodynamic modelling	Toole and Benn (1992)
Ouse – Humber	Coastal Plain	freshwater flow influence on siltation, Ouse turbidity maximum, Humber sediment budget and other fluxes, sediment flux and bed level, morphology	Pontee et al. (2004), Uncles et al. (2006), Townend and Whitehead (2003) and other papers in the same LOIS special issue, Christie et al. (1999), (Reeve et al., 2003)
The Wash	Embayment	wave dissipation, fine sediment suspension, inter-tidal elevation, flow over salt marsh	Cooper (2005), Bass et al. (2002), Mason et al. (2001), Neumeier and Amos (2006)
Ouse	canalised	suspended sediments	West and Sangodoyin (1991)
Blyth (Suffolk)	Bar-built	sediment dynamics after abandoning a reclaimed area	French et al. (2000)
Ore	Bar-built	hydrographic and topographic survey sequence	Carr (1986)
Deben	Coastal Plain	morphology	Burningham and French (2006)
Orwell,	Coastal Plain	sediment regime, saltmarsh erosion	Roberts et al. (1998), Pye (2000)
Stour	Coastal Plain	sediment regime	Roberts et al. (1998)
Crouch	Coastal Plain	saltmarsh erosion	Pye (2000)
Thames	Coastal Plain	saltmarsh erosion	Pye (2000)
Maplin Sands	Linear Shore	sediment (sand) dynamics	Whitehouse (1995), Whitehouse et al. (1996)
Medway	Coastal Plain	extreme discharges, intertidal erosion and sediment budget, managed retreat analogue	van den Boogaar and Stive (1990), Kirby (1990), French)1999)
Pagham Harbour	Bar-built	sedimentary response to barrier breach	Cundy et al. (2002)
Solent	--------	general	Collins and Ansell (2000)
Chichester Harbour	Bar-built	flow over salt marsh	Neumeier and Amos (2006)

Langstone Harbour	Bar-built	sediment transport and morphodynamics	Gao and Collins (1994)
Southampton Water	Coastal Plain	Monitoring, estuarine circulation	Pittam (2004), Ribeiro et al. (2004)
Christchurch Harbour	Bar-built	net sediment transport	Gao and Collins (1995)
Teign	Ria	Currents, vertical mixing, bedload transport and bedforms	Sutherland et al. (2004), West and Shiono (1988), Hoekstra et al. (2004)
Dart	Ria	currents and tidal intrusion front	Thain et al. (2004)
Tamar	Ria	Plymouth Sound circulation; Tamar currents, erosion, sediment suspension; internal waves and mixing	Siddorn et al. (2003); Uncles (2002), Tattersall et al. (2003), Uncles et al. (2003); Sturley and Dyer (1992)
Fowey	Ria	sediment pathways	Friend et al. (2006)
Lough Foyle	Coastal Plain	suspended material movement during dredging	Bates (1996)
Strangford Lough	Complex	sediments related to waves, mud flat stability	Malvarez et al. (2001), Kirby et al. (1993)

[T] ??Estuary “type” to be re-aligned with Future-Coast / FD2117 typology.

13. Conclusions

Interventions have direct impacts according to their purpose. Climate change also affects hydrodynamics and hence sediment dynamics, water quality, ecology and human activities.

Bottom-Up models are well-proven for hydrodynamics (including waves) in one or two horizontal dimensions. The vertical dimension is needed to represent many processes: estuarine circulation; bottom stresses, erosion and deposition sensitive thereto; separate paths of near-bed coarse sediment, finer sediments higher up (and dissolved constituents); turbidity maxima associated with river flow; sediment supply in bottom marine inflow. 3-D models hydrodynamic models are increasingly well-proven but require more knowledge to run. Confidence decreases along the sequence via sediment transport to morphology. Biases influencing long-term evolution may be inherently hard to predict (aside from proper representation in models).

Data are required to ascertain past changes and significant processes, for model calibration, operation and validation. Analysis of historical data for the estuary in question is a vital guide to future prediction. Ultimately comparison with data provides the basis for all approaches, and so results are only as good as the basis in (all) data used.

The choice of approaches and methods should take account of previous work, practice in analogous problems elsewhere, the issues at stake, the resources, data and expertise available. Varied approaches bring understanding, credibility and confidence in results, provided that causes of differences are investigated. Sensitivity analysis is important to estimate uncertainties in models and in future scenarios.

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Annex 1. Elements of guidance for estuary managers

Estuarine environments are facing increasing rates of change: raised temperature, changing freshwater run-off, changes in sea level, likely increases in flooding events.   Outcomes depend on hydrodynamics and on sediments, which affect the ecosystem (through shading and the dynamics of biogenic particles) and water quality (as many pollutants adhere to fine sediments or a contaminated bed is eroded).

A.1 Predictability

Flow in estuaries is governed by well-established fluid-dynamical equations. However, the domain and turbulent flows are complex, so approximations have to be made. The sediment regime is challenging to predict. Net sediment fluxes reflect small biases in many detailed processes, influenced by sediment properties that may be uncertain in models. There is most confidence in modelling the transport of coarser non-cohesive sands; even this depends on correctly simulating asymmetry between flood and ebb currents. Longer-term prediction of morphology is less certain again: feed-backs between the hydrodynamics and bed-forms allow spontaneous growth of sand waves and banks; morphology depends on future balances between ongoing processes (e.g. tides) and "events" (e.g. storms and waves). [Spontaneous bed-form growth can be exacerbated by numerical model instability]. Such uncertainties limit predictability, inherently and in practice for process-based models.

These limits to predictability raise the need for an ensemble of calculations:
- to cover a wide variety of future possibilities
- to estimate the sensitivity of outcomes to context, sediment properties, model formulation
- hence to guide effort to aspects of context and model for which outputs are sensitive to the current range of uncertainty.

If probabilities can be attached to future scenarios, a corresponding probability distribution of outcomes is obtained and can provide input to expected socio-economic impacts.

A.2 Modelling approaches

Process-based "Bottom-Up" models are mathematical (probably numerical), space-resolving and predictive (probably time-stepping). "Top-Down" approaches include: Holocene analysis, accommodation space, Historical trend analysis, sediment budgeting, estuary form characterisation, regime relationships between form and (e.g.) tidal prism, tidal asymmetry, a concept of equilibrium along-axis profile, concepts of translation or "rollover" with rising sea level. "Hybrid" approaches combine Top-Down and Bottom-Up elements.

In the Bottom-Up approach, predictions of water levels, current speed and direction use well-established fluid-dynamical equations.   Typically, models' spatial and temporal resolutions are too coarse for individual turbulent structures and surface waves, and possibly too coarse also for fine-scale features of the domain, e.g. salt-marsh or inter-tidal flats with small creeks and channels. Overall effects of such fine-scale features need an approximate representation in terms of variables calculated explicitly by the model. Otherwise, the flow is supposed to be resolved in time and space, including distortion around features of scale O(0.1 - 1 km) as resolved in the model. Water levels and flow rates driven by tides and winds can be well-described by depth-integrated non-linear equations, if the water is well-mixed through depth. Otherwise the vertical should ideally be resolved; factors countering this may be poor data for heat and fresh-water inputs that inhibit mixing, and computational cost. If an estuary is long (near-resonant) or large, its dynamics probably affect the adjacent coastal sea, which should then be modelled, at least in two horizontal dimensions.

Waves are important for mobilising sediment and also affect wind-forcing of estuarine flow. Specific surface-wave models are well established (either for significant wave height and period, or for more detail as the wave spectrum). Interaction with currents and inputs to turbulence can be modelled.

The flow and waves usually drive sediment transport. [Dense suspended sediment can stratify the water and so affect the flow]. Bed-load sediment transport (of non-cohesive sand or larger grains) can be calculated as a direct function of flow speed, waves, sediment type and perhaps broader-scale bottom slope. Suspended load concentration can be estimated in currents and/or waves: either by formulae for the profile and bottom concentration, or by a transport equation discretised like the hydrodynamics; respective uncertainties are in the bottom concentration or erosion rates. The critical stress for erosion can be increased by cohesion (and perhaps flora and fauna), especially if the sediment has been on the bottom for some time; bioturbation can reduce the critical stress for erosion; wetting and drying can change bed properties in inter-tidal areas; in the water column, particles may combine as flocs. These complications are not so well formulated for model simulations.

Thus models can represent transport of non-cohesive material (sand, if supply is plentiful), along-shore drift of sand given the incident wave "climate", and suspended transport of fines. It is harder to model limited sand supply, mixtures, fluid mud, erosion and consolidation of a cohesive bed. Sediment parameterisations in models need calibrating for the estuary studied. Particle-tracking models for sediment transport enable particle "history" to be followed; this is relevant to biogenic particles, cohesive properties and bed consolidation.

Water quality and/or ecology variables are typically modelled within the hydrodynamic discretisation. Their transport equations have advection and dispersion in common with suspended sediment concentration. However, water-quality and ecosystem constituents have particular sources and sinks. Ecosystem modelling of all individual species is impractical; empirical groupings are used but then growth, respiration and grazing rates can only be approximate. Necessarily primary production is modelled, and often secondary production (zoo-plankton). Quantities higher up the food chain are less predictable.

A.3 Model choice

Computational costs may be an issue for long Bottom-Up model runs. Cost can be reduced by using an acceleration factor for morphological evolution. However, a wide range of scenarios necessarily involves much running of models, of whatever form. Interpretation of ever-increasing model outputs is a growing cost in experts' time, urging careful design of model experiments and ensembles.

The choice of approaches and methods should take account of:
- the issues of concern (e.g., flood risk, morphology, water quality, ecology) in context
- character of the context

- the location's designation (importance), hence level of confidence required in predictions
- scale of any proposed intervention
- previous studies (which should be made use of as appropriate)
- best practice for the type of study or issues involved
- data availability; information needed to set up the model, data to calibrate and test it
- justifiable basis for model parameter values and ability to assess sensitivity thereto
- study budget and duration (limiting the ability to obtain new data)
- investigator's experience; hydrodynamic and morphodynamic complexity favours use of previously-acquired skill.

Uncertainties in models and future scenarios should be estimated. This entails use of varied approaches and sensitivity analyses; knowing why outcomes differ gives understanding, credibility and confidence in results. Hence appropriate model choice may mean several simple models and inter-comparisons to help understanding and prediction. Interpretation of differences between approaches, and the sensitivity of outcomes to model formulation, give a firmer basis for prediction. Models that are simple enough to understand and run quickly may be favoured for multiple runs sampling wide range of scenarios.

Shorter-term prediction is widely regarded as most suitable for (fine-resolution) Bottom-Up model application. This is relevant for questions such as direct impacts of intervention and decadal or shorter-term morphological effects of sea-level rise, climate change, waves, tidal processes, fluvial processes, sediment supply and dynamics. Issues of underlying geology, ecology, water quality, how present morphology arose, require a wider perspective in time or scope. However, Bottom-Up models embody physical conservation laws which may give long-term large-scale constraints. Bottom-Up models are necessary for water-quality modelling. For morphology, Top-Down and complementary studies should help to understand estuarine function and give confidence to interpret model outcomes.

A.4 Validation and data

Validation is generally still needed for numerical models for predicting estuarine behaviour, especially long-term changes in bathymetry. Bottom-Up models need data:
- for their formulation (especially, calibration of sediment-related parameters),
- as forcing (particularly *via* boundary conditions)
- for testing and validation by comparing model outputs with measurements.

Test comparisons should involve all modelled variables critical to overall results. Good simulation of any one variable is not sufficient. Validation needs data sufficient to resolve hydrodynamic biases and uncertain sediment properties, defining the context closely; no "room for excuses". Comparisons with data ultimately provide the basis for all approaches, and so results are only as good as the basis in (all) data used. Confidence in model predictions is best built up by testing them against all available observations in the specific estuary(s) studied – and by understanding differences between model results and measurements.

Data sufficiency concerns resolution in time and space, accuracy, variables measured, location(s) and time(s) of year to be representative. Bottom-Up model calibration needs profiles of current, salinity and suspended sediment concentration through a spring and a neap tidal period. Direct measures of sediment properties should be obtained. Analysis of historical data for the estuary in question is a vital guide to future prediction. At least two bathymetric surveys are needed to test any trend suggested by a model. Activities that may affect the trend need to be known, e.g. dredging or reclamation. If data from the estuary in question are inadequate, it may be necessary to test the model on a similar estuary.

A.5 Scenarios

Simulations may aim to cover various future climate-related and anthropogenic scenarios. In relation to climate, Sections 9.1-9.5, 10.5 suggest ranges of some forcing parameters.

- *Mean sea level*: a 0.30 m rise may be realistic for the next 50-75 years, 0.5 m for the next century. [Some suggest less, but correlations with temperature suggest a metre rise by 2100].
- *Tidal range*: typical amplitude increases (for a 0.5 m rise in mean sea level) are ± 2 cm but up to 10 cm in the Bristol Channel and Eastern Irish Sea.
- *Surges*: typical increases in extremes may be 0.1-0.2 m (5-year return), 0.2-0.3 m (50-year return). [Climate models differ in their results; distributions of the increases are uncertain].
- *Winds*: sensitivity to a 10% increase in speeds, to wind direction and to storm track.
- *Waves*: sensitivity to a 10% increase in wave height, to a 5% increase in wave period, to changes in near-shore depth and to changes in storm track.
- *Rivers*: sensitivity to 20% increase in peak flow; behaviour with small flow.

If responses to extreme events are important, a long period of representative meteorological forcing may be simulated, and sensitivities tested: to wind speeds, direction and storm tracks.

There are benefits from setting findings in a wider context, even if the study only concerns specific aspects of just one estuary. Analogues can help to give confidence in the findings.

Ergon House
Horseferry Road
London SW1P 2AL

www.defra.gov.uk

Department for Environment
Food and Rural Affairs