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A STRATEGIC BASIS FOR ESTUARINE RESEARCH

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ABSTRACT: Global Climate Change threatens to increase the risk of flooding in estuaries worldwide. To address this threat and to maintain a balance between exploitation and conservation, there is an urgent need for improved scientific understanding , expressed in computer-based models able to differentiate and predict the impact of man's activities from natural variability. Long-term data sets are vital for such programmes, systematic marine monitoring programmes must be initiated, involving combinations of remote sensing, moorings and coastal stations. Likewise, continued development of theoretical frameworks are necessary to interpret ensemble modelling sensitivity simulations and to reconcile disparate findings from the diverse range of estuarine types.

Here, developments in modelling, observational technologies and theory are reviewed with a focus on how international co-ordination is necessary to minimise uncertainty and to ameliorate the threats to the future viability of estuaries.

1. INTRODUCTION

The supply of river water and access to inland and ocean waters led to the siting of numerous towns and cities along estuaries. Over the next century, rising sea levels may force many of these to invest in extensive flood protection measures or even to relocate. While the immediate questions concern the changing magnitudes of tides, surges and waves, the underlying longer term (decadal) issue is how the estuarine bathymetries ,which shape their dynamics, will adjust. In addition to the pressing flood risk, there is growing concern about sustainable exploitation of estuaries, in particular how economic and natural environment interests can be reconciled in the face of increasingly larger scale developments. The urgency, magnitude and ubiquity of these questions demands effective international collaboration. Here we attempt to identify related elements which need to be addressed.

While tides, surges and waves are physically the most energetic, many parameters exhibit pronounced seasonal cycles (e.g. temperature, light, waves, river flows, stratification, nutrients, oxygen, plankton). Changes to these seasonal cycles (or to related episodic events) may be extremely significant for estuarine ecology e.g. adjustments in axial intrusion of sea water and variation in vertical stratification associated with salinity and temperature. Likewise, changes to the almost imperceptible larger-scale background circulations may affect the pathways and distributions of persistent tracers.

The processes describing tidal propagation can be accurately represented by linearised 1-D (one dimensional) equations, enabling accurate model simulation of discrete constituents.

momentum $$\frac{\partial u}{\partial t} + g\frac{\partial \zeta}{\partial x} + \frac{f\,u\,|u|}{H} = 0$$

continuity $$B\frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x}Au = 0 \qquad (1)$$

where u is the tidal velocity, V the elevation, $H = D + \zeta$ total depth, B breadth, A cross-sectional area, f is the bed friction coefficient, x axial distance and t time.

By contrast, mixing involves a wider-spectrum of interacting non-linear processes and is thus more difficult to simulate. The 'decay-time' for tidal, surge and wave energy in estuaries is usually measured in hours, as is the vertical mixing rate in strongly tidal shallow waters. By contrast the flushing time for river inputs extends over days, as does the vertical mixing rate for weak tidal currents in deep waters. Hence, while simulation of the

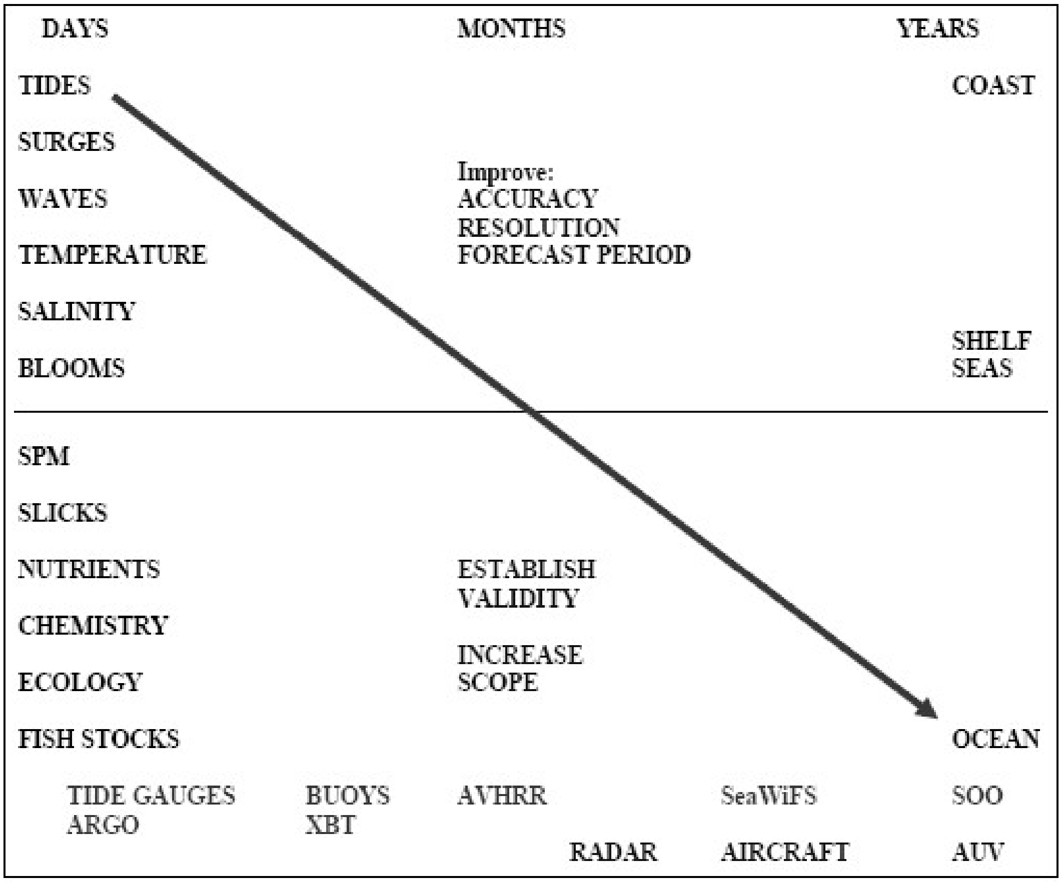


Fig 1 Evolving application of marine models, extending parameters, time and space scales alongside observational technologies.

former is relatively independent of initial conditions, simulation of the latter is complicated by 'historical' dependence and associated accumulation of errors.

Vertical and horizontal shear in tidal currents generate fine-scale turbulence which determines the overall rate of mixing. However, interacting 3D variations in the amplitude and phase of tidal cycles of both current and contaminants severely complicate the spatial and temporal patterns of tracer distributions and thereby the associated mixing. In spring, surface heating stabilises the vertical density profile while in winter surface cooling can produce overturning. Similarly, on Neap tides near-bed saline intrusion may enhance stability while on Springs enhanced near-surface advection of sea water can lead to overturning. Density differences associated with suspended sediment concentrations can also be important in suppressing turbulent mixing in highly turbid conditions.

Figures 1 and 2 show how the scope and foci for modelling have developed alongside the related observational capabilities.

The central questions for estuarine research have evolved to reflect successive theoretical advances and these developing agendas. Thus, since 1980, research has focused on the following sequence of issues (amongst others):

How do tides in estuaries respond to: shape, length, friction, river flow?

How does salt water intrude and mix?

What determines estuarine shape, length, depth?

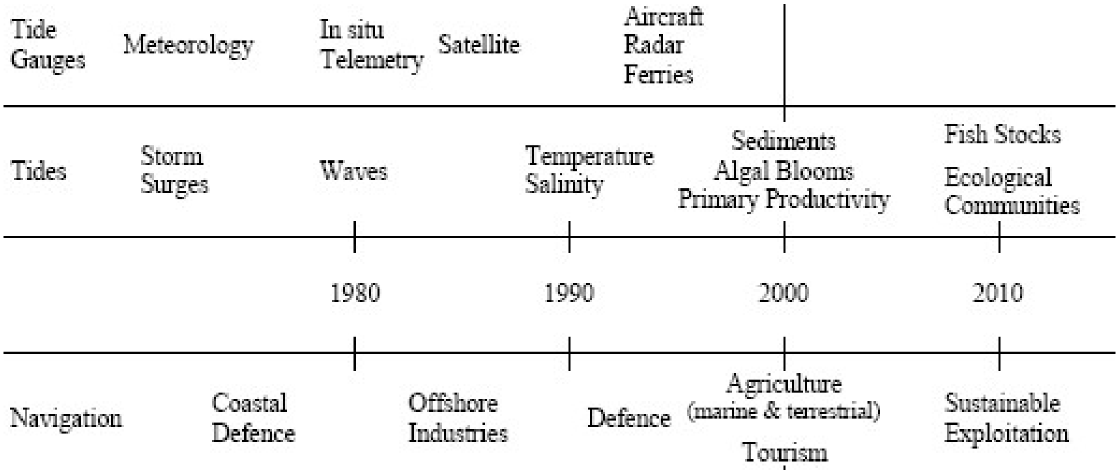


Fig 2. Historical development of marine modelling, processes, observational technology and 'end-users'

Why are sediment concentrations in estuaries 100–1000 mg/l

yet, for the same depths and currents in shelf seas only 1–10 ?

What Causes Trapping, Sorting, Turbidity Maxima ?

Prandle and Rahman (1980) provided a theoretical framework for tidal response, (figure 3), based on analytical solutions to the linearised 1-D dynamical equations (1). The concern then was with the sensitivity of the tidal response in estuaries to the construction of barriers for tidal power. The study explained the influence of the funelling effects of both depth and width variations alongside the sensitivity to bed friction.

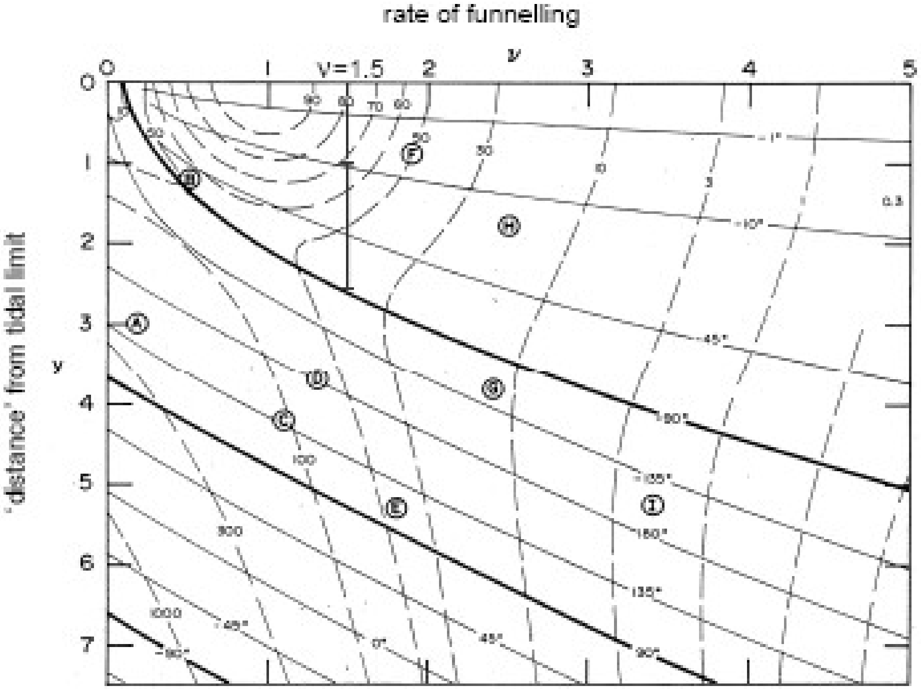


Fig 3 Axial variation in tidal amplitudes (dashed lines) and phase along estuaries.
Axial parameter y = 0 at the head, ν is a bathymetric funnelling parameter.
From Prandle & Rahman (1980)

Prandle (1985) and (2004b) examined the nature and extent of saline intrusion in strongly-tidal estuaries and the sensitivity to spring-neap tides and changes in river flow.

Subsequent sections review recent progress and developments in : modelling (2);observational technology (3) and theoretical frameworks (4). Section 2 includes a critique on the capabilities and limitations of 1D, 2D and 3D models. Section 3 describes the range of instruments and platforms and the importance of synergistic deployments. Section 4 highlights how new analytical solutions for ’synchronous’ estuaries provide insight into the processes of sediment transport and the stability and evolution of their morphology.

2. MODELS

Models synthesise theory into algorithms and use observations to set-up, initialise, force, assimilate, and evaluate simulations in operational, pre-operational and ‘exploratory’ modes.

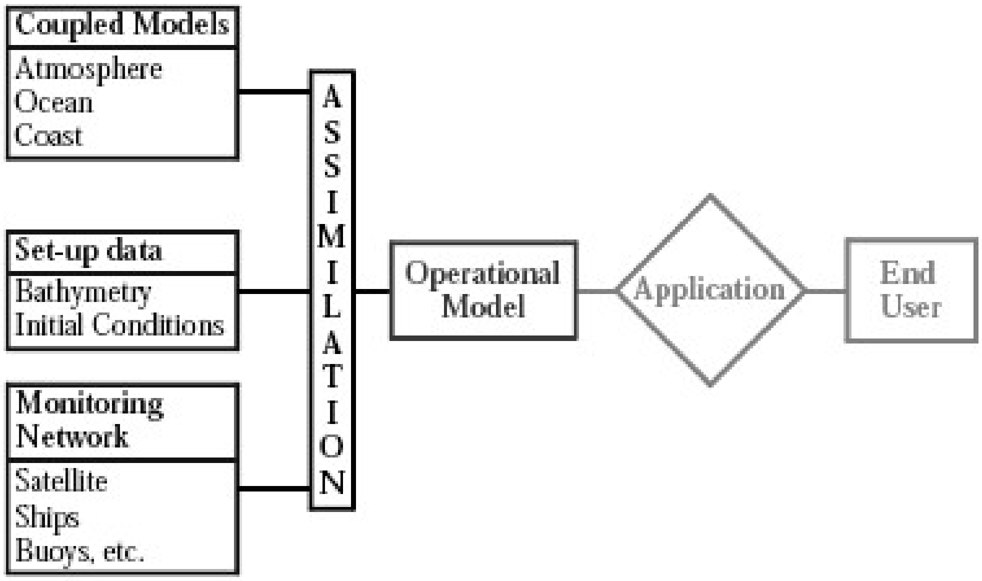


Fig. 4: Components of an Operational Modelling System

Models are limited by the validity of the basic algorithms, by numerical and discretization accuracy and by the quality of the observational data used both to prescribe the external forcing and to evaluate results, Figure 4 .Their restricted capabilities to simulate long term changes (more than a few years ahead) is widely recognised. A particular concern is the uncertainty in predicting longer-term (decadal) bathymetric evolution, where incremental changes can depend on antecedent bathymetry, resulting in random or chaotic model outcomes.

Mode of Applications

Real-time *Operational* uses include tidal predictions and hazard warning for : storm surges, oil or chemical spill movement, search and rescue, eutrophication, toxic algal blooms etc.

Pre-operational simulations often involve assessing and understanding the health of marine ecosystems and resources and their likely sensitivity to changing conditions. These are typically concerned with assessment of absorptive capacity for licensing of discharges, evaluating environmental impacts of intervention (reclamation, dredging, etc.) and climate change.

Exploratory applications extend from formulation of environmental management policies to developing the underpinning science and technology to address both anthropogenic influences and natural trends.

Scope

Models can be: (i) non-dimensional conceptual modules encapsulated into whole-system simulations, (ii) one dimensional (1-D), single point vertical process studies or cross- sectionally averaged axial representations, (iii) two dimensional (2-D), representations of horizontal circulation, or (iv) fully three dimensional (3-D). Over the past 40 years, numerical modelling has developed rapidly in scope, from hydrodynamics to ecology , and in resolution, progressing from the 1-D barotropic models of the 1960s to present-day 3-D baroclinic (incorporating evolving temperature and salinity induced density variations). Comparable resolutions have expanded from 100 axial sections to upwards of 100 million elements, exploiting the contemporaneous development of computing power. Unfortunately, concurrent development in observational capabilities has not matched this resolution, despite exciting advances in areas such as in remote sensing and sensor technologies.

Parameters of interest include tides, surges, waves, currents, temperature, salinity, turbidity, ice, sediment transport, and an ever-expanding range of biological and chemical components. The full scope of models involves simulations across ocean-atmosphere-seas-coasts and between physics-chemistry-biology-geology-hydrology extending over hours to centuries and even millennia.

Human intervention in estuarine environments impacts on flooding, fisheries; ecology, industrial and commercial developments. Regulatory regimes must accommodate such activities alongside their environmental impacts, hence we need to link marine models with their socio-economic counterparts. In practice, coupling might be limited to sub-set representations (statistical emulators) encapsulating integrated parameters such as stratification levels or flushing times. To overcome the limitations of individual modules in such total-system-simulations, methodologies are required both to quantify and to incorporate the range of uncertainties associated with model set-up, parameterisation and (future scenario) forcing. This requirement can be achieved by ensemble simulations providing relative probabilities of various outcomes linked to specific estimates of risk.

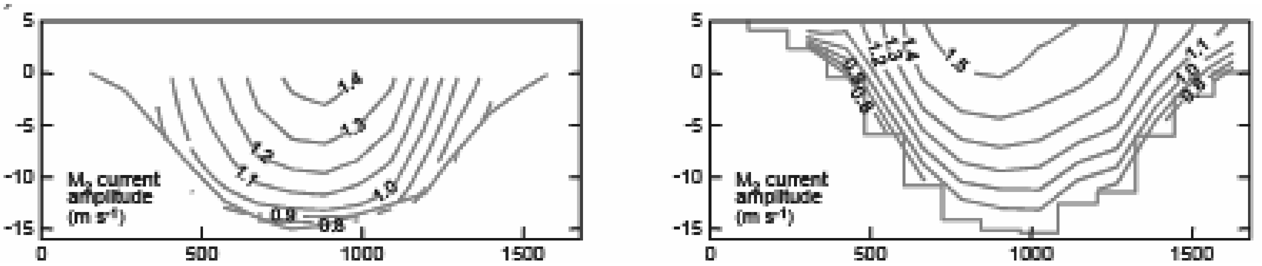
Both proprietary and public-domain model codes typically involve investment of tens of years in software development and continued maintenance by sizeable teams. Such effort is increasingly beyond the resources of most modelling groups. The diversity of marine systems makes it unlikely that a single integrated estuarine model will evolve. Moreover, there is a continuing need for a wide range of types of models with different characteristics to provide genuine ensemble envelopes and cater for a range of environments . Such diversity does not obviate the requirement that all models be validated and robust.

1D, 2D or 3D models?

1-D (cross-sectionally averaged) models provide accurate simulation of tidal elevation amplitudes and cross-sectionally averaged currents for the primary tidal constituents.Prandle (2004b) showed that tidal propagation is generally insensitive to baroclinic density effects. Such models may be adequate for simulating salinity or finer particles (which stay in suspension much longer and are effectively mixed vertically and laterally in high current regimes). However, they are less well suited for simulation of coarser sediments (more sensitive to near-bed current profiles) or to wider estuaries where lateral circulation is often significant and lateral variability in ebb-flow dominance occurs.

The 2-D (vertically-averaged) models afford significant advantages over the 1-D, by resolving the pronounced lateral depth variations. The associated (depth-dependent) non-linear processes involved in tidal propagation are now resolved together with rotational (Coriolis) and spatial accelerations (advection) in accurate simulation of higher harmonics and (especially) fine-scaled residual current circulations. Inter-comparisons between theory and observations of cross-sectional currents for the predominant semi-diurnal emphasise the effect of local changes in bathymetry, (Fig. 5). Corresponding inter-comparisons for the residual component are complicated by questions of definition and accuracy of observations (Lane et al 1997). This enhancement in resolution of currents greatly improves the simulation of pathways of sediments - both fine and coarse.

The 3-D models introduce both vertical current structure and some description of turbulence intensity. Whilst depth-averaged currents are often relatively insensitive to these additional features (and hence simulation of tidal dynamics is relatively little improved), the magnitude of the related bed stress is especially sensitive and, hence the erosion and deposition processes. (This sensitivity is especially marked for estuaries where tidal constituents are close to their inertial latitudes). Although 3-D models introduce significantly more complicated processes such as turbulence modules, they do offer the only realistic possibility of robust sediment erosion, transport and deposition algorithms able to incorporate temporal and spatial variations in turbulent intensity and associated stratification. Lagrangian, random-walk, simulations of sediment transport embedded in the above models can incorporate millions of particles, each with individual properties such as size, shape, density, biological and chemical reactions (Lane and Prandle 2006). Extension of such 3-D models to include a comprehensive range of ecological parameters is often limited by computer hardware. However, the progressive growth in the power and decrease in cost of this resource is continuously eroding this obstacle to progress.



Observed Computed

Fig 5. Observed and computed M_2 currents in a cross-section in the Mersey Narrows (m/s)

Limitations and Development

The validity of models is limited by the degree to which the equation or algorithms synthesise the governing processes and by numerical and discretisation accuracies. The accuracy of model simulations depends further on the availability and suitability (accuracy, resolution and duration) of both observational and linked meteorological, oceanic and hydrological model data to set-up, force and assess calculations (fig 4).

Numerical modelling of tidal and surge elevations in estuaries is well developed, and generally requires only a limited number of elevation measurements for validation. However, tidal currents vary over much shorter spatial scales with localised changes in bathymetry, creating small-scale variability in both the vertical and horizontal dimensions (Figure 5). These changes in velocity produce even more localised variability in erosion, deposition and transport of suspended material. Thus, numerical modelling of contaminant fluxes is less well developed and requires more detailed spatial resolution, with a corresponding increase in the resolution of observational surveys used for validation.

Immediate improvements in the accuracy of simulations can be achieved with adaptable and flexible grids alongside more sophisticated numerical methods. In the horizontal, rectangular grids are widely used often employing polar coordinates of latitude and longitude. Irregular grids, generally triangular or curvi-linear, are used for variable resolution. In Computational Fluid Dynamics, continuously adaptive grids provide a wide spectrum of temporal and spatial resolution in multi-phase processes. The vertical resolution may be adjusted for detailed descriptions - near bed, near surface or at the thermocline. For example, the sigma coordinate system accommodates bottom-following with a uniform number of coordinate surfaces occupying the water column. In estuaries, the influence of turbulence on the dynamics of currents and waves and their interaction with near-bed processes remains to be clearly understood. Understanding and enhanced representation of turbulence effects in models is a central issue. Development of turbulence models is supported by new measuring techniques like the microstructure profiler, providing a direct comparison of simulated dissipation rates with in situ measurements. Presently, most 3-D estuarine models use a 1-D (vertical) turbulence module and there is still no clear consensus on the best turbulence scheme to be implemented .

3. OBSERVATIONAL TECHNOLOGY

Rigorous model evaluation or effective assimilation of observational data into models requires broad compatibility between resolution and accuracy in models and observations — temporally, spatially (horizontal and vertical) and in parameter range (figure 6).

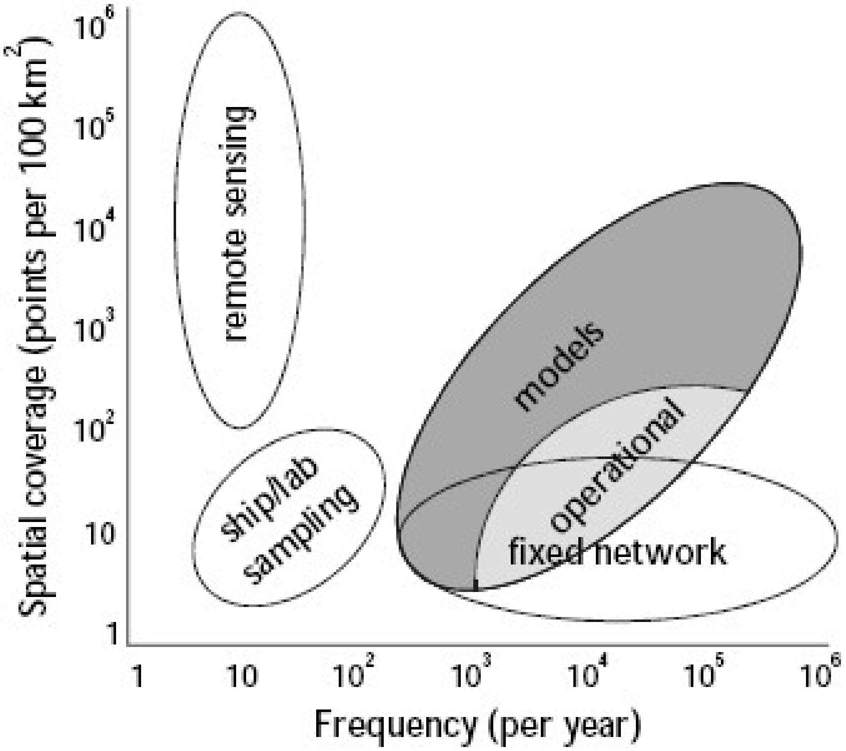


Fig. 6: The Spatial and Temporal Resolution of Models and Monitoring Systems: Remote Sensing, ship-borne and Fixed Networks

(Assimilation involves the combination of information provided by observing networks with the systematic temporal and spatial resolution of holistic knowledge incorporated within numerical models. In operational forecasting, assimilation involves structured incorporation of near real-time observations to improve nowcasts and forecasts. In non-operational modes, assimilation may be used in calibrating parameters, boundary conditions, surface roughness, etc., to improve the accuracy of simulations.)

Requirements And sources of Data

Set-up of estuarine models requires accurate fine-resolution bathymetry, and ideally, corresponding descriptions of surficial sediments/bed roughness. Subsequent forcing requires tide ,surge and wave data at the open-sea boundary together with river flows at the head alongside their associated temperature, sediment, and ecological signatures. Observational data can be obtained from satellites, aircraft, radar, buoys, floats, (cabled) moorings, gliders, AUVs (Automated Underwater Vehicles) and instrumented ferries. Associated data is provided by meteorological, hydrological and shelf-sea models . Ultimately, fully-coupled global models incorporating the total water-cycle will emerge.

Over the past two decades, remote sensing techniques have matured to provide useful products of ocean wind, waves, temperature, ice conditions, suspended sediments, chlorophyll, eddy, and frontal locations. Unfortunately, these techniques provide only sea-surface values and in situ observations are necessary both for vertical profiles and calibration. The improved spatial resolution provided from aircraft surveillance is especially valuable. High frequency radars also provide synoptic surface fields of currents, waves, and winds on scales appropriate to the validation of estuarine models.

Sea surface temperatures are routinely mapped by AVHRR and VISSR . Clouds are a major constraint and such SST data are often patchy in both space and time. Active microwave sensors such as altimeter, scatterometer and Synthetic Aperture Radar (SAR) provide datasets of ocean topography, near surface winds and waves . Passive microwave sensors (SSM/I) are used to monitor sea ice and wind speeds.

In addition to the immediate, localised requirements, information may be needed about possible changes in Ocean circulation - both on regional climates and on the supplies and sinks for nutrients, contaminants, thermal energy etc. Careful monitoring of coastal zones may indicate how such impacts are conveyed . Recognising the long inertial lag of the oceans to impacts from Global Climate Change, detection of systematic regional variations may provide early warning of impending impacts in shelf seas and estuaries.

Development of Monitoring Networks

Permanent coastal monitoring networks have been established in coastal seas and estuaries measuring water level, currents profile, surface winds, waves, temperature, SPM, salinity , nutrients etc using tide gauges, mooring and drifting buoys, platforms, ferries alongside remote sensing from satellites, radar and aircraft. Regional monitoring networks are being established via the GOOS networks (UNESCO 2003).

Despite these advances, the range of marine parameters that can be accurately measured is severely restricted and the cost of observations is orders of magnitude greater than that associated with models. Consequently, the effectiveness of simulations is severely limited by shortcomings in the accuracy, spatial and temporal extent, and resolution of such data.

Instrumentation is already lagging seriously behind model development and application, and this gap is expected to widen. New sensors are needed, in particular sensors suitable for installation on ferries and through-flow sensors for moorings. A new generation of instrumentation is needed for the validation of species-resolving ecosystem models.

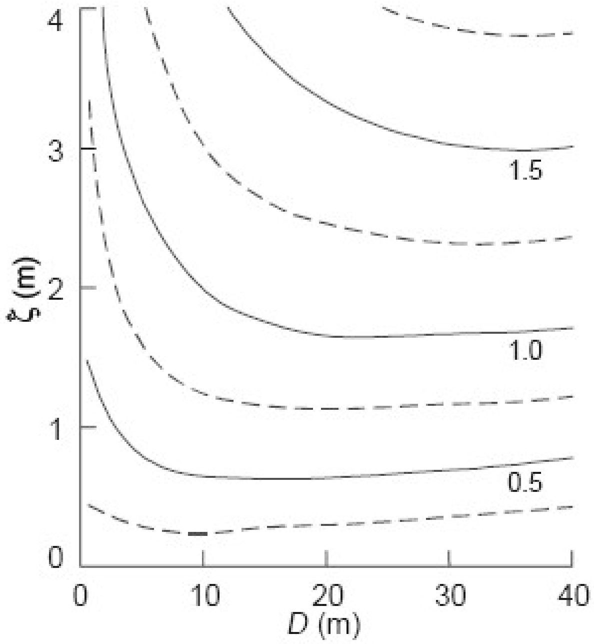


Fig 7: Tidal Current Amplitudes (m/s) as a Function of Tidal Elevation Amplitude, ς and Depth D

4. THEORY

Tidal Elevations and Currents

Analytical solutions for the dynamical equations(1) describing the tidal response of a single (predominant) tidal constituent were reviewed by Prandle (1991). The axial (x) momentum equation for tidal propagation can be approximated by (1)

Harmonic solutions for the predominant constituent take the form: $z = \zeta \exp\{i\,(-\omega t + kx)\}$ and $u = U \exp\{i\,(-\omega t + \theta + kx)\}$. By assuming the surface slope is due to axial variation in tidal phase (rather than amplitude) and substituting for ζ and u, Equation (1) gives:

$$U\{1 + i\,1.33 fU/(\omega/k)\}\,\exp(i\theta) = \zeta(g/D)^{1/2}, \qquad (2)$$

where the phase celerity $\grave{u}/k$ is assumed to be $(gD)^{½}$ and the linearisation of the quadratic friction term follows from *Prandle* [2004a]. Assuming M_2 is the predominant tidal constituent, (2) can provide quantitative insight into the relevant importance of the inertial versus friction terms in balancing the surface gradient forcing, thus :

$$U(1 + i23.7U/D)\,\exp(i\theta) = 3.1\,\zeta/D^{1/2}. \qquad (3)$$

It is evident that in waters of less than 10 m, friction will dominate and a simple expression for tidal current amplitude follows: $U = 0.36\,\zeta^{½} D^{¼}$.

This explains the restricted range of tidal currents in estuaries, with values almost invariably in the range 0.5 to 1.0 m s-1 as indicated in Figure 7, based on a complete solution to (1).

Dynamical bases of Bathymetry

Inter-tidal slopes are typically 0.001. The water interface advances over such slopes at up to $0.14 \times Z$ m s^{-1} across inter tidal areas $2 \times Z$ km wide, where Z is the maximum tidal amplitude. For large values of Z, these strong currents will lead to wide-scale morphological adjustments .This may explain why, globally, Z rarely exceeds 5m.

By assuming a ‘synchronous’ estuary, where surface gradients generated by tidal phase change predominate over those via tidal amplitude variations, *Prandle* [2004a] derived the following expression for the length of tidal intrusion in an estuary

$$L = 123\,D^{5/4}/(\zeta f)^{1/2} = 2460\,D^{5/4}/\zeta^{1/2} \qquad (4)$$

where the bed friction coefficient is taken as 0.0025.

Prandle [2004a] deduced from observations that mixing of river and salt water occurs as seawards as possible, subject to being contained within the estuary. *Prandle* [2004b] showed that in ‘mixed’ estuaries (as considered here), the length of saline intrusion, L_I, is given by

$$L_I = 0.005\,D^2/(f\,U\,U_0) \qquad (5)$$

where U_0 is the residual velocity associated with river flow, Q (m^3 s^{-1}). Relating the estuary length with the length of saline intrusion, the following expression is obtained:

$$D = 12.8\,(Qa)^{0.4}, \qquad (6)$$

where a is the lateral slope of an assumed triangular cross section. This result is independent of both ζ and f, (Fig. 8).

Prandle [2004a] determined a ‘Morphological Zone’ bounded by the requirements that saline intrusion, and its associated tidal excursion, do not extend beyond the estuary:

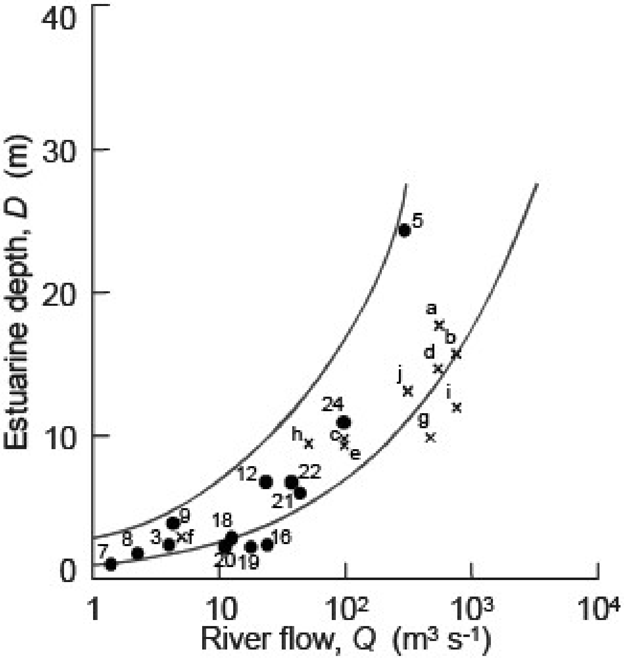


Fig. 8: Theoretical relationship between depth (at the mouth) and river flow. Eq (6)

Tidal excursion: tidal length $E_x / L < 1,$ (7)

Saline intrusion: tidal length $L_I / L < 1.$ (8)

An additional indicator of 'mixed' conditions in estuaries, is the criterion of Simpson and Hunter [1974]:

$$D / U^3 < 50 \ (m^{-2} s^3) \tag{9}$$

Hence, the basic estuarine dimensions of depth and length can be directly estimated from the two fundamental 'forcing' parameters namely tidal elevation amplitude and river flow. Moreover, since these parameters are also the most readily available data for many estuaries, wide-scale assessment of the theories is possible. Figure 9

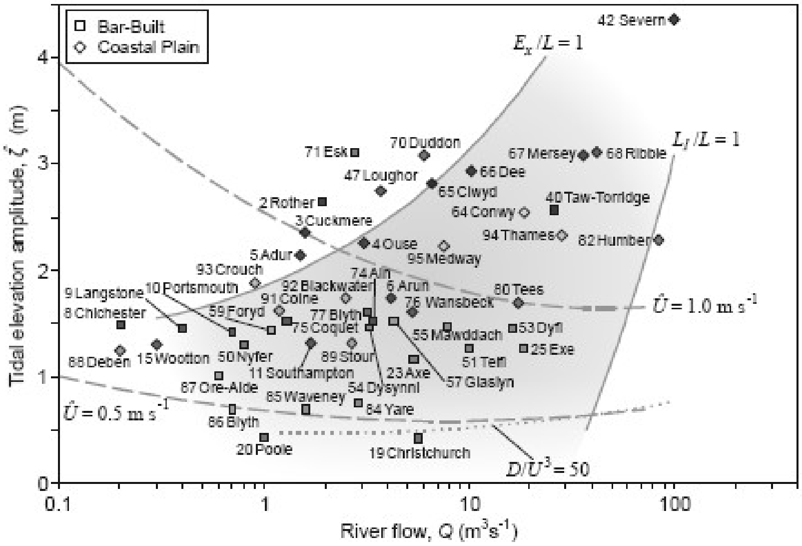


Fig. 9: Morphological Zone, (*æ*, *Q*) coordinates of estuaries

Continuous lines show $Ex/ L = 1$, $L_I/ L = 1$.
Dashed contours for tidal velocity amplitude $U = 0.5$ and 1.0 m s-1.
Dotted line shows Simpson-Hunter stratification demarcation.

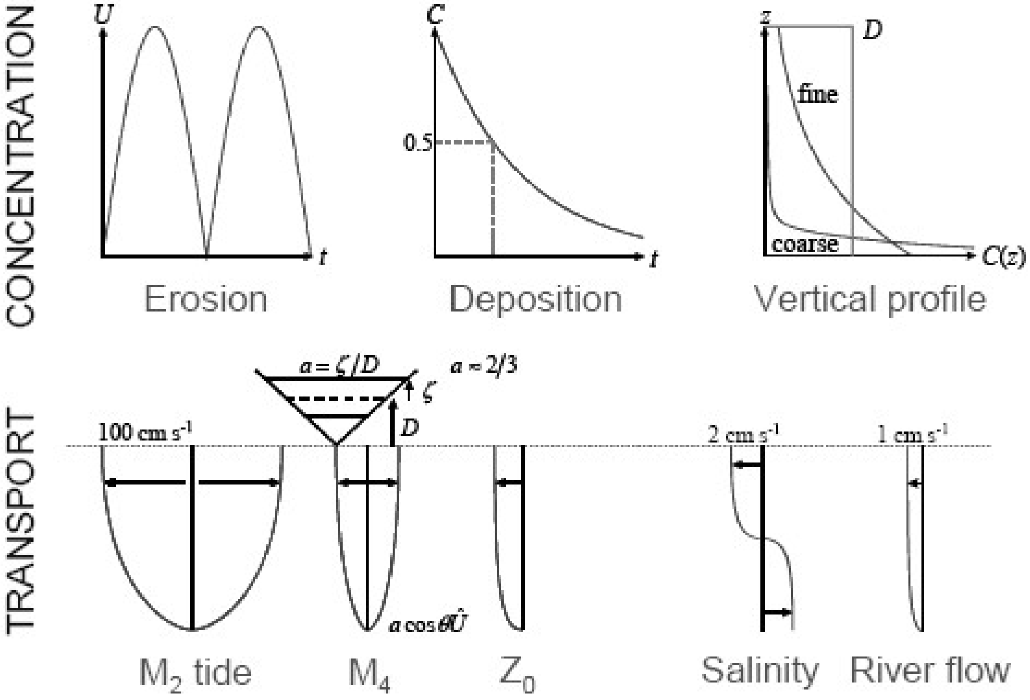


Fig. 10: Component processes integrated in an 'analytical emulator' for sediment fluxes.

shows this zone of 'morphological existence' bounded by these demarcation lines. The figure also shows the corresponding locations of 80 UK estuaries, Prandle et al (2005b).

Bathymetric Stability

Further studies, Prandle (2004c), extended the above solutions for dynamics and saline intrusion in estuaries to consider sediment concentration and net sediment fluxes taking into account the processes shown schematically

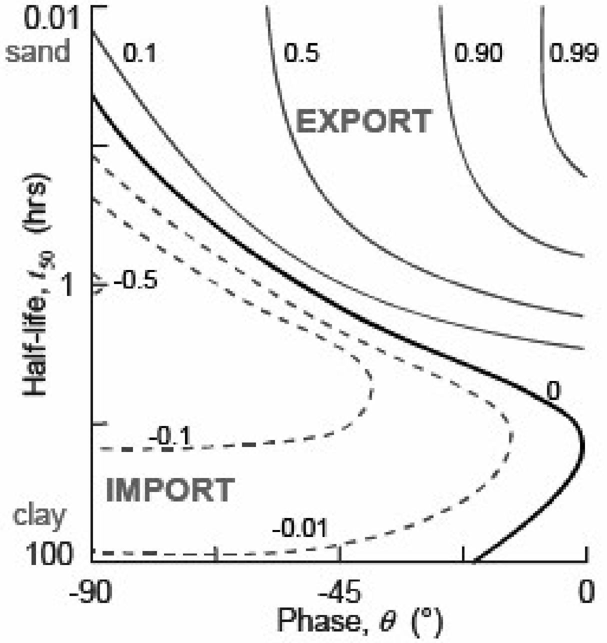


Fig. 11: Import and Export of sediments as a function of sediment half-life in suspension and phase advance, θ ,of ς wrt U.

in Fig 10. This study provided estimates of conditions consistent with bathymetric stability, Figure 12 encapsulates these results. At any location the import or export balance in the tidal rectification terms depends directly on the phase lag θ between tidal elevation and current. Since the net tidal energy dissipation, upstream of any particular location, is directly proportional to ςU cos θ, we see a relationship between the whole estuary scale tidal energy balance and localized cross-sectional sediment flux balance. Such relationships have been suggested previously [Bagnold, 1963], and minimizing net tidal energy dissipation is used as a condition in some morphological models.

The formulation of the emulator, linking tidal dynamics, saline intrusion, and sediment mechanics, involved many expedient approximations. The conditions derived for maintaining stable bathymetry extend earlier concepts of flood and ebb-dominated regimes. Sediment import and export is now shown to vary axially, with sediment type, and over the spring to neap tidal cycle. Of particular interest is that these derived conditions correspond both with maximum sediment trapping and with observations of the predominant settling rates in many estuaries. Overall, the emulator provides new insights into the balance between tides, river flow, and bathymetry and on the relationship of these with the prevailing sediment regime. Interestingly, the new dynamical theories for estuarine morphology ,encapsulated in Fig 9, take no account of the sediment regimes in estuaries. Hence the success of these theories provoke a reversal of the customary assumption that estuarine bathymetries are determined by their prevailing sediment regimes.

5. SUMMARY AND FUTURE CHALLENGES

Estuarine processes range over wide spectra of temporal, spatial and parameter scales, from physics to ecology, from micro-turbulence to whole estuary circulation. Exciting opportunities are presented by the rapid advances in: computational power, monitoring technology and systems, scientific understanding and numerical methods. Nonetheless, furure investment and the associated progress will depend on demonstrable benefits to end users.

An international approach is necessary to quantify the contribution to and effect from Global Climate Change. This extends to : development of models and instruments (and their platforms), planning of monitoring strategies, exchange of data etc. This collaboration should develop structured research, development and evaluation programmes. The ultimate goal is a fusion of environmental data and knowledge, utilising fully the communications and computational capacities.

To understand and quantify the threat of Global Climate Change, whole-system models are required - incorporating the impacts on marine biota and their potential biogeographic consequences The introduction of Water Framework Directives for governance of Regional Seas and coasts emphasises the need for development of well-validated, reliable models for simulating water quality-ecology-fisheries. A systems approach is needed, capable of integrating marine modules and linking these into holistic simulators (geological, socio-economic etc.). Rationalisation of modules to ensure consistency with the latter is an important goal, together with standardisation of prescribed inputs such as bathymetry, tidal boundary conditions, etc.

Coupled hydrodynamic-mixing models are required as the basis for transporting and mixing contaminants both horizontally and vertically. Since the dynamic processes involved occur over time scales of seconds (turbulent motions), to hours (tidal oscillations), to months (seasonal variations) with corresponding space scales from millimetres to thousands of kilometres, a range of models is required. In addition to hydrodynamic and mixing models, sediment and ecological models require robust algorithms for sources, sinks and biological/chemical reactive exchanges.

In Ocean modelling, standardised, generic modules are perceived as the requisite building blocks of future interdisciplinary, international collaboration. The development of generic modules and the ready availability of public domain model codes have removed much of the mystique that traditionally surrounded estuarine modelling. Rationalisation of modules within modelling systems is a recognised goal, together with standardisation of pre-scribed inputs such as bathymetry, tidal boundary conditions, etc. Such enhanced rationalisation will enable the essential characteristics of various types of models to be elucidated including the inherent limits to predictability. The diversity of estuaries makes it unlikely that a single integrated model will evolve. Moreover, retention of flexibility at the module level is both necessary and desirable to accommodate a wide range of applications and to provide ensemble forecasts. Further development of theoretical frameworks are important to interpret such ensemble simulations.

Operational Oceanography is essential to minimise damage from future events (from storms on a short-scale to longer-term sea level change) by enhancing probabilities in related forecasting. Operational Oceanography will provide valuable spin-off benefits to pre-operational modelling required for sustainable exploitation and management of our marine resources. Assimilating in-situ observations with remote sensing data, alongside rapid data processing and appropriate communications is essential for operational modelling. Particular challenges arise in estuarine models because of their rapid response times and large tidal excursions.

Successful application of models are generally limited by the paucity of resolution in observational data (especially bathymetry) used for setting-up, initialising, forcing (meteorological and along model boundaries), assimilation and validation . This paucity of data is a critical constraint in environmental applications. More and better observational data, extending over longer periods are essential if modelling accuracy and capabilities are to be enhanced.

Comprehensive observational networks are needed exploiting synergistic aspects of the complete range of instruments and platforms and integrally linked to modelling requirements. Permanent in-situ observations are likely to be the most expensive component of any operational system, and it is important to optimise the observational network in relation to the modelling system for the requisite forecasts. There is a parallel requirement for accurate (model) descriptions of the state of adjacent shelf seas to define estuarine boundary conditions.

Up-scaling of knowledge from comprehensive test-bed process studies is required to link small scale (micro) measurements to larger and longer (macro) scale algorithms employed in numerical models. Ideally such measurement programmes should extend to: water levels, currents, temperature and salinity, waves, turbulence, bed features, sedimentary, botanical, biological and chemical constituents. The associated costs dictate these would cover a limited but representative number of estuaries. Specific ‘deliverables’ would be: (i) complete, consistent, documented, accessible bench-test observational data sets for model validation *; (ii)* development of monitoring strategies, elaborating synergistic values of the range of systems and sensors; (iii) assessment and development of sensors, instruments and platforms.

ACKNOWLEDGEMENTS

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