ANALYSIS AND MODELLING GUIDE

Introduction

The various methods available for examining change within estuaries, based on the types of method identified in the EMPHASYS guide are outlined in Tables 1 to 5. The methods are grouped under the following headings and described in more detail in the text linked to each of the methods:

- Data Analysis Methods
- Regime and Equilibrium "Top-Down" Methods
- Process Based "Bottom-Up" Methods
- Hybrid Techniques that Combine "Top-Down" and "Bottom-Up" Methods
- Related Modelling and Analysis Topics

Further information can also be found further down in this section and at:

US Army Corps: http://cirp.wes.army.mil/cirp/cirp.html
The Corps of Engineers research and development program is developing knowledge and predictive technology needed to reduce the cost of dredging and improve navigation reliability while considering adjacent beaches. The program includes field data collection, numerical modelling, physical modelling, lessons learned, and basic research on hydrodynamics (waves, currents, water level), sediment transport, and morphology change.

STOWA/RIZA guide on modelling practice
Guidelines for the correct use of water management models, aimed at both clients and modellers.

Techniques available

Table 1. Data analysis methods

Method	Brief Explanation
Accommodation space	Changes in sediment storage capacity over Holocene time scale (10,000 years)
Analytical Solutions	Characterisation of the estuary system or estuary processes into manageable stand alone mathematical equations.
Expert geomorphological analysis	Using many of the above techniques, together with an understanding of how different types of landform evolve, to assess the expected development of the estuary system
Historical trends analysis	Documents changes to estuary over time from charts, maps and historical archives. Identifies any trends. Should include chronology of human developments (e.g. reclamation, dredging, etc)
Holocene analysis	Description of geological development of basin. Usually includes estimates of sea level change and identification of periods of marine regression and transgression
Saltmarsh analysis	Relates properties of exposure and tidal range to the presence and distribution of species
Sediment budget analysis	Reconciliation of sediment inputs, outputs and sources/sinks within the estuary
Statistical, spatial and time series analysis techniques	Uses standard data analysis techniques to identify dominant components, trends, cycles and relationships between variables, to give insights into the dynamics and complexity of the system

Table 2. Regime and equilibrium "Top-Down" methods

Method	Brief Explanation
EstSim prototype simulator	The Prototype Simulator takes a systems-based description of the geomorphological elements present within an estuary, and through a mathematical formalisation of the influences between the morphological and process components, investigates its response to natural and anthropogenic changes
Estuary translation (rollover)	Defines the vertical and horizontal movements of the whole system as a consequence of changes in sea level
Form analysis	Uses shape descriptions to characterise the estuary form (e.g. exponential width decay, or power law width and depth)
Intertidal form analysis	Considers the equilibrium shape of the cross-shore profile
Regime relationships	Relates estuary form properties such as cross-sectional area, plan area of intertidal or subtidal to tidal prism, volumes to given elevations, sediment type, and erosion threshold
Tidal asymmetry analysis	Examines changes in tidal wave propagation as a function of estuary form

Table 3. Process based "Bottom-Up" methods

Method	Brief Explanation
Advection-diffusion models	Calculates the movement and dispersion of a constituent (particle matter or solute), given an initial concentration field (e.g. dispersion of a heat from a power station outfall)
Hydrodynamic modelling	Process based modelling of water levels, discharge, current speed and direction, waves, density currents and secondary circulation patterns
Morphological bed-updating models	Prediction of changes to bed levels based on sediment transport modelling. The bed is updated at regular intervals to provide a feedback to the hydrodynamic and sediment transport models.
Particle tracking	Prediction of particle movement by seeding particles into the flow regime with given properties (size, density, settling velocity, etc) and tracked in a Lagrangian manner
Sediment transport modelling	Process based modelling of bed load and suspended sand and/or mud movement, with relationships to determine the rates of erosion and deposition

Table 4. Hybrid techniques that combine "Top-Down" and "Bottom-Up" methods

Method	Brief Explanation
Behaviour models	Describes the net behaviour of the system (or some aspect of it) using simplified descriptions, or relationships derived from the use of more detailed process models.
Coupled hydraulic and energy relationships	Examines the distribution of bed shear stresses and compares these with erosion thresholds for the types of sediment present.
Coupled hydraulic and entropy relationships	As above but defines a target steady state based on the concept of minimum work in the system as a whole
Coupled hydraulic and regime relationships	Given a perturbation to the estuary system this method uses a target equilibrium, defined by some form of regime relationship, to iterate to a new equilibrium
Uniform sediment flux or sediment balance	In this type of model, sediment is moved within the estuary until a steady state is achieved when equal amounts are moved on the flood and ebb tide.

Table 5. Related modelling and analysis topics

Method	Brief Explanation
Ecological modelling	Models to describe the interactions between physical, chemical and biological components. Generally these are limited to specific interests (e.g. bird/fish populations, benthic communities, vegetation cover, etc).
Sediment quality	Techniques to establish the transport pathways of sediment and the way in which contaminants are adsorbed and released from the sediment
Socio-economic modelling	Techniques to address the pressure-state-impacts-response cycle, usually in terms of some form of economic valuation, as a basis for predicting societal responses and so identifying how the pressures may change in the future.
Water quality	Models that represent the advection and dispersion of suspended matter, dissolved oxygen and contaminants

Further information

Regime and equilibrium "Top-Down" methods

Top-down methods are related to an assumed target state or equilibrium condition for the estuary. There are a range of 'Top-Down' methods available which include (i) regime theory, (ii) form analysis, (iii) consideration of tidal asymmetry and (iv) the concept of estuary transgression or rollover (Table 2).

Process based "Bottom-Up" methods

In an estuary the motion of fluid can be determined by a set of physical laws (Abbott, 1979). The laws of motion attributed to Isaac Newton quantify the motion of physical objects. The process based 'bottom-up' approach employs models that rely on solving a set of equations to describe the behaviour of fluid particles flowing in 3D space, acted upon by various forces (EMPHASYS report). The value of these models lies in the fact that the results obtained are based on the representation of physical process, which have a sound and widely accepted basis.

There are a number of basic types of process-based models. These include hydrodynamic models, advection diffusion models, sediment transport models, particle tracking models and morphological bed-updating models. Hydrodynamic models, which can simulate water levels, discharges, currents, waves, density currents and secondary circulation, are usually considered as the basis of the 'bottom-up' approach. The other four types of model all rely on results obtained from the hydrodynamic model. The models can be 1, 2 or 3 dimensional, offering results of increased realism, but with increased difficulties in calibration and validation.

Process based models rely on solving the basic shallow water equations for water flow and sediment transport (Clayson & Kantha, 2000). These equations representing physical processes can be written in the form of differential equations (i.e. they involve the rates of change of basic quantities such as velocity) and can be solved in a number of different approaches. Most approaches solve the equations numerically using finite elements methods or finite difference, but other solving techniques include 1-D vector methods, statistical models and spectral transform approaches. This final method is however, much better adapted to atmospheric rather than estuary related models.

A brief description of the finite difference and finite element solving techniques is given below.

Finite difference: the underlying principle of finite differences is that the gradient of a slope at a particular point can be estimated by knowing information about the slope at points either side of the chosen point (Abbott & Basco, 1989). The equations of motion for a fluid particle are estimated by substituting derivatives for differences, of which there are three types: forward, backward and centred differences, where values are based on information from the left, right or both sides, respectively). In numerical modelling all gradients in horizontal and vertical positions as well as time are replaced by these differences.

Finite element: The principle behind finite elements is that a region is covered with small, usually triangular, faces (Abbott & Basco, 1989). These faces are small enough so that variables such as velocity vary only a little over a single face. This allows for key variables to be expressed as simple linear expressions.

In finite difference methods, the equations are calculated horizontally to provide outputs of the eastward and northward current and water levels over a rectangular, curvilinear or spherical grid. Depending on whether water levels or currents are calculated on the corners, sides or centre of the grid, the grids are called Arakawa A, B, C, D or E grids (Clayson & Kantha, 2000). Finite element methods are becoming increasingly popular because the method allows almost unlimited flexibility in adapting the grid locally to any desired resolution.

'Bottom-up' methods are also best suited when considering localised change (EMPHASYS Consortium, 2000). When modelling a whole estuary it is unlikely that the horizontal resolution will be finer than about 10m. It is also unlikely to be applied uniformly throughout the whole estuary because of constraints in computing power. Finite element and curvilinear grids and techniques such as grid nesting are useful in this respect because certain areas of an estuarine system can be refined to a higher resolution. Vertical resolution is likely to be a few centimetres, in terms of overall depth, which in a 3D model may be represented by X forms of subdivision similar to that used in the horizontal.

Process based models are used to give short-term predictions (days to months) of morphological change. Applying these models for long-term predictions (months to years) may result in large uncertainties as the errors in prediction begin to accumulate.

Morphological change in an estuary may be inferred from the results of the process-based model or may be predicted directly by the model. But, in order to obtain adequate and accurate results it is very important firstly, that the models include the appropriate physical processes occurring in the estuarine system, and, secondly, that the models are set-up, calibrated and validated by experienced individuals who undertaken appropriate sensitivity tests, recognising that the model calibration is dependent on the field data available and the interpretation of the data (Dyke, 1966).

Further information on model types can be found in an EMPHASYS project report from Posford Duvivier (2000) and from the USA compiled by Dr Chris Sherwood (USGS) in circa 2003 as part of the project to develop a Community Sediment Transport Model.

Hybrid techniques that combine "Top-Down" and "Bottom-Up" methods

A number of the top-down concepts use a description of the flow field as one of the inputs. To-date these have most often been applied to conditions at a given time interval. With this approach the time-dependent predictive capability of top-down methods is limited, although they may well say something about the equilibrium condition or possible states that a system can occupy. The concept of hybrid modelling is to link the long-term goal defined by top-down methods with the more detailed description of the prevailing processes at any given time as defined by suitable 'bottom-up' process models.

One can consider a number of ways in which a hybrid model could be constructed. One option is to define the equilibrium or target state, assume this remains constant, or changes in a defined way (dependent only on *external* conditions), and use the hydrodynamic model to drive an iterative process that continually adjusts conditions towards the defined state. This is how many of the existing regime models work (O'Connor *et al.*, 1990; Spearman *et al.*, 1998, Wright and Townend, 2006). An alternative is to define an equilibrium condition for some dependent parameter such as zero net sediment gradient. This is the approach adopted in hybrid models such as Estmorph (Wang *et al.*, 1998).

This is an area that is currently the focus of attention within the international research community. For example, work undertaken for the Estuaries Research Program (ERP2) looked at coupling regime relationships with standard hydrodynamic models under a single program called the "Hybrid Shell Interface". It is likely that the techniques available will develop rapidly over the next few years. The grouping of techniques in the following sections is slightly arbitrary but is the one adopted by the EMPHASYS consortium as a basis for giving some guidance on the techniques currently available (see the EMPHASYS guide). It therefore serves as an introduction to the subject area but reference should also be made to recent research publications.

Within the EMPHASYS guide the types of hybrid model available were sub-divided into the following groups:

- Behaviour models
- Coupled hydraulic and energy relationships
- Coupled hydraulic and entropy relationships
- Coupled hydraulic and regime relationships
- Uniform sediment flux or sediment balance

Conclusions

These various methods provide a range of approaches each with their own strengths and weaknesses. Selection of the most suitable techniques for a particular problem will depend on the nature of the problem, the relative scale of the change with respect to the estuary, and the data that is available both historically and from project specific field work (see section on study process in the Morphological Change Guide). The results from the different methods will invariably need to be summarised and then drawn together to reach some overall conclusions (see section on syntheses in the Morphological Change Guide).

References

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