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Identifying change in estuaries

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Abstract. Strategic management and planning within estuaries seeks to identify a framework that enshrines sustainability. Any management initiative must address the issues of long-term change; physical, chemical and biological interactions; and system response (including socio-economic interactions). Achieving such a programme will need to take advantage of studies and research at a number of different spatial and temporal scales. These range from global climate change initiatives, through catchment and estuary wide studies to work on specific features (banks, mud flats, etc.). They necessarily consider changes over time scales of seconds to aeons. For strategic planning and management, the goal is to be able to predict change, with a reasonable degree of confidence over a 20 to 50 year time horizon. Given the highly non-linear and complex adaptive nature of estuary systems, absolute predictions may not be possible. Rather, it will be necessary to identify probable/possible outcomes, or system states, as a basis for guiding management actions. This, in itself, will require managers and planners to move away from a prescriptive interventionist approach towards a more adaptive one.

Keywords: Conservation; Humber; Management; Morphology; Reclamation, Sea level rise; Sediment budget.

Estuary management

Estuaries are a focal point for the full range of human activities. Throughout history man has settled near to the coastline and has used estuaries and rivers as a transport artery to inland areas. At first estuaries were places of relative shelter and also provided a source of food and means of transport. With growing populations trade has increased and there has also been a greater need for drinking water and the disposal of human waste, which is often taken from and/or discharged into rivers. Land for agriculture to feed the population and space for dwellings and industry is also required and leads to reclamation or draining of low lying areas. Thus as man's ingenuity has evolved, increasing pressures have been imposed on the natural river and estuary system.

With growing pressures, comes the increasing risk that the long recognized nature conservation importance of estuaries will be compromized and increasingly, a more pro-active approach is being adopted towards positive management for future generations. Estuaries are also extensively used for recreational activities, such as sailing, fishing and walking. Conservation and recreation have to take place alongside social and economic development and as such require careful balancing. Hence, an integrated approach is needed to address multiple uses and interests, with sustainability central to the management process.

Changes such as reclamation, dredging and the removal of flood storage areas by the introduction of flood defences, all alter the dynamics of the system. Ironically schemes to protect fresh water habitats at the margin of estuaries are progressively having the same effect. Many of these anthropogenic changes can be likened to various geological features that occur within estuary basins (such as variations in the underlying bed formation, some areas being relatively soft and erodible and other areas being hard and more resistant). Both serve to apply constraints on how the estuary can evolve. As the estuary adjusts to these various constraints, particular features within the estuary, such as the extent or position of intertidal mud flats, salt marshes, sandbanks, etc., will also change. It is important to recognize

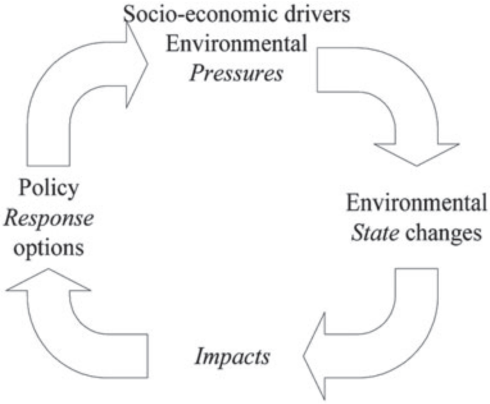


Fig.1. P-S-I-R model (Turner et al. 1998).

that the estuary will adjust to the imposed constraints, both natural and anthropogenic. Consequently there is little point in seeking to define what the 'natural' estuary system would look like. The central question for management is, rather, whether any changes that are imposed will alter particular estuary features, that we as a society value, in a way that we consider unacceptable?

Management framework

The need for an adaptive approach, to respect the dynamic coastal environment, has led to management frameworks being proposed, which are modelled on a cycle with a continuous feedback process. In an institutional context, the pressure-state-impact-response model has been suggested as a means of identifying key issues for environmental management, Fig. 1 (Turner et al. 1998).

Nested within this high-level framework, more specific frameworks have been proposed to address some of the issues found on the coast (Townend 1990, Townend 1992; Capobianco et al. 1999) and in estuaries (Barham 1997; Pontee & Townend 1999b). For instance, when considering the morphological response of an estuary, it is possible to consider two approaches (Fig. 2). One strand considers the resource to be developed or protected (e.g. existing or proposed infrastructure) and requires the impacts on the estuary as a whole to be identified. The second, parallel strand seeks to establish how the estuary will evolve subject to ongoing changes in the environment (such as sea-level rise) and determine how this might impact on anthropogenic interests in the estuary (e.g. flood protection or navigation).

In order to carry out either of these assessments it is necessary to predict the system response. This is encapsulated in the cause-consequence model in Fig. 2 and refers to a process of identifying causes of change at a number of spatial and temporal scales, determining the system response, and hence predicting the consequences, again at various spatial and temporal scales (Fig. 3). For the present, there is no one model that provides the response component. Rather, there are a whole range of analytical and numerical tools that collectively provide a basis for making an assessment (Pontee & Townend 1999a; Anon. 2000a).

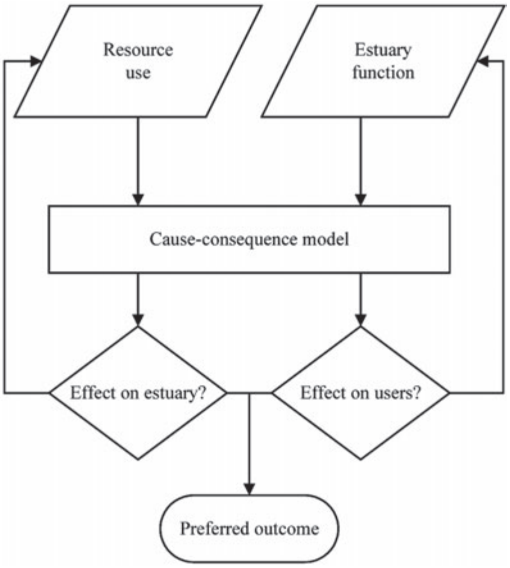


Fig.2. Parallel strands for the assessment of management actions (Pontee & Townend 1999b).

The limitations of this tool box and in particular the ability for the outputs to inform the management process is one of the key drivers for further research (Townend 2002).

Identifying and predicting change

The estuary system behaviour, with complex feedback loops and a multiplicity of spatial and temporal scales interacting, as described above, means that representing this in some form of analysis or model is not straightforward. Whilst this is an active area of research in many organizations around the world, there is currently no single model capable of representing the complex interactions of the estuary environment. For this reason, a carefully structured approach is needed to develop a proper understanding of the governing processes over a range of spatial and temporal scales. This starts with the geological setting (i.e. thousands to millions of years), at a scale of the whole river basin/regional sea, and spans down to a single wave moving sediment particles. Time and space scales are linked and great care is needed to ensure consistency. A simple

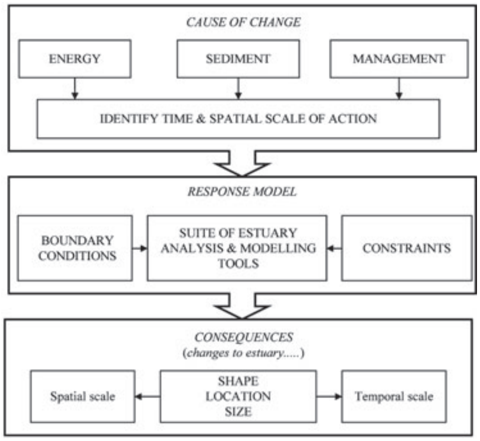


Fig. 3. Cause-consequence model for morphological response in an estuary (Pontee and Townend 1999a).

example arises when comparing field data with the output from numerical models. The former often provide data at a point averaged over some period of time, whereas the latter output spatially averages information at a given instant. Due allowance must be made for these differences. More difficult cases involve the interaction between different space-time scales, which are quite often associated with very different equilibrium states and response times.

To establish an understanding of how a system has developed, currently functions, and is likely to evolve in the future, it is necessary to consider at least some elements of the following combinations of space and time (Table 1).

There is of course significant overlap and interaction between the different space and time scales, as presented in Table 1. In terms of our present state of knowledge, the geological time scales and the contemporary time scales (years to seconds) have been well researched. The decadal time scale is now receiving greater attention through a number of national and international research programmes. Whilst useful historical information can be gleaned from the archaeological record, the ability to link decadal change into the Holocene evolution is currently the weakest aspect of our knowledge (Townend 2002).

Summary of process

The need to identify and predict change usually arises as part of a strategic planning exercise (e.g. estuary management plans or climate change impact assessment) or some site specific activity (e.g. flood defence, dredging, reclamation, etc.). As with any project or planning initiative, there are likely to be specific goals to be achieved, with constraints defined by the time and funds available. For this reason, it is important to have a clear understanding of the problem to be addressed at the outset. Furthermore, this understanding should be reviewed at intervals through the project, as knowledge increases, in case there is a need to refine or revise some of the project objectives.

Once the problem is clearly defined, it is possible to scope possible approaches. There is no one approach and a number of factors will influence the choices to be made, notably:

- degree of certainty required to address problems;
- timescale for study;
- the available funding;
- access to resources (trained staff and appropriate equipment/models, etc.); and
- existing sources of information/data.

Even at this early stage it is helpful to start formulating a conceptual model. The aim is to identify the mechanisms and hence the system behaviour that, for a given set of circumstances, will determine the likely modes of change. This can be done using the literature for well studied estuaries, or by comparison with other

Table 1. Indication of the relevant space and time scales.

Time	Space
Geological (thousands-millions of years)	Underlying form and geology of the whole catchment and adjacent sea area
Recent geology (i.e. Holocene covering the last 10,000 years)	Development of the main features of the estuary and distribution of mud and sand features
Historical (centuries)	Refinement down to large-scale features in the estuary, such as channels and islands. Begin to take account of human activities such as early settlements, reclamation and dredging
Decadal (10 to 100 years)	Intertidal flats, saltmarshes, meandering channels, creeks, spits, banks and shoals. Small cumulative signals, such as long-term changes in sea-level, begin to have significant effect on the morphology of the estuary. This may result in horizontal and vertical changes to the position of given features, including the estuary as a whole
Seasonal/annual	Changes to fluxes in and out of estuary and on and off intertidal areas (due to changes in river flows, storminess, etc.)
Tidal period (12.4 hours for a semi-diurnal tide)	Ebb and flood channels, drainage channels, tidal excursion distance
Wave period (a few seconds)	Bed features such as ripples and sand waves

similar estuaries for those that are less well studied. In a well developed case this may be a quantitative set of predictions. Alternatively, where there is only limited information, the conceptual model is likely to be more qualitative.

By considering how the various methods of analysis and modelling contribute to the solution, a work programme can be developed. This will need to be reviewed and agreed. It may be that the work can best be progressed in a series of phases. For instance, some analysis of the existing data may identify important data gaps, or improve understanding, so that subsequent phases of work can be modified to make best use of information from earlier phases. Whether the work is done in phases or not, it is always helpful to set out key milestones at which particular outputs are to be delivered. This helps to ensure progress towards the overall objectives.

As the work is progressing, documentation and careful record keeping is important, as this will greatly aid the resolution of conflicts and uncertainties during the interpretation phase of the work, particularly if a number of different types of analysis are being undertaken in parallel. Individual components of the work will need to be summarized and key findings clearly identified. In this process it is essential to distinguish between factual information and interpretation that relies on particular assumptions.

Bringing the findings of the various studies together involves the process of synthesis. To some extent, this is a subjective matter and each individual will go about it in a slightly different way. However, where the conclusions have to be presented to a range of users (perhaps as part of the consultation process) the basis for any conclusion will need to follow logically from the factual information and be as transparent as possible. A framework, which is as objective as possible, is therefore desirable.

For this the conceptual model provides both a framework and a test bench to help explore the meaning and consistency of the various study outputs. This will necessarily need to be on a number of spatial and temporal scales and may address the response of specific features (such as saltmarshes) as well as the estuary system as a whole. Each of the various outputs is mapped onto the conceptual model. For some aspects there will be only limited information. For others there may be several sources. In each case it will be necessary to evaluate the uncertainty and, if necessary, consider what further information would help to reduce the level of uncertainty. Where different sources are incompatible, or conflict, the uncertainties need to be clearly identified and, where possible, resolved. It may be that the conceptual model can help to resolve the differences by indicating which source is most consistent with the overall picture. The aim is to establish a description of how the system works and how it will be affected by particular changes. The findings of the synthesis and, in particular, the conceptual model can then form the basis for assessing the future changes and the resultant impacts.

The overall process of identifying change can therefore be summarized as four steps:

1. Define problem;
2. Scope approach;
3. Implement work programme; and
4. Synthesize the results.

Any changes identified then feed into the impact assessment process. A breakdown showing the main considerations for each of these steps is shown in Fig. 4.

Synthesis

The various studies provide factual information and outputs from analyses and models. Either individually or collectively these establish or refine the understanding of particular mechanisms in the estuary. However for the reasons already given, these may not be sufficient to define the overall behaviour (particularly in the long-term). The task of synthesising the results therefore aims to formulate a behavioural summary of the estuary system as a whole.

The process of synthesis to establish or refine the conceptual model should utilize as much of the available data and knowledge of the estuary as possible. This allows the conceptual model to be tested against the different sources of information, to establish supporting evidence, or possible conflicts. Where there are contradictions that cannot be reconciled, the results should be presented to highlight the uncertainty, or further studies undertaken to resolve the uncertainty.

The steps involved are also summarized in the Synthesis box in Fig. 4. An initial process of testing the conceptual model against factual data helps to eliminate any obvious misrepresentations and identify any areas of uncertainty. It is important that this is not done using interpreted results as these may depend on assumptions that underpin the particular outputs and this may mask the real behavioural response. Most computational modelling results fall into this category. At this stage the conceptual model is founded on established behavioural concepts (as documented in the literature) and the factual information for the particular estuary. The next step is to introduce the additional information from the various analyses and modelling studies. These again provide a basis for evolving the conceptual model but this should now be done with much greater caution; recognising that the study results and the underlying

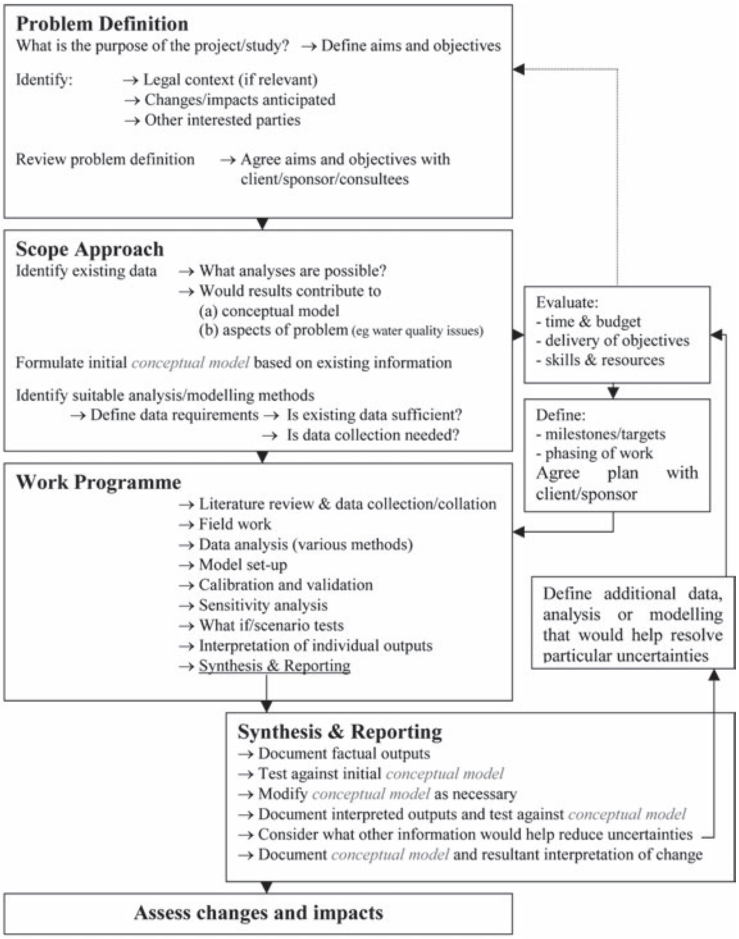


Fig. 4. Summary of the process to identify/predict change.

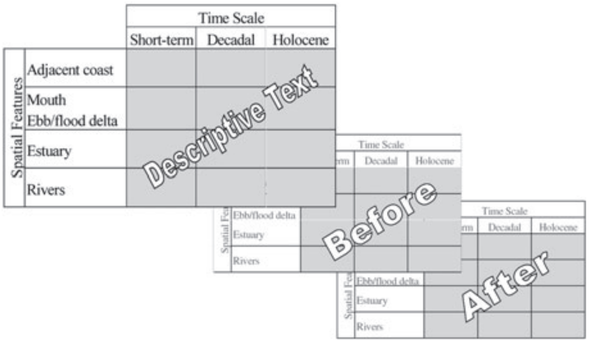
assumptions may be the cause of any discrepancy, rather than some aspect of the conceptual model. (This can include field data which may itself be subject to error and uncertainty.)

Uncertainties in the conceptual model should now be much clearer. In some instances, there may be the opportunity to consider further modelling or field data collection that might help reduce the level of uncertainty. Sensitivity studies, in particular, can help to bound the level of change associated with particular variables and so focus attention on the more significant areas of uncertainty.

Finally the results must be documented in a way that explains the conceptual model and makes clear any uncertainties. There is no established way of doing this and the approach is likely to vary from one situation to another. In most cases the conceptual model will comprise a written description, illustrated with results, schematic figures and flow diagrams. The complexity arises because one is often trying to present a number of behavioural concepts that interact over different space and time scales. Without any clear hierarchy this can be difficult to communicate. Whilst there are various forms of system diagram that allow the linkages to be identified, such techniques often fall short of encapsulating the behaviour of the system.

One way of communicating this complexity to the user is to describe the behaviour in a series of space-time intervals. Using a table, where the columns define time intervals and the rows various spatial elements that make up the system, an explanation of the mechanisms at work and the resultant behaviour can be given, as illustrated in Table 2. Individual cells in the table can then link to sections in the explanatory text (or separate reports) that provide a more complete explanation. In addition the same format can be used to summarize the existing situation and the behaviour predicted for a given set of imposed changes (e.g. sea-level rise, new development, etc.). This is particularly valuable if there is a need to use the results in some form of impact assessment.

Table 2. Summary of space-time changes.



Conceptual model

As already noted, the conceptual model is usually a description, or picture that provides some understanding, of how the system works. This may comprise information about the processes (tides, waves, etc.) some indication of key energy and material pathways (energy flux, sediment transport, etc.) and a description of behavioural responses (of the estuary and component features). A basic conceptual model may be no more than a sketch of the assumed transport pathways. With progressively more information and analysis it may be possible to quantify the pathways and define how the system will respond to change.

A fully developed conceptual model should endeavour to present the key components of a behavioural system in a way that provides a clear understanding of how the system will respond to a given change. Even when all the relevant elements and mechanisms have been identified, this is not an easy task for two reasons:

(1) the complexity of interactions taking place at a range of spatial and temporal scales, with the dominant influence often depending on the nature of the change and the specific characteristics of the coast or estuary; and

(2) the limits to current understanding of behaviour, which give rise to a level of uncertainty which must be acknowledged when presenting the model.

Hence, great care is needed in the way in which the system is presented.

Whilst the starting point for a behavioural system description is invariably the energy and sediment pathways, it is important to identify the causative mechanisms as a basis for building a robust means of predicting the response to change. This must take account of variations in sediment supply and forcing parameters, such as tide and wave energy. However, perhaps the most difficult aspect to capture is the response to thresholds, or the effect of major perturbations, where the system response is to switch to a different state. For example the catastrophic failure of a spit, or the switching of channels as a consequence of episodic storm events.

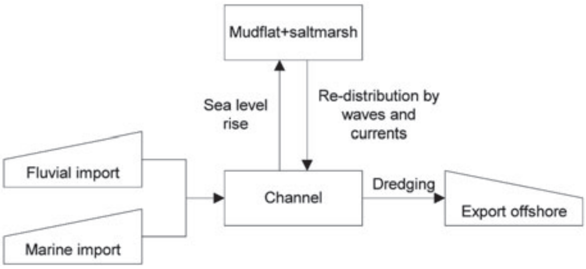


Fig. 5. Simple example of the sediment budget concept.

There are a number of behavioural models that summarize steady-state conditions, or explain transitional behaviour (Townend et al. 2002). These provide an indication of the likely mode of change. The use of such behavioural models allows the mode of change to be examined, and the likely outcome (or range of outcomes) to be determined, even when it is not possible to make quantitative predictions. A more extensive discussion of behaviour systems is to be found in the literature (Capobianco et al. 1999; Townend 2003).

The conceptual model must be coherent and provide a self-consistent summary of the how the estuary functions. At its most basic, the model may be no more than a sediment budget. However this says little about the system behaviour and so a better developed conceptual model will identify both the mechanisms and the behavioural interactions that are likely to give rise to particular forms and states.

Worked examples

Simple model

One of the simplest ways to encapsulate the behaviour of an estuary is through a sediment budget. This describes the main sediment exchanges, both in and out of the estuary and internally(Fig. 5). Further refinement can add detail to the description of the various sediment transfers. It must be recognized that this says very little about the current state of the estuary, or how this state may change in the future.

In many cases it can be difficult to identify, let alone quantify, all the mechanisms that give rise to sediment transfers. It may however be possible to derive approximate estimates of the amounts moving to and from sources and sinks based on measures such as transport potential and sediment demand. In effect one establishes an account and as with any account, the prime requirement is that it balances. For this reason, Pethick suggested the sediment audit as an approximate balance that could be carried out on a number of scales (e.g. local, sediment cell, or regional). The relative importance of changes in supply and demand could then

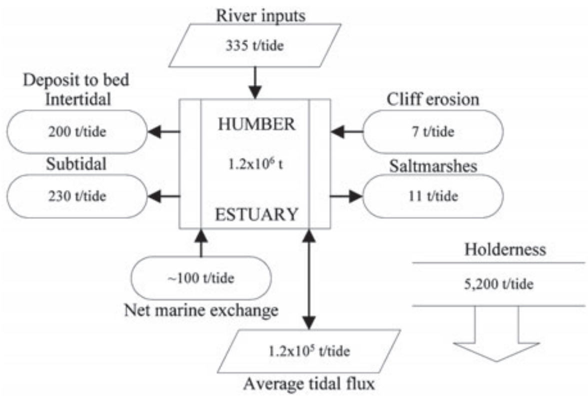


Fig. 6. Schematic for net sediment budget for the Humber.

be assessed at the different scales being considered (Pethick 1992).

An example of a net sediment budget for the Humber estuary, UK, is proposed in (Townend & Whitehead 2003), as illustrated schematically in Fig. 6. This does not describe the gross movements of sediment (e.g. the amount moving back and forth on every tide) but focuses on the net exchanges between key features of the system.

Complex model

As a result of further detailed studies, a more complete description of the behaviour of the system as a whole, and its component parts, can be developed. Such a range of studies has been undertaken for the Humber as part of the preparatory work for the development of an estuary wide flood defence strategy (Townend et al. 2000; Townend & Pethick 2002). These were synthesized using the space-time tabulation, as described above, where each space-time cell is based on a synthesis of a number of relevant studies (Table 3).

The explanation of this table and the assessment of how the estuary may change under different scenarios of sea-level rise or the removal of various lengths of sea defence are explained more fully in the synthesis report (Anon. 2000b). Hence in this case the conceptual model is not a single description but rather a multiple space-time description, where there is an appreciation of the relative importance of individual behavioural components but the precise interactions between components is not fully understood.

Table 3. Summary of space-time changes for the Humber Estuary.

Time scale Feature	Holocene change (8000BP–present)	Decadal change (10-100 years)	Short-term change (tides and storms)
Estuary	Landward transgression due to predominantly monotonically increasing sea-level. Physical constraint of the sill at Hull has had a major influence on the estuary form as sea-levels have risen.	Continued adjustment to both sea-level and the reclamation of large areas of upper intertidal. Estuary has infilled whilst maintaining the overall volume of water as sea-level has risen. Some evidence of landward transgression, with shorter-term response to variations in sea-level (e.g. lunar nodal cycle).	Significant sediment flux and bed level changes dominated by tidal flows, with fresh water flows having increasing influence landwards and waves and density currents influencing movements in outer estuary.
Mouth	Mouth retreats along line of channel from New Sand Hole to present position.	Acts as a tidal embayment. Spurn has been held by defences but is now beginning to realign as defences fail.	Major circulation cell around Bull Sand Fort. Storm action eroding the Holderness cliffs influences sediment supply to Spurn and the estuary.
Meanders	Channel alignment seaward of Hull cut into the tills by ice melt and subsequently fluvial flows. Tidal waters have progressively occupied and infilled the channel, with periods of stable alignment and periods of migration.	Meanders in the outer Humber are constrained by underlying till. In the inner Humber, channel switching from south to north of Read's Island is a result of large river flows, in conjunction with periods of relatively high tidal range. The training works at Trent Falls have reduced the length over which this switching occurs.	Switch of meander from south of Reed's Island into the Redcliff channel happens in response to major flood events. The switch back, to north of Read's Island is more of a progressive migration. If the period between flood events is long enough, the channel switches to south of Reed's Island.
Rivers	Humber lake infilled initially with fluvially derived sediments, followed by the formation of tidal channels once sea-level rose over the sill at Hull. Some evidence for substantial movement of the river alignment.	Heavily constrained by flood defences all the way to the tidal limit on the main rivers. There is a gradual switch, some 20km above Trent Falls, from tidal to fluvial dominance. There appears to be a cyclical link between fresh water flows and sedimentation in the outer estuary.	High flows during winter periods with very little storage space. Trent is artificially charged and so low summer flows not as significant on this river.
Ebb/flood delta	Only evidence is the scour holes in the palaeo-channel out to New Sand Hole, which suggests that any sand bank/delta formations migrated with the mouth.	No evidence of a delta in the vicinity of Spurn. Hydraulic and sedimentary evidence indicates circulation cells around Foul Holme Spit and Middle shoal, suggesting that the delta may operate about a "mouth" at the neck just west of Hawkins Point and Grimsby.	Middle shoal exhibits rapid change and also responds to longer-term trends, which appear to be linked to variations in fresh water flow. Foul Holme Spit exhibits less rapid, more progressive changes.

Conclusions

One of the difficulties in identifying morphological change in estuaries is that there is as yet no well defined theoretical framework. The constituent processes are understood to a greater or lesser degree but the basis for formulating the behaviour, related to dynamic equilibrium states, is far less developed. The process outlined seeks to use the methods and techniques that are currently available, to identify system behaviour in a way that is transparent, with a clear recognition of the current uncertainties.

A key to this process is the synthesis of the study findings and the way in which the results are presented. Both of these areas would merit further research. For the former, the development of a more formal experimental basis may be of benefit (Mayo 1996). For the latter, interactive presentations, with the user able to investigate particular aspects in more detail, supported by a mix of graphics, animation and text, may well provide the way forward.

Further information

The work of the EMPHASYS consortium is summarized in a series of reports available on the HR Wallingford web site (http://www.hrwallingford.co.uk/projects/ERP/doclist.asp). In particular, there is a guide to the prediction of morphological change within estuarine systems (Report No TR 114 2000). A number of relevant papers are also available on the *ABPmer* web site (http://www.abpmer.co.uk/Experience.htm and <http://www.estuary-guide.net'>http://www.estuary-guide.net).

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