STUDY APPROACH

The study approach is an integral part of understanding morphological change in estuaries. This chapter:

- Outlines the techniques used in the study approach to estuaries and reviews the importance of a study approach;
- Introduces issues of spatial and temporal scales within an estuarine system. This includes looking at the importance of understanding process and geomorphology of an estuary within a wide range of timescales and spatial scales; and
- Outlines the programme of work for studying estuaries. There is a description of the scope of work, the approaches to be taken, methods of reporting and the development of conceptual models. This may include the degree of certainty required to address the particular problem; the timescales required to undertake the study; the amount of funding and resources available and the existing information sources.

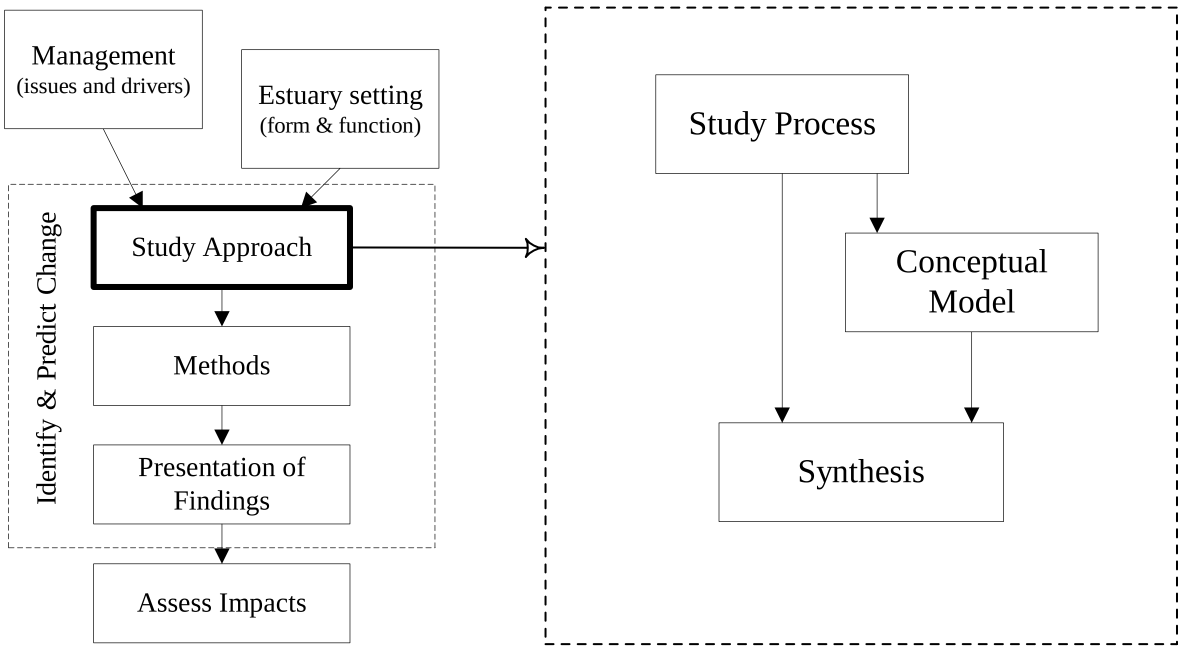

Figure 4.1 Flow diagram of the techniques for the study approach

Issues of Scale

The estuary system behaviour, with complex feedback loops and numerous spatial and temporal scales interacting means that representing this in some form of analysis or model is not straightforward. Whilst this is an active area of research in many organisations around the world, there is currently no single model capable of representing the complex interactions of the estuary environment, particularly given that all estuaries have a unique setting and this leads to great variety. 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 (short-term); (Table 4.1). Time and space scales are linked and great care is needed to ensure consistency. A simple example arises when comparing field data with the output from numerical models. The former often provides data at a point, averaged over some period of time, whereas the latter outputs spatially averaged information at a given instant (see section on study methods). Due allowance must be made for these differences. In addition, it must be recognised that there are errors in both measured and model estimates, as neither are exact. More difficult cases involve the interaction between behaviour on 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 (1) developed, (2) currently functions and (3) 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 4.1 Temporal and spatial scales of estuary systems

Time	Space
Geological (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.
Anthropogenic history	In the UK, effectively since Roman times; begin to take account of human activities such as early settlements, land reclamation and the impact of agriculture.
Near Historical (Centuries)	Refinement down to large-scale features in the estuary, such as channels and islands and further anthropogenic influences such as dredging; written records available.
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. Accurate data available, and anthropogenic impacts of dredging and port development are apparent.
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.

There is of course significant overlap and interactions between the different space and time scales as presented above. 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 (Pye & Allen, 2000), the ability to link decadal change into the Holocene evolution is currently the weakest aspect of our knowledge (Townend, 2002).

For the case of studies supporting estuary management decisions the time-scales of interest relate to "engineering geomorphology", i.e., years and decades, and exceptionally (in the case of very large schemes) a century. Certainly, the study of estuary morphology over the whole spectrum of time scales is helpful in understanding the behaviour of any particular system. However, the dominance of the shorter time scales in deciding management policy means that the emphasis in estuary geomorphological studies, has to be towards engineering geomorphology (HR Wallingford *et al*., 2006).

Here, we mainly apply ourselves mainly to engineering geomorphology. The exceptions to this occur where a knowledge of geological or historical geomorphology will aid the understanding of a system so as to improve the quality of the estuary studies. Henceforth we will use the following terms to describe the temporal scale of estuary response:

- Short – seconds, through spring-neap cycle to a few years;
- Medium – a few years to a few decades; and,
- Long term – a few decades to centuries.

Summary of Study Process

The overall process of identifying and predicting change can be considered to comprise of four main steps:

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

Any changes identified then feed into the impact assessment process (see section on assessing impacts), as shown in Figure 4.2. A breakdown showing the main considerations for each of these steps is outlined and detailed in the following sections.

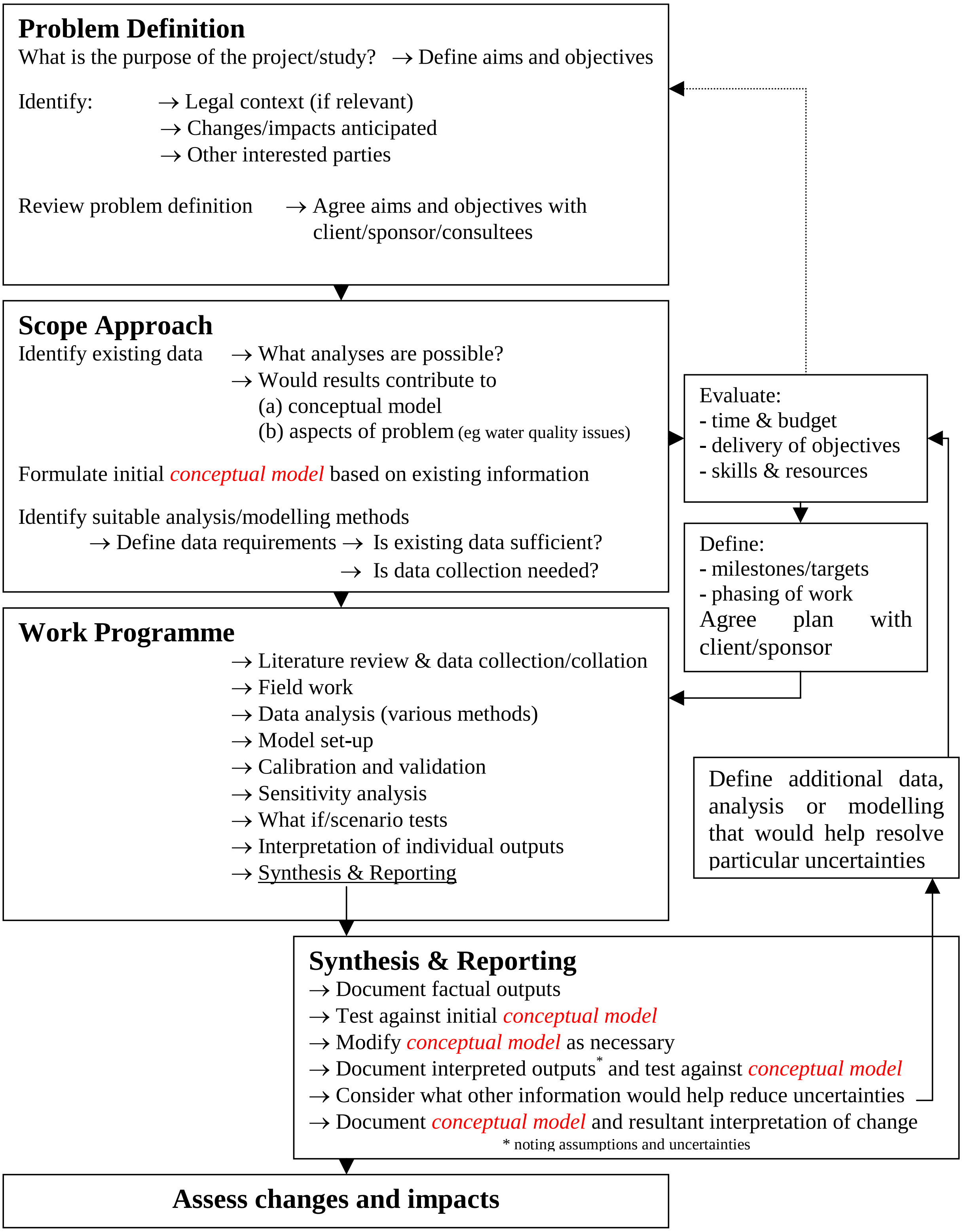

Figure 4.2 **Summary of process to identify/predict change**

Problem definition

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.

There are a number of steps within the project definition that generally apply:

- Identify the client's requirements;
- Identify regulators' concerns or any regulatory issues;
- Define study objectives, as a result of the considerations outlined above;
- Define study area and time-scale: The study area should include all areas that could be affected by the considered management option; and defined spatial scales must be relevant to the morphological evolution observed in the current system and any anticipated evolution resulting from a management option; and
- Define project resources.

Scope approach

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, depending upon:

- Degree of certainty required to address problem;
- 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. Put simply, the conceptual model should provide a picture, or explanation, of how the system works.

The initial assessment of what models might be applied to aid the conceptual model development and predictive studies will be made on all the criteria listed above. The suitability of the various top-down approaches together with hybrid and bottom-up approaches to different causes for change and different temporal and spatial scales is summarised in Table 4.2. In broad terms, local changes and shorter time scales usually correspond to the use of bottom-up models while large-scale changes and longer time scales are more likely to require top-down methods to be considered.

The problem can become more difficult if small changes to mechanisms dominate the long-term evolution of the estuary system, e.g. with wave activity under sea level rise. By their very nature, these can be thought of as process-based, episodic and corresponding to very short time-scales. In such circumstances the application of a range of top-down/hybrid/bottom-up approaches may be required to assess the resulting changes in morphology.

Table 4.2 Generic models and applicability to causes of change

Cause Of Change	Spatial Scale	Temporal Scale	Data Analysis Methods			"Top Down" Methods						Hybrid Methods	
			Accommodation Space	Historical Trend Analysis	Sediment Budget Analysis	Regime Relationships	Analytical Methods	Tidal Asymmetry Analysis	Intertidal Form Analysis	Estuary Translation (Rollover)	Process Based "Bottom Up" Methods	Regime Based	Energy/Entropy Based
Freshwater	Xt	Lg		x		x		x				x	x
	Xt	S/M					x				x		
Tide	Xt	S/M					x				x		
	Xt	Lg		x		x		x				x	x
Sea level	Xt	Md					x				x		
	Xt	Lg	x	x	x	x		x		x		x	x
External waves	Xt	S							x		x		
	Xt	M							x		x		
	Xt	Lg				x						x	x
Local waves	Lc	S							x		x		
	Es	S/M									x		
	Es	Lg										x	x
Sediment inputs	Xt	S			x				x		x		
	Xt	M			x				x		x		
	Xt	Lg	x	x	x	x						x	x
Barrage	Lc	Fx								x	x		
	Es	Fx				x	x	x			x	x	x
Barrier	Lc	Fx									x		
	Es	Int					x	x			x		
Deepening	Lc	S		x	x						x		
	Es	M/Lg		x	x	x		x		x	x	x	x
Fauna	Lc	M									x		
	Es	M									x		
Flora	Lc	M									x		
	Lc	Lg											
Intake/outfall	Lc	Fx									x		
	Es	Fx									x		
Jetty or pier	Lc	Fx									x		
Reclamation	Lc	Fx									x		
	Es	Fx				x		x		x	x	x	x
Sea defences	Lc	Fx									x		
	Es	Fx				x		x		x	x	x	x
Training works	Lc	Fx									x		
	Es	Fx				x					x	x	x
Managed realignment	Lc	Fx							x		x		
	Es	Fx	x	x	x	x		x		x	x	x	x
Intertidal recharge	Lc	S							x		x		
	Es	S		x	x	x		x			x	x	x

KEY:	Spatial Scale of Action		Time Scale of Action	
	Local	Lc	Short-term (days to month)	S
	Estuary	Es	Medium term (seasons to a decade)	M
	External	Xt	Long-term (decades to a century)	Lg
			Intermittent	Int
			Fixed (in human terms)	Fx

The suitability of models to different mechanisms can also be expressed as follows (Table 4.3):

Table 4.3. Models of mechanisms types

Mobilising Mechanisms	Advection Mechanisms	Sedimentation Mechanisms
Mechanisms specifically requiring process models for investigation: • Wave breaking; • Wave-driven flow; • Fluidisation of the bed; • Fluid mud formation from settlement; • Pick up by wind; • Re-suspension by dredging; • Re-suspension by vessel movements; • Side slope subsidence; • Biological effects leading to disturbance or re-suspension of sediment.	*Mechanisms specifically requiring process models for investigation:* • Secondary currents; • Wave-driven flow; • Littoral drift; • Wind driven flow; • Meteorologically induced flow; • Vessel induced currents; • Movement of fluid mud and other near bed high concentration suspensions.	*Mechanisms specifically requiring process models for investigation:* • Reduction of: - wave breaking; - wave-driven flow. • Interception of: - fluid mud; - wind load; - side slope subsidence. • Ecological stabilisation of sediments.
Mechanisms which can be investigated using a range of techniques: • Wave stirring; • Erosion by currents; • Sea level rise.	*Mechanisms which can be investigated using a range of techniques:* • Tidal currents; • Fluvial flow; • Sea level rise; • Mixing/dispersion of material in suspension; • Density currents.	*Mechanisms which can be investigated using a range of techniques:* • Reduction of: - wave stirring; - tidal flows. • Interception of littoral drift; • Deposition from suspension; • Sea level rise.

The availability of data is also important: in broad terms the less data available, the more relevant top-down methods become, as bottom-up models generally require more data. However, a lack of data may give rise to a decision to collect more data, rather than to restrict the study to top-down approaches.

Work programme

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 with the client/sponsor and those contributing to the programme. Where the studies are part of a consents process for a development, it may also be necessary, or appropriate, to agree the methodology with the relevant regulatory bodies. In many cases, the work can best be progressed in a series of phases. For instance, some analysis of the existing data and literature 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 being progressed, 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 summarised and key findings clearly identified. In this process it is essential to distinguish between factual information and interpretation that relies on particular assumptions.

Synthesis and reporting

The various techniques used each look at different aspects or components of the system. Some of the techniques are well proven and tested, whereas others have a far greater degree of uncertainty associated with them. By looking at the results collectively and noting points of agreement (and disagreement) it is possible to distil an understanding and to assign degrees of confidence to that understanding. This is essentially a process of synthesis, working from the parts to the whole[1](Odum & Odum, 2000).

Hence, bringing the findings of the various studies together involves this 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 the process of synthesis, 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.

Conceptual Model

> *A conceptual model is a formal explanation of how the system (or sub-system) functions, including the key controlling mechanisms and their relative importance, of the reasons for the historical development (if relevant over the defined model area and time-scale) of the system (or sub-system) and of the reasons for present trends within the system (or sub-system).*

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, but with progressively more information and analysis it may be possible to quantify the pathways and define how the system will respond to change.

Depending on the system, a conceptual model can be expressed through bottom-up or top-down approaches. However, whatever basis the understanding is derived from, it should be

[1] 'Parts' refers to component parts of the system and results that provide partial, or limited amounts of information.

demonstrated how physical processes support this conclusion, i.e. the effect of currents, waves, etc, in forming sediment pathways, sources and sinks in the system. Particularly important is whether the sediment supply to the system is sufficiently large/small to support conclusions regarding long term trends.

A fully developed conceptual model should try 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:

(i) 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
(ii) 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. The definition presented above is deliberately limited to an understanding of the system (or sub-system) relevant to the spatial and time scales of the defined problem. Within the context of most studies there is a specific set of management decisions that must be addressed and the development of the conceptual model should be targeted towards these. For example, if the study area is a specific mudflat then the conceptual model may not have to consider the estuary-wide components and long-term evolution of the system. On the other hand if the management options included construction of a barrage across a large estuary the conceptual model will have to include the long-term evolution of the system, its estuary-wide functioning and perhaps the functioning of the offshore area outside the estuary.

The development of the conceptual model to a particular estuary system (or sub-system) is an iterative process; as studies continually develop more information and understanding, the conceptual model is improved. Formally, however, the stages of the development are as outlined in Figure 4.3.

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 predicting the response to change in a robust way. 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.

There are a number of behavioural models that summarise steady-state conditions, or explain transitional behaviour (Townend and Pethick, 2002). 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 Coast & estuary behaviour systems (Capobianco *et al.*, 1999; Townend, 2003, EstSim Consortium, 2007).

When a robust conceptual model has been developed there is a necessary step of formalising the conceptual model into a description which can be conveyed to another party. This is not a trivial exercise since the system may be complex and have a hierarchy of spatial and temporal scales (Townend, 2002). Forms which have been suggested and or implemented are:

- A flow-diagram approach (e.g. Capobianco *et al*., 1999; Townend, 2004);
- A matrix approach (e.g. Townend, 2002); and,
- A sediment budget approach (e.g. HR Wallingford, 2001).

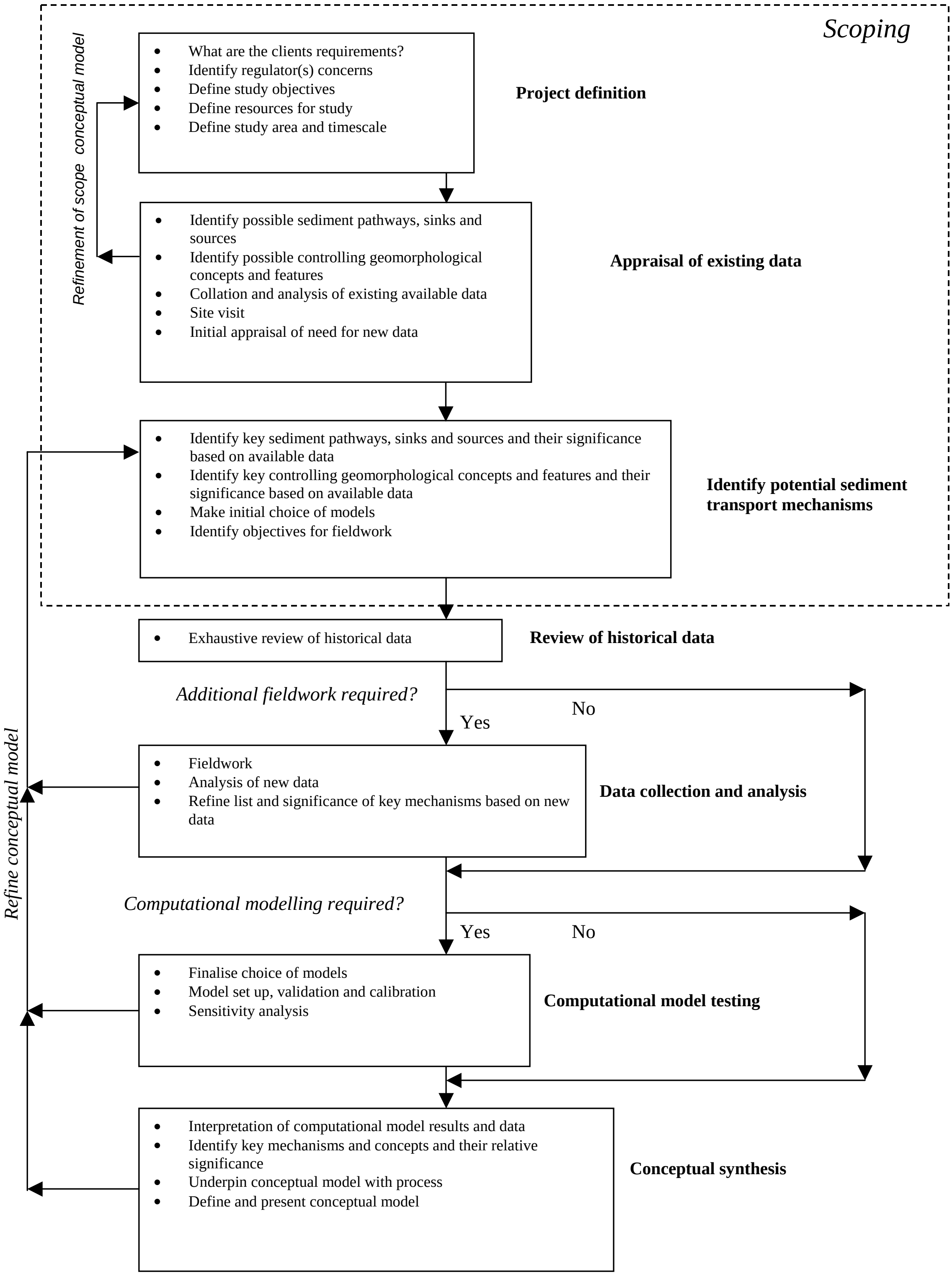

Figure 4.3 Summary of stages of development of conceptual model

Synthesis ⇒ Understanding

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 utilise 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 summarised in the Synthesis box in Figure 4.2. 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, as can the interpretation of field data. This may be due to the degree of spatial and/or temporal coverage, or because one or more data sets have been used to construct another variable (e.g. using a known physical relationship). 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 assumptions may be the cause of any discrepancy, rather than some aspect of the conceptual model.

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 identify the range of change (upper and lower bounds) associated with particular variables and so focus attention on the more significant areas of uncertainty.

The process of synthesising the available information to formulate the conceptual model can be time consuming, often taking as much as effort as the data analysis and modelling (EMPHASYS Consortium, 2000). However, if does provide a route to a far greater understanding of how the system behaves and is likely to respond to future change and so warrants being given a higher priority in studies of this kind.

References

Capobianco M, de Vriend H, Nicholls R, Stive MJF, 1999, Coastal area impact and vulnerability assessment: the point of view of a morphodynamic modeller, Journal of Coastal Research, 15(3), 701-716.

EMPHASYS Consortium, 2000, A Guide to prediction of morphological change within estuarine systems, Estuary Research Programme, Phase 1, HR Wallingford, Wallingford, Report No: TR 114, 51pp.

EstSim Consortium, 2007, Development and Demonstration of Systems-Based Estuary Simulators. R&D Technical Report FD2117/TR, Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme, 247pp.

HR Wallingford, 2001, Bathside Bay Development Studies, Impact of proposed scheme on sediment transport and estuary morphology, HR Wallingford Report EX4426, In: *Bathside Bay Tidal Works, Environmental Statement, Supporting Document 1, Harwich Harbour Strategic Studies*, Report prepared by Posford Haskoning Ltd. for Harwich Haven Authority and Hutchison Ports (UK) Ltd., October 2001.

HR Wallingford, ABPmer, and Pethick, J., 2006, *Review and formalisation of geomorphological concepts and approaches for estuaries.* Defra/Environment Agency flood and coastal defence R & D programme. R & D technical report FD2116/TR2.

Odum HT, Odum EC, 2000, Modelling for all scales: An introduction to system simulation, Academic Press, London.

Pye, K. and Allen, J.R.L., 2000, Coastal and Estuarine Environments: sedimentology, geomorphology and geoarchaeology, Geological Society, London.

Townend IH, 2002, Marine science for strategic planning and management: The requirement for estuaries, Marine Policy, 26(3), 209-219.

Townend IH, 2003, Coast and estuary behaviour systems, In: Coastal Sediments '03: Crossing Disciplinary Boundaries - Proceedings of the Fifth International Symposium on Coastal Engineering and Science of Coastal Sediment Processes, East Meets West Productions (EMW) Inc., Corpus Christi, USA, pp. 1-14.

Townend, I.H., 2004, Identifying change in estuaries. Journal of Coastal Conservation, 10, 5 – 12.

Townend IH and Pethick J, 2002, Estuarine flooding and managed retreat, Phil.Trans.R.Soc.Lond.A, 360, 1477-1495.