Estuaries Research Programme, Phase 1
MAFF Contract CSA 4938

EMPHASYS Consortium

A Guide to Prediction of Morphological Change within Estuarine Systems

Version 1B

Research by the EMPHASYS Consortium for MAFF Project FD1401

December 2000

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Report TR 114
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For further information on the Estuaries Research Programme Phase 1 visit the web site:

http://www.hrwallingford.co.uk/projects/ERP/

Contract

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Prepared by ....

(name)

....

(Title)

Approved by ....

(name)

....

(Title)

Date ....

Members of the EMPHASYS Consortium

HR Wallingford Ltd
Howbery Park
Wallingford
Oxon OX10 8BA

Posford Duvivier
Rightwell House
Bretton Centre
Peterborough
PE3 8DW

Royal Holloway University of London
Department of Geology
Queens Building
Egham
Surrey TW20 0EX

WL | Delft Hydraulics
Marine & Coastal Management Division
P.O. Box 177
2600 MH Delft
The Netherlands

British Geological Survey
Kingsley Dunham Centre
Keyworth
Nottingham NG12 5GG

Centre for Ecology and Hydrology
Dorset
Winfrith Technology Centre
Newburgh Road
Dorchester
Dorset DT2 8ZD

Professor K.R. Dyer
Norton Hayes
Bradford-on-Tone
Taunton
Somerset TA4 1HP

ABP Research & Consultancy Ltd
Pathfinder House
Maritime Way
Southampton SO14 3AE

University of Newcastle
Department of Marine Sciences &
Coastal Management
Ridley Building
Newcastle Upon Tyne NE1 7RU

Proudman Oceanographic Laboratory
Bidston Observatory
Birkenhead
Merseyside
L43 7RA

Plymouth Marine Laboratory
Prospect Place
West Hoe
Plymouth PL1 3DH

School of Ocean and Earth Sciences
University of Southampton
European Way
Southampton SO14 3ZH

CEFAS
Lowestoft Laboratory
Pakefield Road
Lowestoft
Suffolk NR33 0HT

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HOW YOU CAN BENEFIT FROM THIS REPORT

The morphology of an estuary (its shape and underwater contours) affects, and is in turn affected by, issues relating to *flood defence, water quality, conservation* and *navigation.* This report, and companion reports[1], provide answers and guidance to some of the key questions that face those concerned with such issues: estuary managers, stakeholders and interest groups. The reports result from Phase 1 of the UK Estuaries Research Programme undertaken by the EMPHASYS[2] consortium, which comprises 13 partners including practitioners and researchers with widely varying and complementary areas of expertise. Links are made between the understanding and prediction of changes in estuarine morphology and the resulting changes in the ecology and water quality that are subject to legislative constraints, policy and directives.

The key concerns for estuary managers, stake-holders and interest groups are usually triggered by a plan to make some change to the estuary they have an interest in – a proposed project such as a construction, intervention or development that would alter the status quo. If they are the organisation planning to make the change they will have questions like:

- *Will the project achieve what is intended?*
- *What is the most effective and economical design for the project?*
- *Will the project fall within current legislation, policies and directives?*
- *Will it be acceptable to other stakeholders, or will it be blocked by public pressure?*

If they are not the ones making the change, they will have questions like:

- *How will this affect public safety (e.g. flooding of populated areas)?*
- *How will it affect other commercial concerns (e.g. shell-fisheries, tourism)?*
- *How will it affect the environment, ecology and habitats?*
- *Will a localised project have undesirable impacts further afield?*

Cont'd

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[1] Reports (listed in the Bibliography below) on: Modelling Report, Legislative Context, Directory of Predictive Methods, Research Recommendations, and Database
[2] Estuarine Morphology and Processes Holistic Assessment SYStem

Even in the absence of such an intervention, questions can be raised such as:

- *How "healthy" is this estuary?*

To help provide answers to all these questions, predictions need to be made about how the estuary might alter if the project goes ahead, compared with how it would alter in the absence of the project (since natural changes will occur anyway). This requires predicting changes in the short term (up to one year) or the long term (some years to decades) in the morphology of the estuary, at both the local and the whole-estuary spatial scales, together with the changes to the ecology and the water quality. The report highlights issues that the promoter or regulator should look for in work undertaken by specialists on their behalf such that the confidence in the outcome of the studies is maximised.

Many varied techniques have been developed to make these predictions, ranging from expert opinion based on analysis of the behaviour over time of a large number of estuaries, to highly complex computer-based models. As with weather forecasting, no one method is indisputably superior to the others – all have their strengths and weaknesses, and their suitability to the kind of problem, the kind of estuary, and the time and space scale.

This report offers a structured approach to tackling these types of estuarine problems and draws on the experiences of the EMPHASYS Consortium in undertaking Phase 1 of the research.

Having decided that a prediction technique is needed to tackle the stakeholders' concerns, the next level of questions includes ones such as:

- *What questions can be answered now?*
- *What information is needed to answer the questions?*
- *What tools and techniques are available and what are their limitations?*
- *How can the results be interpreted?*

Answers to these questions can be found in this report. Along with a summary of the steps to be taken when applying the available methods to a particular plan or activity.

The guide stresses the importance of fully appreciating available historic information concerning the site/estuary, the requirements for further data collection, the importance of calibration and validation of any method applied, and synthesis of the available data and model results to develop an understanding of how the estuary functions. Building from this understanding it becomes possible to explore 'what-if?' scenarios for development and change.

The use of the guide is illustrated by a worked example.

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Executive Summary continued

PROJECT BIBLIOGRAPHY OF OTHER KEY REPORTS

EMPHASYS Consortium (2000). Modelling Estuary Morphology and Process Final Report. Research by the EMPHASYS Consortium for MAFF Project FD 1401. Report TR 111. HR Wallingford, UK. December 2000.

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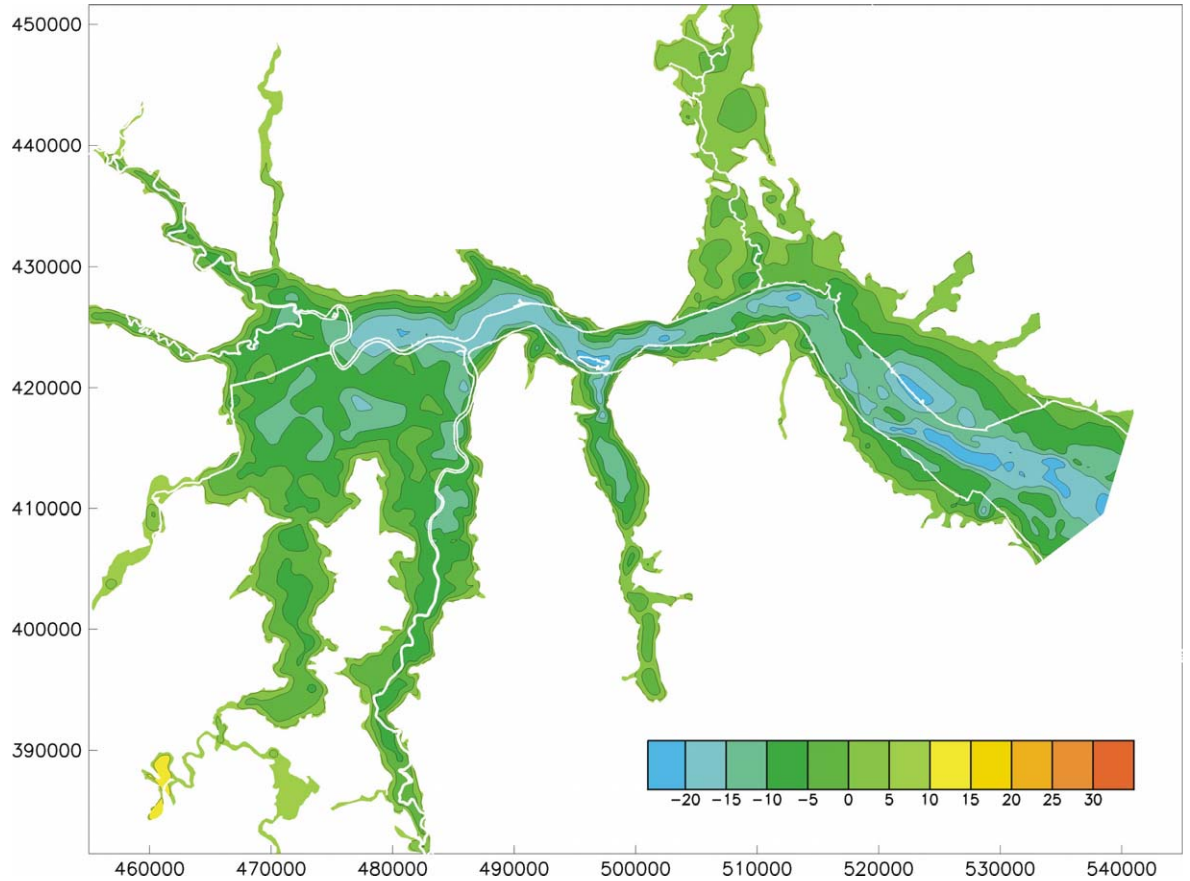
ABP Research and Consultancy Ltd. The Estuaries Research Programme, Phase 1- Databases. Research by the EMPHASYS Consortium for MAFF Project FD 1401. Report No. R.848 and CD-ROM. November 1999.

1. RELEVANCE TO ESTUARY MANAGEMENT?

Chapter 1 provides an introduction as to why we need to predict morphological change and the purpose of Phase 1 of the Estuaries Research Programme undertaken by the EMPHASYS Consortium. The chapter clarifies the link between morphological change and estuary management.

The chapter describes the structure of the Guide and the style of presentation that has been adopted, and lists the Appendices that accompany this report and the other key outputs from the first phase of the Estuaries Research Programme.



Digital Terrain Model of the base of the Holocene estuarine sediments in the Humber Estuary (Source: Paper 11, Reference 4)

1.1 Estuary functioning and morphology

Estuaries are a focal point for a wide range of human activities of increasing social and economic importance. The semi-enclosed basin that forms the estuary provides an area that is relatively sheltered, with a complex interplay of physical, chemical and biological processes, all of which are influenced by the marine environment and the surrounding catchment. With growing pressures comes the increasing risk that important habitats, such as mudflats and saltmarsh, will be lost or severely diminished.

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. As trading between different locations developed, ports grew up, initially as far inland as possible, since boats and ships offered the simplest form of transport. With time ships have become larger so that the ports have moved progressively nearer the coastline where deeper water has caused benefits in economy of scale.

The industrial revolution increased the use of rivers and estuaries not only in transport of raw and finished goods but also in new uses, such as water extraction and discharges of waste. As populations grew there became a greater need for drinking water and the disposal of human waste, which was often taken from and/or discharged into rivers. Land for agriculture to feed the population and space for dwellings and industry was also required which led 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.

Today there are probably relatively few estuaries (particularly in the developed world) which have not been affected in some way by man's intervention. Furthermore, this interaction has now been ongoing for many hundreds of years, although most significant effects have taken place in the last 100 to 200 years.

Anthropogenic effects are therefore a major agent influencing the morphology of an estuary either directly by means of engineering works and/or indirectly by modifying the physical, biological and chemical processes at work within the estuary. Since any change rarely has an instant effect, changes to the governing processes caused by an intervention in the past may not have completely worked through the system before further modifications are made thus increasing the complexity of the interactions. The timing of any anthropogenic effects relative to previous modifications along with the magnitude of the effect are important when trying to predict future estuary evolution.

With growing pressures, comes the increasing risk that the long recognised areas of nature conservation importance will be compromised and hence a much more proactive 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 the potential to both contribute to, and conflict with, 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.

A basic requisite of making management decisions within the estuary environment is a sound understanding of estuary functioning. The timescales of concern to the estuary manager range from short (up to one year) to long (one to 100 years) periods. The space scales of interest range from local to estuary-wide or regional.

Estuary functioning can be regarded as both the interactions within process areas and the interactions between those areas. Present day 'functioning' is a result of natural forcing and variability and the history of human influence on a site. Estuary functioning was divided into six process areas in the Scoping Study that preceded the Estuaries Research Programme (Reference 1). Those areas were as follows:

- Hydrodynamics
- Sediment dynamics,
- Morphology[3]
- Water quality,
- Ecology, and
- Human activities.

Different degrees of understanding of the six process areas will be required for different management decisions, possibly with greater emphasis on water quality, morphological or ecological issues in different situations. However, because of the integrated manner in which most estuarine management decisions have to be made, particularly because nearly all UK estuarine systems are designated in some manner under the European Habitats Directive (Reference 2), it is usually necessary to consider a combination of these process areas in making decisions.

In most circumstances understanding the morphological functioning of an estuary system will be a requirement for present day and future management decisions. This understanding may not be the most critical aspect of the decision making. In many cases decision making may be focused on a specific detail of one of the other process areas, a water quality parameter for example. However, morphology arguably directly or indirectly influences all the other process areas and, therefore, provides a tangible focus from which to develop an understanding of estuarine functioning for the purposes of estuarine management and decision making.

It will not be necessary in all cases for morphological understanding to be based upon an extensive knowledge of hydrodynamic and sediment transport processes. For preliminary planning it may often be enough to identify the underlying morphological trends at a site and use those as the basis for considering the influence of conservation and socio-economic activities. In other situations, such as those associated with a major estuarine development, it may be necessary to develop an understanding of the detail of the hydrodynamic and sediment transport processes at a site in order that a credible prediction of the short term (up to one year) impact of the development can be made and used to inform operational decisions, such as future maintenance dredging requirements. Without adequate knowledge of this short term impact, consideration of the significance of the development and its operation in the longer term (decades) is not possible. For other situations, such as development of an estuarine flood defence strategy, the main issue is understanding the long-term morphological evolution of the system so that the impacts of flood defence decisions can be identified.

1.2 The Estuaries Research Programme

The Estuaries Research Programme funded by MAFF, the Environment Agency and English Nature was established in response to the need for methods to predict changes to estuary functioning. The first phase of the Programme was aimed at producing guidance on the techniques that can be applied to achieve this understanding. The approach presented here is based on consensus amongst the different representatives of the EMPHASYS Consortium[4] who undertook the first phase of the Estuaries Research Programme.

The linkages between the physical process areas and water quality, ecology and human activities must be established for effective long term management of estuarine systems, but an in-depth exploration of these issues is outside the scope of the present phase of the research. An initial review of processes and

[3] In science morphology consists of the study of form and shape. In the context of estuary research “morphology” is commonly used as a noun relating to the form or bathymetry of an estuary, although the word can also relate to the study of such changes in form over time, hence “geomorphology”.

[4] The EMPHASYS Consortium comprises: HR Wallingford; ABP Research and Consultancy; Department of Marine Sciences and Coastal Management, University of Newcastle; Department of Geology, Royal Holloway College; Proudman Oceanographic Laboratory; Posford Duvivier; Professor Keith Dyer; British Geological Survey; CEFAS Lowestoft Laboratory; WL|Delft Hydraulics; Plymouth Marine Laboratory; Centre for Ecology and Hydrology, Dorset; School of Ocean and Earth Science, University of Southampton.

predictive linkages related to water quality and ecology is provided in the Appendices to this report. However, the focus of this report is guidance on the prediction of morphological change in estuarine systems.

1.3 Objective

The objective of this document is to provide a statement based upon the consensus of the EMPHASYS Consortium as to the choice of approach, the data required, and the methods available for predicting morphological change within an estuarine system.

1.4 Structure of the Report

This report comprises a further six chapters. Each of Chapters 1 to 5 seeks to answer a question, being the title of the chapter. The final two chapters provide a summary of the guidance and an example of application.

Chapter 2 – What questions can be answered now?
Chapter 3 – What information is needed to answer the question?
Chapter 4 – What tools and techniques are available and what are their limitations?
Chapter 5 – How can the results be interpreted?
Chapter 6 – Summary of Guidance
Chapter 7 – Worked Example

The report has been written for an audience who could comprise project promoters or regulators, rather than specialists in estuary morphology. The report highlights issues that the promoter or regulator should look for in work undertaken by specialists on their behalf. The most detailed chapter is Chapter 4 where the various different techniques that are available are listed. In all the other chapters issues are dealt with in a generic manner, with examples given of particular issues and techniques. A hypothetical worked example is given in Chapter 7, although it is impossible to illustrate all the enormously wide range of possible applications in a single example.

Throughout the report the narrative is complemented by information provided in tables (Tables 1 to 6), summary boxes (Boxes 1 to 9) and in examples which are in boxes highlighted in grey.

The report is accompanied by four Appendices:

Appendix 1	A brief summary of techniques available for prediction of water quality within estuarine systems
Appendix 2	A brief summary of techniques available for prediction of ecology within estuarine systems
Appendix 3	A brief summary of techniques available for prediction of morphology within estuarine systems
Appendix 4	List of outputs of project

These Appendices contain additional summary information.

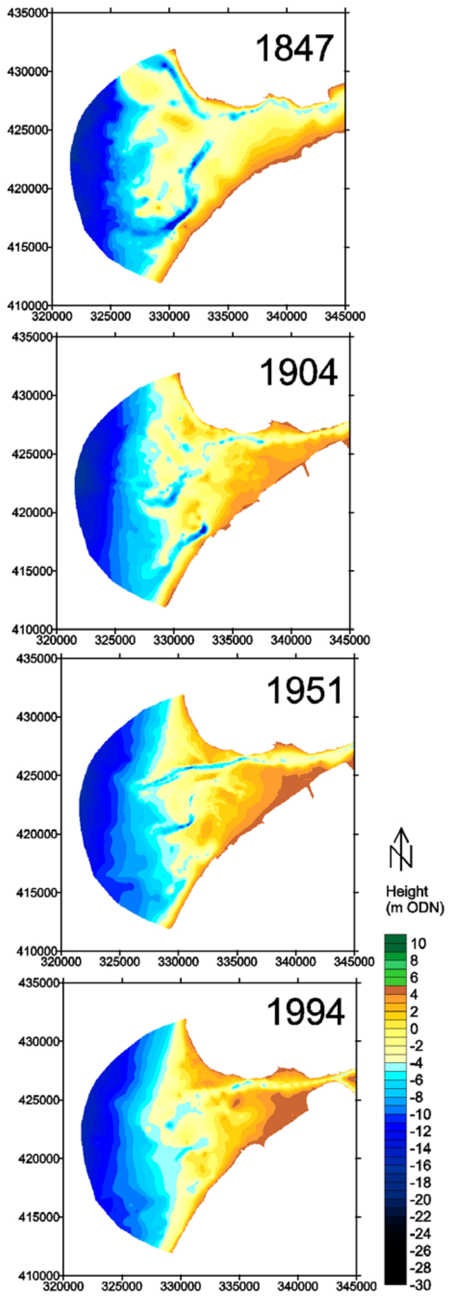
Four further key documents have been produced by the Consortium as part of Phase 1 of the Estuaries Research Programme:

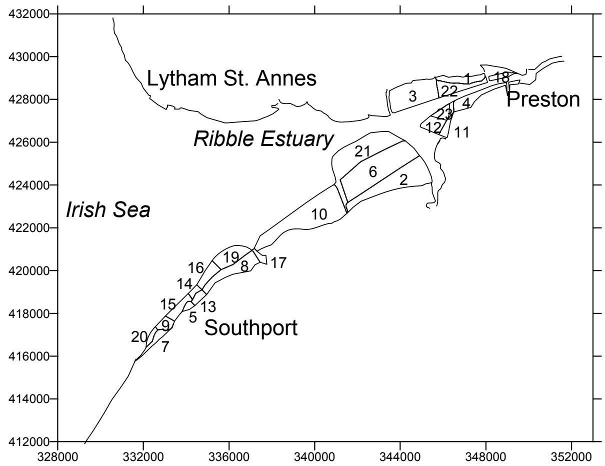
Reference 2 - Estuaries Research Programme – Legislative Context
Reference 3 - Estuaries Research Programme – Predictive Methods Report
Reference 4 - Estuaries Research Programme – Morphological Modelling Tests Report
Reference 5 - Estuaries Research Programme – Research Recommendations Report

2. WHAT QUESTIONS CAN BE ANSWERED NOW?

Chapter 2 provides a general introduction to the key development issues and pressures that arise in estuaries (often as a result of human activity). This provides the context within which morphological change needs to be considered.

Chapter 2 therefore addresses the questions concerning morphology that can be answered based on our present knowledge. A key aspect of this chapter is the idea of different spatial and time-scales of morphological change. Gaining an understanding of change over these scales will allow questions concerning morphology to be answered. It also addresses the accuracy with which these questions can be answered.





Nr	Site	Year	Area (km^2)
1	Clifton Marsh	1854	0.666
2	Hesketh Marsh	1859	2.961
3	Freckleton	1864	2.470
4	Penwortham, Howick and Hutton	ca 1878	0.995
5	Southport	1881	0.143
6	Hesketh New Marsh	1883	4.319
7	Southport	1884	0.366
8	Southport	1891	1.404
9	Southport	1895	0.366
10	Bonny Barn and Banks Marsh	1895	4.390
11	Hutton Marsh	1899	0.277
12	Hutton Marsh	1899	1.094
13	Southport	1900	0.251
14	Southport	1929	0.179
15	Southport	1967	0.522
16	Marshside Marsh	1968	0.565
17	Southport	1969	0.206
18	Lea Marsh	ca 1970 ?	0.239
19	Marshside and Crossens Marsh	1974	1.103
20	Southport	1975	0.185
21	Hesketh Out Marsh	1980	3.539
22	Clifton Marsh	1982	0.894
23	Hutton Marsh (breached)	1927	-0.344

Bathymetric surveys of the Ribble Estuary and accompanying information on reclamation during the period
(Source Papers 14 and 15, Reference 4)

2.1 Estuary development issues that need consideration

The key development issues and pressures that arise in estuaries are hugely varied, as evidenced by the responses to the consultation during the Scoping Study (Reference 1). Fundamentally, users interests may be at a strategic, whole estuary or regional level, such as the development of a new flood defence strategy or a habitat management plan, or they may be at a local level, such as the design and positioning of an outfall or a slipway. As a result different questions are raised and different approaches to decision making are required.

Strategic issues are likely to require an in-depth analysis of the existing dynamic relationship between the different process areas of an estuary system. They are also therefore likely to require a more comprehensive baseline study. However, it should be noted that a requirement of the EIA Regulations and the Habitats Directive is that the cumulative and in-combination effects of a development in conjunction with other plans or projects are addressed. This means that local/single issues will also often require broad baseline investigations and morphological prediction.

Summaries of legislation and Directives that are relevant to estuarine issues are listed in the Legislation Report (Reference 2). This includes summaries of relevant legislation under the headings of: Development Planning Control; Ports and Harbours (including dredging); Marine Extraction; Water Quality and Pollution Control; Flood and Coastal Defence; Nature Conservation and Fisheries.

One interest may influence others, for example, a strategic framework will influence the approach adopted for addressing more local needs.

Box 1 - Strategic plans relevant to estuaries include the following:

- Estuarine shoreline management planning
- Strategies for sustainable flood defence
- Integrated estuary management planning
- Habitat Management Plans
- Biodiversity Action Plans
- Consideration of the effects of climate change and sea level rise

Box 2 - Site specific activities relevant to estuary morphology, ecology and water quality include the following:

- Flood defence works; Managed realignment
- Habitat creation; Foreshore recharge
- Direct placement/trickle charge of dredged material
- Maintenance, Capital and Aggregate dredging
- Disposal and use of dredged material
- Construction
- Expansion of existing port facilities; New port development
- Reclamation (land claim)
- Vessel traffic and other Navigation issues
- Marina development; Harbour expansion; Slipway development
- Pipelines; Outfalls; Intakes; Freshwater abstraction
- Bridge development, Immersed tube tunnel crossing
- Barrier/barrage development; Change in the position of the tidal limit
- Generation of tidal power; Generation of wind power
- Development on floodplains; Industrial users that require a water edge location
- Removal of structures
- Mariculture; Trawling
- Recreational use

Many of these plans and activities are linked: for example ‘New port development’ will involve ‘Construction’, ‘Disposal and/or use of dredged material’, ‘Capital dredging’, ‘Maintenance dredging’ and ‘Reclamation’. It will also be necessary to consider the relevance of the work within an overall management framework for the estuary if a strategy is in place.

Plans and activities will be associated with a specific estuary. That estuary may be small or large, the processes within it may be complex or relatively simple, the estuary may have coherence as a whole or may be comprised of identifiable regions based upon its functioning. Within the estuary there may be multiple users and multiple strategies in place. The estuary may be particularly sensitive to certain types of development or may be largely unaffected. All of these factors should have an influence on the overall approach that is adopted to develop an understanding of the significance of the development or strategic issue on morphology in order that decisions can then be made in a scientifically credible manner.

2.2 Morphological questions that may arise

For the plans and activities identified in Boxes 1 and 2 a series of questions relating to morphology can be raised. The form of such questions may be general or issue specific, such as the following:

“What will be the impact of sea level rise and climate change on the habitat resource of an estuary?”
“Will construction of a new bridge affect adjacent flood defences?”
“Will deepening of a riverside berth affect the adjacent inter-tidal mudflats?”
“Will increased freshwater abstraction lead to enhanced siltation in the upper estuary?”

These types of questions cannot necessarily be answered by the available methods. However, generally the questions concerning morphological change can be simplified to those shown in Box 3:

Box 3 – Morphological questions

- What are the impacts of sea level rise or climate change on morphology?
- What are the influences of tidal processes on morphology?
- What are the influences of wave action on morphology?
- What are the influences of fluvial processes on morphology?
- What are the influences of sediment supply and dynamics on morphology?
- What are the influences of the underlying geology on morphology?
- What are the influences of the associated ecology on morphology?
- What are the impacts of changes in water quality on morphology?
- How did the present morphology arise?
- What are the direct impacts of the plan, or activity, itself on the morphology?

All of the questions in Box 3 can be asked at different spatial and temporal scales. The spatial scale varies from local to estuary wide (or regional) and the temporal scale from short term (up to one year) to long term (decades to century).

In some cases the required output from an investigation is an answer to just one of the questions identified above, but more often a general understanding of morphological change within the estuary system is required. Such an understanding can be developed by attempting to answer the questions above over the full range of scales. This can then be used as a baseline against which the impact of a new pressure can be considered.

For consideration of a specific development (from here on referred to as a project) within an estuary the impact can be determined by considering Questions 1 to 8 above. Initially doing this without the project in place helps to develop the baseline understanding (Question 9) and leads to the development of a conceptual model (see Chapter 5) of the functioning of the estuary system. Within this conceptual model the importance of the history of evolution is critical. Then the direct impact of the project can be considered with the project in place (Question 10) and the indirect impacts of the project identified by reconsidering Questions 1 to 8.

For a strategic study the same or a more rigorous understanding of the baseline is required. A wider range of scenarios or sensitivity tests of assumptions about long term change might be considered as part of the strategy. The strategy thus evolves from the answers to the questions for the different scenarios investigated.

Consideration of the effect of short term localised changes on the longer term functioning of an estuary system as a whole is required under the Habitats Directive (Reference 2) and should also be considered to be best practice.

Following a port development, the impact of a localised increased requirement for annual maintenance dredging may lead to a reduction in estuary-wide inter-tidal levels - through trapping of sediment in deepened areas - which would only become apparent over the longer term. In this case, if the short-term localised morphological changes were considered in isolation, the significance of the change for the operational practice of the port (increased maintenance dredging) would have been identified but the longer term, larger scale, morphological changes to the inter-tidal areas would have been overlooked.

2.3 What questions can be answered now?

All of the questions identified in Box 3 can be addressed to varying extents by one or other, or combinations, of the techniques that are presently available. However, the level of certainty in the answer to the question will vary from one situation to another. The absolute accuracy[5] in many situations is likely to be low whilst the relative accuracy[6] may be high. Certainty is likely to be greater where historical data is available and the project proposed is similar to those already implemented in the system.

The available methods for prediction of morphological change are described in Chapter 4 (note that these are methods: not just models, they also include the interpretation of data and model results). The extent to which the questions can be addressed and the accuracy or level of certainty in the answers derived from the available methods will depend on the complexity of the estuary system, the project under consideration and the amount of data available for verification of the method. Note that no single method is available which can adequately answer all of the questions over all spatial and temporal scales. In some cases the selection of the method to address a particular issue will depend upon the overall suite of methods being used for a particular investigation since some methods require input from other methods in their application.

In many cases application of more than one method to address the same question will be helpful. This approach is most likely to be beneficial for complex strategic studies. Use of more than one method will not necessarily lead to greater certainty in the answers but is likely to lead to a better understanding of the estuary system and its functioning. The different method should always build on the same observational evidence, utilising it in different ways.

The diversity of functioning of UK estuaries, combined with potentially unique project proposals, makes provision of generic guidance as to which questions can be answered with more certainty than others difficult. The certainty in the answer comes from developing a credible understanding of the morphological processes within the estuary. This understanding should be based on observational evidence. It is therefore reasonable to assume that for estuary systems where large resources of historical data relating to morphological change exist a greater certainty in the answers to any questions relating to

[5] The absolute accuracy is the ability to make a quantitative prediction: for example to predict that following construction of a new port 4.2ha of inter-tidal area will be lost, or that the maintenance dredging requirement will increase by 25%.

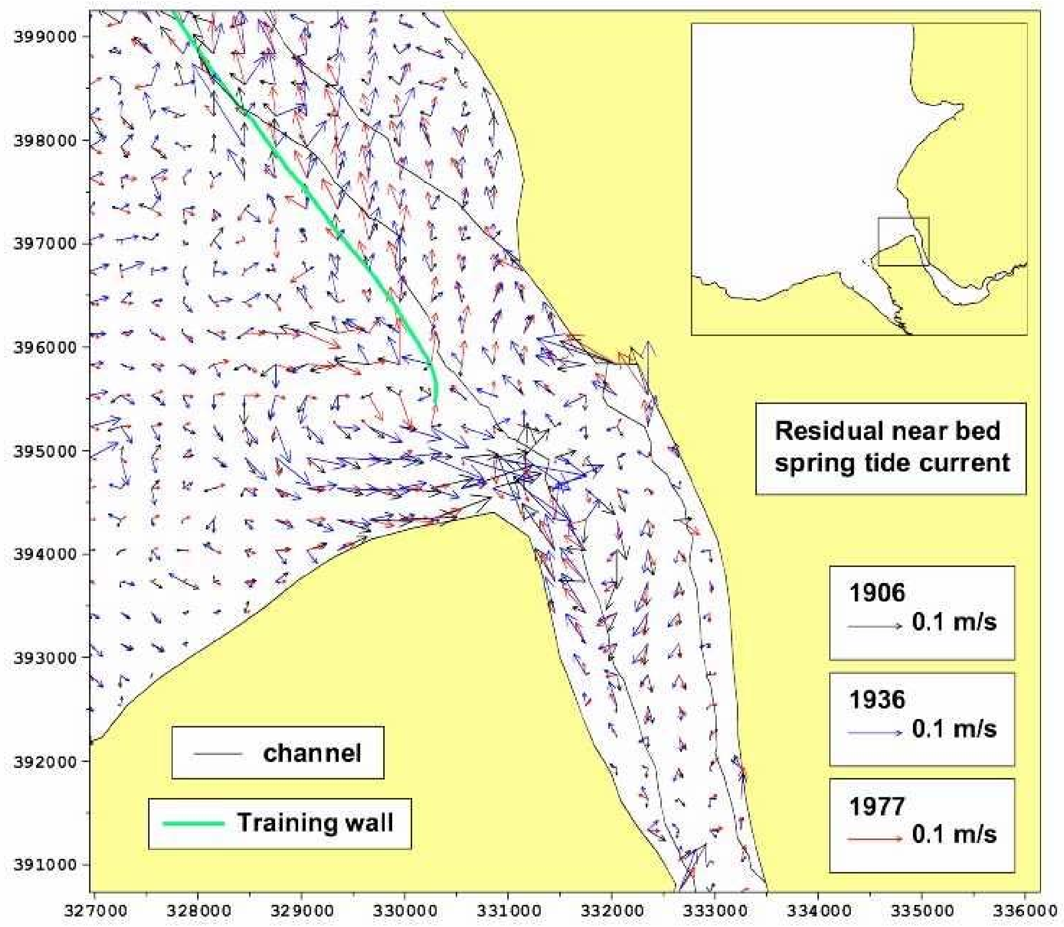
[6] The relative accuracy is the ability to rank the results from testing of a series of scenarios: for example Option A being preferred to Option B.

morphology should be expected. However, the complexity of the estuarine system must also be considered. Unless the data relating to historical morphological change can be understood (via a conceptual model of estuary functioning) the volume of available data has no bearing on the certainty with which questions can be addressed.

With the methods presently available, greater certainty is always likely to be achieved for questions where a relative answer is required (e.g. ranking of a number of options). Absolute prediction of change is subject to greater uncertainty and therefore the estuary manager should expect to see this uncertainty recognised in the derivation of impact associated with a project.

3. WHAT INFORMATION IS NEEDED TO ANSWER THE QUESTION?

Chapter 3 discusses the information needed to address the issues outlined in Chapter 2. It outlines the criteria that are important in selecting predictive techniques in order to address a given question and plan projects effectively. The following factors are highlighted as being important for consideration: budget for investigation; timescales of interest; the potential effects of a project on estuary morphology; data requirements; the previous application of morphological models for previous projects of this type or for adjacent locations; the timescale available for the study.



Residual near-bed spring tide currents predicted by 3D model for the mouth of the Mersey for historic bathymetries of 1906, 1936 and 1977.
(Source: Paper 5, Reference 4)

3.1 Spatial and Temporal scales of interest

A credible understanding of the existing estuary functioning must be provided as the basis for enabling decisions to be made. The impact of a specific development or the implementation of a strategy can then be considered against this baseline.

The first stage of any study involving morphological change is development of this baseline understanding. In defining the baseline it is often necessary to consider the following spatial and temporal extents:

Table 1 Temporal and spatial scales

Time	Space
Geological (millions of years)	Underlying hard and soft geology of whole region/catchment
Recent geology (Holocene period covering last 10,000 years)	Development of the main features of a region/estuary
Historical (centuries)	Large scale features within an estuary associated with human activities, such as reclamation, port development, flood defence
Decadal (10 to 100 years)	Exposed flats, salt marsh cliffs, meandering channels, creeks
Annual/Seasonal	Local areas of sedimentation
Storm event	
Tidal period (12.4 hours)	Sand waves and drainage channels, suspended sediment concentration
Wave period (a few seconds)	Bed features such as ripples

The level of detail that should be investigated in the baseline depends on the scale of the project being considered. For example, the development of a new slipway should not necessarily be considered in the same detail as the implementation of a new estuary wide flood defence scheme. For the slipway, it may be possible to restrict the temporal scale to decadal and the spatial scale to the adjacent intertidal and subtidal areas. For an estuary wide flood defence scheme the scales of interest are likely to be Recent Geology/Geological and development over the whole region. In some situations the requirement to consider episodic events such as storms and extreme fluvial flows will be important.

The choice of scales of interest should be made in consultation with the appropriate regulators. There may be conservation or water management interests that require addressing at a larger scale than might be perceived on the basis of engineering significance of the project. Similarly, the spatial area of importance for the project may be enlarged as a result of the project including a requirement for the disposal of material arising from capital dredging, and, subsequently, maintenance dredging. The disposal activity will need to be included in the study as it may have implications for the region. When the project is of a sufficient scale that the sediment budget of the estuary system needs to be considered (see Table 4) it is usually necessary to consider the adjacent coastal waters and the mechanisms whereby the exchange of sediment occurs.

3.2 Scoping - Considering the potential effects of a project on estuary morphology

In the examples in the previous section it can be seen that by considering the potential effects of a project at an early stage it is possible to identify the appropriate scales of interest and investigation. This is a key stage in developing the methodology for investigation of a particular project and essentially represents the means by which the likely effects of a project are identified. This is significant because it enables identification of the spatial and temporal scales of concern, the broad linkages between the process areas and the data and techniques to be utilised.

The assessment of likely influence/effect of a project requires a reasonable knowledge of the interactions that can occur between the different process areas within the estuary system. Direct effects are often fairly obvious, e.g. direct loss of inter-tidal area through reclamation, and a pathway for the assessment of morphological change usually can be identified. However, due to the diversity of environmental parameters and complexity of interaction within the estuarine environment, it is inevitable that direct effects lead to indirect effects which can in turn lead to further more subtle effects. This train of cause and effect resulting from one project may involve a large number of elements within an estuary system. Effects once or twice removed from the initial direct effect are often more difficult to determine and may require more detailed analysis before assessment of the change can be made. However, this is not to say that secondary or tertiary effects are of less significance in relation to the scale of change/impact they may generate.

A change in local tidal flows due to construction of a jetty may lead to a change in sediment transport characteristics that has a greater influence on the estuary morphology than the local impact resulting from the hydrodynamic change.

This scoping activity requires a good knowledge of estuarine processes as well as an understanding of the characteristics of the system in question and is a key element of developing a credible understanding of the effect of a particular project on the estuary system.

3.3 Data requirements

The key data requirement for morphological studies is spatial historic data relating to change in estuary wide morphology. Data sources include:

Table 2 Principal morphological data sources

Data Source	Comment
Bathymetric survey	Unlikely to cover entire inter-tidal area, typically to MHWS –2m
Admiralty Charts	Unlikely to cover inter-tidal area in detail and also likely to be shoal-providing information for safe navigation
Ordnance Survey Maps	Provide approximate positions of Mean High and Low Water and features in the floodplain
Aerial photographs	Covering inter-tidal and floodplain areas
Remote sensing data (including LIDAR and CASI)	Covering inter-tidal and floodplain areas
Local topographic surveys	Covering inter-tidal and floodplain areas

Additionally it may be possible to process some point source data to infer morphological change from boreholes and short cores. Borehole data is required for analysis of morphological change over geological periods. Shorter cores can provide information on local rates of accumulation and horizon relative to sea level for periods from a few months to the entire Holocene. Archaeological data may also provide evidence of horizon and lateral position relative to water bodies over longer timescales[7].

Data sets of the types described above require considerable processing in order to identify and quantify morphological change. In the course of such processing it is important that the accuracy of the data source is acknowledged. Over time, different methods of measurement have developed and when assessing historical data this needs to be considered. For example, care should be taken interpreting data where a change over from lead lines to acoustic echo sounders that happened in the 1930's. Typically lead lines gave an overestimate of the depth and an appropriate reduction should be applied.

For accurate interpretation of historical data it is vital that records of other significant activities, including dredging and reclamation, are known for the period covered by the records and that the evolution of the system is understood. Without such knowledge, interpretation of wide-scale change can be misleading. However, obtaining historical records can be difficult. MAFF (RMED) holds a database of dredging disposal license information that dates back to 1985. Records extending back a further decade or so exist in paper form. National sources of information on construction and related dredging are less well documented. A consequence of this is that alternative, usually local, records concerning activities within estuaries will need to be utilised when developing an understanding of the other factors that influence observed morphology in an estuary system. For a small estuary, possibly with only one major operator, this may be a manageable task. However, for the larger estuary systems, developing a credible understanding of the impact of various activities that influenced morphology over a period for which some data exists can be tremendously complex. Inevitably the more complex a system the less likely it is that an unambiguous interpretation of the available data can be made.

The expert analysis of data relating to morphological change is a key step in developing a credible understanding of the baseline situation. Whilst the analysis of available data may not yield sequential data sets that can be utilised for calibration purposes, the outcome of the analysis will form the basis of any verification of predictive and interpretative techniques that are employed. Inadequate analysis of available information can compromise the results of the application of such techniques[8].

The availability or otherwise of good quality data will remain a key issue for the prediction of morphological change in estuary systems for many years to come. The value of data and data collection programmes should not be underestimated. Data collection now will provide future generations with the information they will require to manage estuary systems in the future.

3.4 Selection of technique(s)

In Chapter 4 the various techniques that are available for considering morphological change within an estuary are described. In order to select one or more of these techniques for application, knowledge of the different types of technique is required. However, before moving on to consider the different techniques in more detail some simple questions should be considered concerning the project of interest and the estuary system in which it is proposed.

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[7] Further information can be found in Paper 11 of Reference 4.
[8] Further information can be found in Papers 14 and 15 of Reference 4.

Have morphological prediction techniques previously been applied in this estuary?

If the answer to this question is yes, then it is possible that at least some of the work that may be required has already been undertaken. An early stage in the investigations should include a review of the previous work. If the work is recent and involved input from the appropriate regulators, then application of the same methodologies may be the most practical way forward. This assumes that the morphological changes expected to be associated with the present project are comparable to those considered previously in the estuary. If the present project is likely to create changes orders of magnitude different to projects previously considered, then the previous methodologies will require review.

Have morphological prediction techniques previously been applied for this type of project?

Knowledge of the approaches adopted by others for the same type of project is important. However, it must be recognised that all estuary systems exhibit different characteristics. Consequently the approach adopted for a particular project must be considered alongside the functioning of that system.

A system which is characterised by a minor input of marine sediment and is stratified at times may respond differently to a system without significant fluvial input.

An estuary which is canalised by reclamation may be dominated by different processes, giving rise to different concerns compared to a system with extensive inter-tidal areas.

What is the main morphological concern for this estuary?

If this question has not been answered by previous project proponents and is not self evident from the proposed project, consultation with the appropriate organisations and stakeholders will be required to identify the main concern(s) for the estuary. For most estuaries, concern over losses or changes to inter-tidal habitat will exist. For some systems, flood defence issues will be important or safe navigation will be the dominant issue. In many situations all of these concerns (and more) will need to be addressed.

Are there significant design or operational issues associated with this project?

Within a project there may be design issues that require resolution. There may also be engineering issues associated with the construction and subsequent operation of the project. When such questions arise it is likely that some of the studies required to assist with the development of the project will have to involve relatively high resolution of the development in space and time. This will require so-called "bottom-up" or "process based" models (see Section 4.1). It may even be necessary for a physical model to be used. If these models have to be applied for design and/or operation purposes it will make sense to utilise them for other aspects of the investigation.

It can be seen that the choice of technique applied to a particular issue will be governed by many factors including:

- Type of question being asked
- Designated status of the site
- Scale of works in relation to the estuary system
- Available data
- Available duration and budget for study
- Degree of certainty required in predictions
- Other issues such as water quality and ecology

The question of duration is important. In nearly all practical situations there will never be enough time within a project for data relating to morphological change to be collected. Project durations are typically order of a few weeks to a few years. Consequently if data is required then it will either be complementing existing morphological data or it will be collected for purposes of understanding process.

The most useful activity to carry out in a short duration project is to develop an understanding of the existing baseline information (Chapter 2) and then scope the potential effects of the project (Section 3.2).

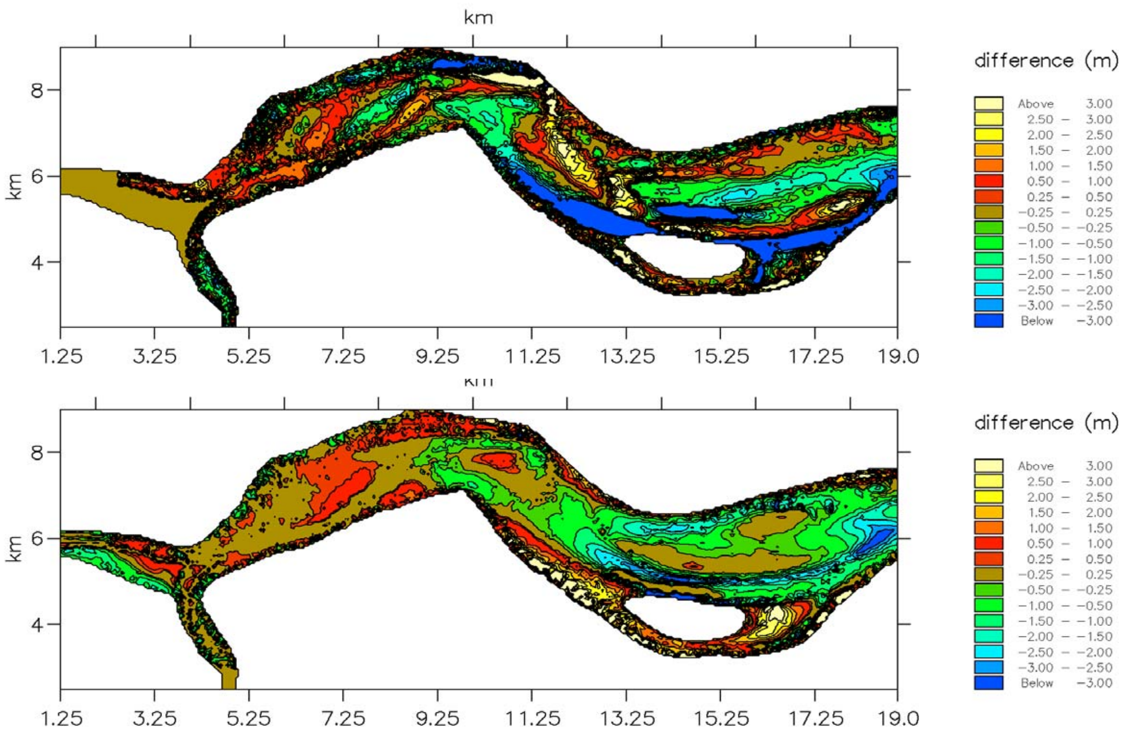
If only limited data is available then it may become necessary to collect more data before the process can be sufficiently understood to warrant applying any predictive techniques.

The question as to whether process-based modelling will benefit other aspects of a project through providing input data for design studies and water quality or ecological assessment, should also be taken into consideration.

4. WHAT TOOLS AND TECHNIQUES ARE AVAILABLE, AND WHAT ARE THEIR LIMITATIONS?

Chapter 4 reviews the different types of predictive techniques currently available. 'Bottom-up' or process based models examine estuary processes, whether individually or in some combination. 'Top-down' methods are those which represent the entire estuary in a way that summarises the cumulative effect of the various processes, without considering them specifically. A hybrid model is a specialised combination of the two. For the different approaches, different temporal and spatial scales may be addressed.

Chapter 4 provides a generic overview of the different types of approach: their data requirements and the scales that can be addressed. Further detail of the different methods and models is provided in Appendix 3 and in References 3 and 4.



Observed bathymetric changes between 1950 and 1956 (top figure) compared to morphological updating prediction (bottom figure) of the evolution of the channels in the Humber Estuary between Trent Falls and Reeds Island
(Source: Paper 7, Reference 4)

4.1 Introduction to the techniques available

Morphological changes within an estuary are the result of a variety of different forcing factors on the estuary system. Two approaches have generally been taken to the prediction of morphological change within an estuary system: ‘bottom-up’ (also known as process-based) and ‘top-down’ (also known as systems approach).

As described in the preceding chapter the starting point for evaluation of the morphological changes is consideration of what can already be deduced about the processes acting within that estuary system and the changes that have occurred. It should be possible to extend this review activity to scope the likely morphological changes associated with a particular project.

It may be possible, based upon this initial appraisal, to determine that a ‘top-down’ approach can be applied to deliver the appropriate information to enable decisions to be made. Alternatively it may be determined that the processes at the site are sufficiently complex that ‘bottom-up’ process-based modelling is required before the required information can be generated. It might also be determined that further data is required before a predictive methodology can be applied. Furthermore in many cases it will be found that, subsequent to process-based modelling, ‘top-down’ techniques are also required. In all cases the initial step of process review should be a user-orientated and pragmatic review of what is known about the estuary system with particular regard to the proposal of concern.

The **‘bottom-up’ approach** employs models which are based on physical principles (processes) and give local **short-term** predictions of morphological change. The information on hydrodynamics provided by these process models can form the basis of other process-based predictions of change, such as sediment transport and water quality. Morphological change may be inferred from the results or may be predicted directly. In this context ‘short-term’ means a few weeks. If these models are applied for longer periods the errors in the prediction may begin to accumulate. The value of these models is that the results they can provide are based upon representation of physical processes which have a sound and widely accepted basis.

The **‘top-down’ approaches** are largely empirical and do not represent individual processes themselves. The most common of the ‘top-down’ methods, the regime approach, assumes that an estuary can be considered to be in some form of dynamic equilibrium over the **medium to long-term** period of morphological change to be predicted and that there is a characteristic function which describe the equilibrium relation between the hydrodynamics and the morphology. In this context ‘long-term’ usually means decades.

The ‘top-down’ approaches do not in general predict the physical processes of morphological change by sediment transport. Consequently predictions can be made simply and computationally cheaply for the whole estuary area over periods of several decades. This has tremendous advantages to the estuary manager who wishes to ask many ‘what if?’ questions. Furthermore, because detail of process is not included, if the approach can be adequately validated against observational data it has the advantage of implicitly including the effects of other processes such as biological and sedimentological effects which may not be well understood. The corollary of this statement is that if such validation is not possible, the lack of a physical basis to these methods introduces considerable uncertainty into their predictions.

The simplicity and speed of the ‘top-down’ predictive approaches have much to commend them and in terms of developing a usable tool the simplicity implicit in the methodology is a key asset. ‘Top-down’ techniques generally do not cater for prediction of localised changes. They are thus better suited for considering the impact of large scale works liable to affect whole estuary systems than for detailed design work. However, the credibility of ‘top-down’ techniques relies on their validation and expert interpretation.

Historical bathymetric data sets are presently the only available data against which to validate tools for the prediction of morphological change. The data sets that are available are limited in time to perhaps the last one hundred and fifty years, and limited in accuracy to perhaps plus or minus half a metre in the vertical over this time period. Furthermore, it is unusual for bathymetric data sets to extend across the entire estuary system including intertidal areas. Quality of data apart, changes between two successive data sets for an estuary may represent the cumulative effects of numerous processes and human interventions that occurred between the two surveys and possibly the longer term impacts of larger effects that occurred prior to the earlier survey. In order to utilise these limited data sets for validation purposes it is necessary that the user of the predictive tools is aware of the sensitivity of the tools to the different processes that may have influenced change within the data set. This sensitivity can only be established using a tool that specifically includes the relevant processes.

For example, bathymetric changes within the Mersey Estuary have been recorded over the past century[9]. Within that time there have been major engineering works within the estuary and its approaches and there have been changes to the sediment supply to the inner estuary. Assessment of the significance of different processes based upon available data will help to establish the sensitivity of the estuary system to the forces acting upon it.

Based upon the understanding arising from such sensitivity analysis it may be identified that a simple 'top-down' approach could be employed for the purposes of decision making. Similarly it may be determined that for the issues of concern more data is required, or that 'bottom-up', process based, modelling is required to understand the significance of process further. Only by expert consideration of process first would it be possible to benefit from the simplicity of the 'top-down' approach. This combined use of 'bottom-up' and 'top-down' techniques is an example of a **'hybrid' approach**.

4.2 Modelling estuarine processes

Modelling is a compromise between reality and practicality. Simple models are practical, but their simplicity means that they may only be realistic in a small number of instances. As models become more complex, they are more likely to reproduce the natural system effectively. However, this is only true if they contain the relevant processes. If one is missing then no matter how sophisticated the model, there will inevitably be shortcomings.

Realistic and detailed modelling of estuarine morphodynamics involves the highly non-linear interaction between the bathymetry and the tidal flow. This interaction results in residual circulations and spatial variation in sediment fluxes. The important non-linearities are the results of bottom friction and flow curvature.

Bathymetric changes are caused by spatial divergence and convergences in the small net sediment movements that take place. Such movements are themselves the result of differences between fluxes on the flood and on the ebb tide. Measurements or estimates of these fluxes are prone to large errors as sediment transport is perhaps understood qualitatively but not well described quantitatively due to the complexities involved. The fact that these will increase with time, is why the long-term prediction capability of this type of model is poor.

The residual circulations produced by the interaction are important for the evolution of sedimentary features such as sand banks, meanders and scour holes. These all involve cross-channel changes in depth distribution, without necessarily affecting the cross-sectional areas. The consequent alteration in the effect of bed friction produces asymmetry in the tidal flows, also called overtides, and these are important in producing differences in the relative strengths of the flood and ebb flows, the phase lag between the flow, the sediment fluxes, and the net sediment transport. Along the channel the changes in the depth distribution in the cross section produces modifications in the flow that can result in a longitudinal

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[9] Further information can be found in Paper 9 of Reference 4.

sequence of sediment movement cells, and in temporal instabilities that give cyclic variations in the bathymetry.

The vertical structure of the flow and suspended matter concentration produce phase lags between the water flow and the sediment movement. Such phase lags influence the net transport of sediment and the spatial distribution of erosion and deposition. The phase lags depend upon the erosion threshold of the sediment, its settling velocity, and the character of turbulence in the near bed currents.

An additional problem is that the equilibrium for sand (non-cohesive sediment), which often forms the main structure of the bed, will be different from that for mud (cohesive sediment), since the phase differences for the two modes are different. In the upper parts of estuaries where sand may not be abundant, modelling the suspended sediment movement may be adequate, but near the mouth where the sand is more abundant, the modelling of bedload may also be necessary.

Many models do not consider the details of the frictional distribution across the cross section, or the vertical distribution within the water column. There are also a large number of sediment transport formulae and these can give more than an order of magnitude difference in the quantification of the sediment transport rates for the same flow velocity. Consequently, predictions need to be considered in the light of experience and data on past responses.

4.3 Introduction to different techniques available

In Section 4.1 the ‘bottom-up’, ‘top-down’ and ‘hybrid’ predictive methods were introduced. Further detail of examples of some of these techniques is provided in the Predictive Methods Report (Reference 3) and Appendix 3 which is taken from that report. In the following sections of this chapter the different types of approach are considered in more detail. Note that in this guide the techniques have been described in a generic manner. Within the Predictive Methods Report and on the EMPHASYS website the specific names of models used within the EMPHASYS Consortium are given. Details of models submitted by researchers and practitioners worldwide are included in these summaries.

4.4 Data requirements for different techniques

‘Bottom-up’ predictive methods require all the above information plus sufficient site-specific data against which to calibrate the detail of the process model. This may include detailed measurement of parameters such as current speed, current direction, salinity and suspended sediment concentration through the water column, in addition to information about sediment properties and behaviour. Typically a minimum of data from a single spring and a single neap tide is required.

‘Top-down’ methods for prediction of morphological change require as a minimum information on the present day morphology of the estuary. They can utilise information on past bathymetries. They are also likely to require readily available information on tidal range, freshwater flow etc. ‘Top-down’ models also need some sort of validation either by observations (rare) or at least a process basis to the predictions.

Detailed data on six representative estuaries (Blackwater, Humber, Ribble, Mersey, Tamar and Southampton Water) has been gathered together in the EMPHASYS Data-base (Reference 6). This also contains summary information on 18 estuaries, and present-day bathymetries for 79 UK estuaries, of which 66 have information on the tidal prism and cross-sectional area at mean tide level[10]. It is subject to licensing restrictions but parts will be made public. It has also established a standard format for storing estuarine data.

[10] Further information can be found in Paper 12 of Reference 4.

4.5 Scales that can be addressed by different techniques

'Bottom-up' methods are best suited to considering short-term (days to months) localised changes. Typically a process-based model of a whole estuary system is unlikely to have a horizontal resolution finer than about 10m and this is unlikely to be applied uniformly throughout the whole estuary because of constraints on computing power. Vertical resolution in a process-based model is likely to be a few centimetres.

'Top-down' methods are best applied to whole estuary systems to examine long-term (years to decades) system-wide changes. The horizontal resolution of these methods is typically of the order of kilometres although the vertical resolution will often be better than a tenth of a metre.

'Top-down' methods may be used to explore sub-systems of the estuary such as tidal creeks. When applying these techniques to smaller sub-systems the scales outlined above will change accordingly, with horizontal resolution increasing and timescales shortening. 'Long-term' in an estuary-wide context may be decades, for a sub-system it may be years.

The combination of 'top-down' and process-based methods provides a means of interpolating morphological change over the range of scales outlined above. Such combinations are classed as 'hybrid' methods.

Issues that arise from considering scale are the ability of a particular method to represent the scale of a project being considered and the fact that bathymetric data can at best be reliably measured over large areas with an accuracy of 0.05 to 0.1m. Historical data sets should not be assumed to have an accuracy of no more than 0.5m although it may be possible to demonstrate accuracy of 0.1m to 0.2m in some circumstances.

4.6 'Bottom-up' process-based methods

Numerous different 'bottom-up' models are available. In this section we summarise the basic types of model.

Table 3 Available 'bottom-up' process based techniques

Method	Comment
Hydrodynamic modelling	Process based modelling of water levels, discharge, current speed and direction, waves, density currents, secondary circulation
Sediment transport modelling	Process based modelling of bed load and suspended sand and/or mud movement and patterns of accretion and erosion – uses hydrodynamic modelling as input
Particle Tracking	Prediction of particle movement in a Lagrangian manner – uses hydrodynamic modelling as input
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 – uses hydrodynamic and sediment transport modelling as input

It is not the intention within this guide to review these different models. This is done in References 3 and 4.

The key issues for the project proponent concerning selection of a process based model are:

Does the model adequately represent the governing physical processes at the site and within the estuary?
Does sufficient reliable information exist with which to set up the model?
Are the assumptions associated with the various parameter selections understood? – can the sensitivity of the results to changing these parameters be investigated? – does this sensitivity compromise the model predictions?
Is sufficient data available against which to calibrate/validate the model?

Provided that the models include the appropriate physical representation, and they are used by experienced individuals who undertake appropriate sensitivity tests, they should provide adequate results. However, it should be noted that the calibration of hydrodynamic models will be dependent on the field data available and the proper interpretation of the data by the modeller, in a manner consistent with the model formulation. For this reason, the user should have a sound understanding of how the model is formulated so that the model is not treated as some sort of black box that simply requires the inputs to be provided. It is thus essential that they are used by expert modellers: they are not universal tools that anyone can use. The use of a poorly calibrated hydrodynamic model in unrepresentative conditions for subsequent sediment transport modelling can result in highly misleading information. When process based models are employed the calibration/verification of the models and the manner by which representative conditions for predicting sediment transport are selected must be demonstrated to ensure the credibility of the results.

In the following sections some additional comments on the choice of available process-based models and their use are provided:

Flow models

The first step in process-based methods is generally a good flow model. The following main types of flow model have been identified:

- 1D models
- Hydrostatic 2DV models
- 2D 2 layer models
- Hydrostatic pressure 2DH models
- Boussinesq 2DH models
- Hydrostatic pressure 3D flow models
- Fully 3D flow models

(The description 2DH or 2DV signifies a two dimensional model developed in the horizontal or in the vertical). The most common models are 1D models, 2DH models and Hydrostatic pressure 3D flow models.

There are various commercially available flow models. Some of these are listed in Reference 3. It can be assumed that all these models will perform acceptably in the hands of appropriate experts. Some of the models are simpler to use and some will require less computational power than others. Generally the complexity and cost of a study increases from using 1D models to 3D models.

The question of whether, for any particular estuarine site, a 1D, 2D or 3D flow model is used is in practice a function of the use to which the model results will be put. Essentially the model must be able to adequately represent the mechanism which is of concern. Since for morphological studies the hydrodynamic output resulting from the model is to be subsequently used for sediment transport modelling then the nature of the transport under consideration and the information required from the sediment transport model should drive the choice of model. The following is a brief guide to the applicability of each type of model:

- 1D models - Estuarine water levels, flow (and sediment transport) in rivers, as long as local detail is not required, should not really be used for sediment transport in estuaries. Note that 1D models are only really applicable to channels.
- 2DH models – Water levels, flow (and sediment transport) for all coastal systems, as long as secondary currents (occurring at bends or where there is a saline gradient) are not important and as long as there are no significant vertical transport processes.
- 2DV models – Can be used for water levels and flow, (even flow with density currents from saline gradients) for systems that are fairly "canalized".
- 3D models – Can be used for all problems but the time/cost of these models makes them impractical for simpler uses where a large number of runs might be undertaken.

Wave models

The requirements for including knowledge of wave conditions in the predictive methodology needs to be considered and included in the approach if necessary. Computational wave models fall into three broad categories:

- wave generation models
- wave transformation models
- wave disturbance models

Of particular importance to the prediction of estuary morphology is the ability to predict wave conditions over large areas of shallow water. Near the mouth, the wave conditions will be a combination of waves propagating into the estuary from offshore and local wind wave generation within the estuary. Further upstream, wind-waves will be increasingly fetch limited and generated within the estuary. On some estuaries, ship waves may also make a significant contribution to the wave energy incident on the estuary shores.

Since the constraints of time do not allow the full range of wave conditions to be represented in a spatial model, the selection of a representative set of wave conditions for a study is necessary and important to a project outcome. Further discussion of the selection of representative wave conditions is beyond the scope of this guidance document.

Sediment transport modelling

The morphology depends on the gradient of the tidally-averaged sediment fluxes. Most commercially available sediment transport modelling packages can:

- represent potential[11] sand transport (non-cohesive material)
- represent the transport of mud (cohesive material) in suspension
- predict the potential littoral drift (non-cohesive material) at a particular location based upon an input wave climate

Specialist models and organisations are presently required when it comes to modelling sediment transport in three dimensions or modelling of the following in 2DH:

- representation of unsaturated (i.e. not potential) sand transport
- interactions between sand and mud particles
- representation of the formation and transport of fluid mud
- representation of the evolution of a muddy bed
- prediction of morphological evolution of the bed

[11] The term potential implies an infinite supply of sediment.

4.7 'Top-down' techniques

'Top-down' methods are those which represent the entire estuary system in a simple way. They can take a variety of forms, some completely empirical, others appealing to physical principles. 'Top-down' methods do not consider the small-scale features of hydrodynamics or sediment transport. Their strength is that they can predict large-scale changes to the whole system over long periods, often without requiring information on the detailed properties of the system. They are not suitable in general for local or short-term changes. They can be split into methods based on data analysis and intrepretation and those involving an assumption that a system is in equilibrium before perturbation and will re-adjust to a new equilibrium afterwards.

Table 4 Available 'top-down' methods relying on data analysis

Method	Comment
Holocene Analysis	Description of geological development of basin. Usually includes estimates of sea level change and identification of periods of marine regression and transgression
Accommodation Space	Changes in sediment storage capacity of the estuary over Holocene timescale (10,000 years)
Regression Techniques	Use simple regression models to relate sediment types and vegetation to environmental variables
Historical Trends Analysis	Interrogation of time series data to identify directional trends and rates of processes and morphological change over varying time periods
Sediment Budget Analysis	Establishment of scenario(s) of sediment inputs, outputs and sources and sinks within the estuary system. Can use results from 'bottom-up' modelling
Saltmarsh Analysis	Relates properties of exposure and tidal range to the presence and distribution of species. Can use results from 'bottom-up' modelling
Expert Geomorphological Analysis	Using results from many of the different methods, together with an understanding of how different types of estuary form evolve, to assess the expected development of the estuary system

Of these methods the first three are strictly data analysis, the second three could also be considered hybrid depending on the extent to which they draw on the results of 'bottom-up' models.

Sediment budget analysis is based on the general principle of conservation of sediment, and uses whatever information is available to estimate long-term, large-scale sediment fluxes into and out of the estuary. Clearly an adequate understanding of dredging and disposal activities within an estuary system is required for this type of analysis.

Table 5 Available 'top-down' methods relying on equilibrium assumptions

Method	Comment
Regime Relationships	Relates estuary form properties such as cross-sectional area, plan area of inter-tidal or sub-tidal to tidal prism, volumes to given elevations, sediment type, and erosion threshold.
Form Analysis	Uses shape descriptions to characterise the estuary form (e.g. exponential width decay, or power law width and depth)
Tidal Asymmetry Analysis	Examines changes in tidal wave propagation as a function of estuary form
Inter-tidal Form Analysis	Considers the equilibrium shape of the cross-shore profile
Estuary Translation (rollover)	Defines the vertical and horizontal movements of the whole system as a consequence of changes in sea level

One of the best known types of top-down model is the regime theory method. The basis of this method is to relate the size and shape of the estuary cross-section to the amount of flow which passes through it. This is typically represented by the tidal prism (the volume of water passing a particular cross section of the estuary on the flood tide) or the peak tidal discharge (the maximum rate of movement of water through a particular cross section throughout the tidal cycle). The assumption implicit in this method is that, in response to constant external forcing, the estuary will reach an equilibrium shape which can be characterised by power-law relationships between tidal volume and width and depth of the cross-section. Many estuaries can be shown to fit this assumption quite well, although the values of the coefficients and exponents in the power-law are different for different estuaries. If a change is imposed on the system, for example to decrease the tidal volume by constructing a barrage, then the new form of the estuary can be calculated using the power-law relationships developed for the pre-disturbance equilibrium. It is possible that the coefficients change with time, or as a result of a disturbance, and this imposes a limit on the reliability of such methods. The rollover method is similar in some ways to the regime method, but it applies specifically to the landward transgression of an estuary in response to sea level rise.

Comparison of the results of 'top-down' techniques with the results of historical data analysis is critical. Similarly intercomparison of results from the different techniques can add confidence to the results.

4.8 Hybrid techniques

A number of hybrid techniques have been considered in the course of the Estuary Research Programme:

Table 6 Available 'hybrid' techniques

Method	Comment
Coupled hydraulic and regime relationships	Given a perturbation to the estuary modelled this method uses a target equilibrium, defined by some form of regime relationship, to iterate to a new equilibrium
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
Zero divergence of sediment flux	In this type of model, sediment is moved within the estuary and equilibrium is achieved when equal amounts are moved on the flood and ebb tide
Coupled hydraulic and energy relationships	Examines the distribution of bed shear stresses and compares these values with an erosion threshold
Other combinations of 'top-down' and 'bottom-up' techniques	Catch all category – but important to recognise that nearly all predictions of long-term morphological change associated with process based models utilise some form of 'top-down' input as the basis of inferring change.

The first three methods identified here utilise the results of flow models as input. Where these are one-dimensional the resolution of change over the estuary is limited to changes over cross sections and reaches. A few of the techniques currently available involve the results of more complete representations of the estuary (2D or 3D).

4.9 What can the various techniques do and not do?

Many varied techniques have been developed to make predictions of estuarine morphology and processes, ranging from expert opinion based on analysis of the behaviour over time of a large number of estuaries, to highly complex computer-based models. As with weather forecasting, no one method is indisputably superior to the others – all have their strengths and weaknesses, and their suitability to the kind of problem, the kind of estuary, and the time and space scale. Many of the available techniques have been tested against data from six representative estuaries, chosen on the basis of (a) adequate availability of data, and (b) complementarity of types of estuary. The results can be found in Reference 4, which includes short papers on the individual tests and a Synopsis which summarises the results.

The tests of the methods help to provide answers to questions such as those below. The bracketed numbers refer to papers in Reference 4, with "S" referring to the Synopsis.

- *What type of model is most suited to my problem and my estuary?* (S, 25)
- *If a gridded computer model is most suitable, should it be a one, two or three-dimensional model?* (4, 5, 6)
- *If a "top-down" model is most suitable, what type is designed for this problem?* (S, 14-18)
- *What is a Hybrid model, and what are its advantages?* (S, 19, 21, 22)
- *How does the geological setting influence the morphology?* (11, 23)
- *Are biological factors likely to influence the morphology?* (8, 23)
- *How can the effects on the ecology, bird populations, etc. be predicted?* (S, 22,23, 24)
- *How can changes in the water quality be predicted?* (24)
- *How well do model predictions compare with measurements?* (6, 7, 19, 21)
- *How much confidence can one have in these models?* (All)
- *How does this estuary fit into the pattern of other UK estuaries?* (12, 13, 18, 20)
- *What are the specific models in each category, and who owns or operates them?* (All)

Answers to these questions can be found in this report, drawing on the knowledge and experience of the EMPHASYS consortium. The consortium has performed a large number of tests of 15 models and methods against six key representative estuaries. Because every problem and every estuary is different it is impossible to draw many universally applicable conclusions. Instead, each case must be treated individually, but the results of most of the model tests can be regarded as a generic result for that time and space scale, that type of estuary, and that type of problem.

Having decided which questions are relevant to the problem in hand, the reader can obtain first-pass answers to the questions by reading the Synopsis, which gives summary findings for each model test. This guides the reader to the individual papers in which more detail can be found. If a greater level of detail than this is required, the reader can follow up the reports and papers referenced in the papers, or contact the authors whose addresses are given in the papers.

The techniques are only as good as the data relating to morphological change that they are founded upon – hence the importance of the initial analysis of historical data.

Generally the 'top-down' techniques are unable to provide local short-term detail of change. The exceptions to this are Expert Geomorphological Analysis and feature-specific studies of inter-tidal profiles and saltmarshes, which are principally limited only by availability of data. 'Top-down' techniques are therefore unlikely to yield information that relates to operational activities such as planning the construction phases of a project or managing the day to day operations of the project. 'Bottom-up' processed-based techniques are required to provide input to these issues.

In isolation, 'bottom-up' techniques are unable to yield good quality information about spatial change over long periods of time unless the processes involved are particularly simple. Hybrid methods are required to interpolate between the domains of local, short-term and estuary-wide, long-term. Regime-based techniques are compromised if the estuary is not originally "in regime". Determining whether a system is "in regime" is currently the subject of ongoing research and consequently requires specialist input.

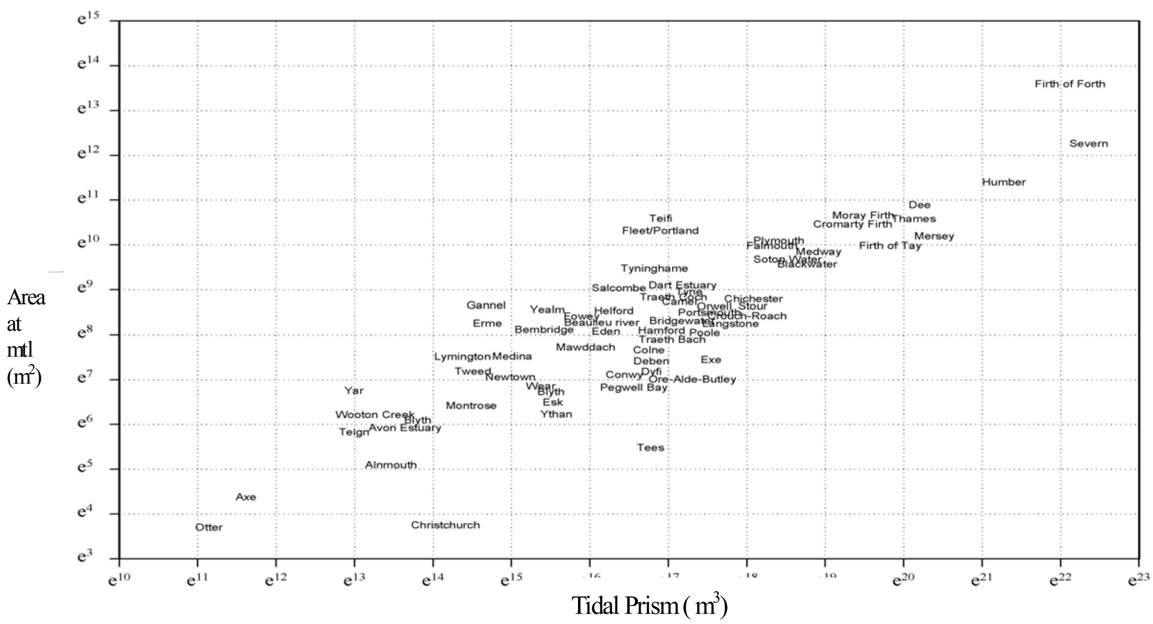
4.10 Relationship with prediction of ecology and water quality

Predictive tools for morphological change will also need to be linked to other process areas such as water quality and ecological predictions as these are regulated processes and are important in the functioning of estuaries and the decision making framework. For water quality predictions, models are presently linked to ‘bottom-up’ (physical process-based models) and not ‘top-down’ models. Linking present models for ecological and water quality prediction requires more research into both improving our understanding of the scientific processes (forcing functions and parameters of importance) and into the validation and sensitivity of existing approaches and methods. Presently such models are likely to require site-specific validation. (See Appendices 1 and 2).

5. HOW CAN THE RESULTS BE INTERPRETED?

Chapter 5 outlines good practice in terms of using the tools and information available, so that appropriate decisions can be made. It is about the steps that the estuary manager can check have been taken so that confidence in the results derived from different predictive methods is maximised. It involves a discussion on data assimilation, use of different techniques in conjunction with one another and addresses what can be done with the results. It considers the importance of the validation of the different data sources and predictive techniques at the interpretation stage. The use of results to develop a conceptual model as a basis for management is discussed. Chapter 5 also deals with sensitivity testing (which is a critical aspect of best practice) and considers issues regarding the reliability and accuracy of model results.

The predictive techniques available (see Chapter 4 and Appendix 3) will provide output in different formats for interpretation. Chapter 5 discusses the differences in types of output generated by the different techniques and considers whether the predictive tools being applied are likely to provide the level of information required for making decisions in different circumstances, or whether reprocessing and the introduction of further parameterisation or assumptions might be required.



Plot of tidal prism (m^3) against cross sectional area at the mouth of the estuary at mean tide level (m^2) for 66 UK estuaries
(Source: Paper 12, Reference 4)

5.1 Developing confidence in model outputs

Model selection

Decision makers require confidence in the basis for their decision making. The application of the methods described in Chapter 4 is only part of the process of building this confidence. The analysis of existing data and the subsequent interpretation of the results from the different techniques are equally important. Synthesis of the outcome of these three elements of analysis leads to the development of a conceptual model which provides a credible understanding of how an estuary system functions. (See Box 4.)

Box 4 – Stages in the development of a conceptual model:
1. Analysis of existing data
2. Application of predictive methods
3. Interpretation
4. Synthesis

Further confidence can be provided by the model being demonstrated to be robust under different scenario testing: for example the conceptual model being established for a flood defence strategy but also being applicable to consideration of port development and a local construction project. The format in which the results are presented and the experience of the individuals involved also contribute to the confidence building.

Selection of the techniques to use depends upon the project being considered. However, in all cases a conceptual model of how the estuary system functions will need to be developed. For small localised projects the detail within the conceptual model may not need to be as great as for a major project or a strategic study. The development of a conceptual model will require consideration of information from a variety of sources, including model results. For major strategic studies the whole range of 'top-down' techniques may need to be applied to help to build the required level of understanding of how the estuary functions. These will need to be combined with application of 'bottom-up' techniques that adequately represent the important processes in the estuary.

In Tables 3, 4 and 5 the generic types of predictive tool are summarised. In References 3 and 4 further details of the specific tools available amongst researchers and consultants are provided. Selection of the techniques to be used may be a matter of open competition amongst a number of different organisations, such as for a major strategic study. Alternatively it may be a question of an organisation that has previous experience of the estuary applying further techniques from their suite of tools or working alongside another organisation who bring some of their tools to the study.

The estuary manager does not need to understand the details of the different techniques available beyond the level described in Tables 3, 4 and 5. What the manager does need to consider is the manner in which the confidence in the application of these tools to a specific project can be maximised. This is achieved through the steps of calibration and validation and consideration of the resolution and accuracy of the results.

Calibration and validation

Calibration is the stage where model parameters are adjusted to optimise the fit of the model results to the measured data. Validation then tests the model against a different set of data, without any further adjustment of the model parameters. Typically a flow model might be calibrated for a spring tide and validated with measurements taken at neaps. For calibration and validation of a morphological prediction technique the required data set might contain several (more than three) estuary-wide historic bathymetries. It might thus be possible to establish the predictive method based on changes between two of the data sets and then validate the method by hindcasting changes between a different set of observations.

If a 'top-down' method is to be employed it will be necessary to have sufficient additional information to support the assumptions inherent in the method over the period of observations. If 'bottom-up' process-based modelling is to be employed sufficient (temporally consistent) data concerning hydrodynamics and sediment transport will be required to calibrate the process model in the first place. Additionally detail of any change to process during the period of the available data will be required.

Guidance with regards to confidence building for the different stages in the development of a conceptual model is summarised in Boxes 4 to 8.

Box 5 – Confidence building in historic data analysis

This needs to be undertaken at scales appropriate to the project. The more credible this analysis the easier it is to use the results of different predictive techniques to add to understanding of the baseline and subsequently to prediction of change.

- Ensure that the right type of data is available
- Take care in the treatment of datums and map/chart projections, particularly when merging data from a number of sources
- Ensure that data is subject to rigorous quality assurance
- Explore available sources of information, and their quality, concerning evidence of morphological change

Some types of historical data are often of questionable accuracy, such as dredging and disposal records, details of operational activities such as barrage operation, sluicing and even dates of construction of major engineering works. Information shown on an Admiralty or Port Charts might be perceived as accurate but it is not unknown for positions of coastlines from one chart to another to move as survey techniques and data sources change, or construction activities are shown as complete when they are only underway.

A further source of concern can be surveys of large areas. Any detailed whole estuary survey will take a significant time to complete. However, if the duration extends over a number of years it is important to consider the order of magnitude of changes and forcing events that might have occurred over the period of the survey. Instantaneous estuary wide surveys may well be a thing of the future but they do not exist for the past or the present. Validation therefore requires judicious use of available historic data alongside careful documentation of changes that have occurred or are ongoing including: reclamation, dredging, engineering works, vessel traffic, water abstraction etc.

From the work undertaken to establish the database for the Estuary Research Programme (Reference 6) it might be thought that in the UK ideal data sets exist for the Humber, Mersey, Southampton Water and the Stour Estuary. However, for all four of these estuaries unravelling the history of events covering the period of survey data is complex and in some cases impossible. This does not preclude the use of these data sets for validatory purposes but a certain amount of caution must be applied.

In the short to medium term (say 5-10 years) methods for predicting morphological change must be based upon the type of data that presently exists. New data needs to be collected so that the database for some UK estuary systems moves towards the ideal status outlined above[12].

[12] See recommendations section from Paper 12, Reference 4

Data exists that shows the position of a navigation channel migrating over time. The mechanisms for such movement can be explored.

Data exists showing that significant changes in morphology accompanied some particular estuarine works. This may represent evidence around which to base a 'top-down' methodology.

Box 6 – Confidence building for data collection

- Ensure quality of data collected is adequate
- Record the source of the data, as well as how it was collected and processed to its final form (including details of any corrections or adjustments made)
- Be aware of the errors inherent in the measurement techniques used
- Where necessary ensure data that is collected complements existing data (particularly important for bathymetric data)

Whilst it is unlikely that in the course of a particular project data will be collected that demonstrates long term morphological change, it must be recognised that data collection is often an important part of a study. If no baseline data exists then the data must be collected. If 'bottom-up' process based models are to be employed then sufficient data pertaining to the processes represented by the models must be collected for calibration and validation of the models.

In any measurement programme consideration must be given to the accuracy and resolution of the data being recorded. For instance, if a vertical profile of current speed and direction is made every 30 minutes and it is known that there is a very short lived period of peak flow then care will be needed to resolve the short term feature. A bed mounted acoustic current profiler can be set up to provide a better picture of the flow. If the flow in a particular area exhibits strong gradients in speed and direction (such as at the confluence of two tidal channels) care would be needed in siting a single station for measurements. Roving measurements with a vessel mounted acoustic current profiler might be better in this situation.

Measurement of suspended solids concentrations is often undertaken by remote means such as optical transmissometers. These instruments require careful calibration, as the output depends strongly on grain/floc size as well as concentration. The calibration may need to be changed over time reflecting seasonal or shorter term variability in the properties of the suspended material.

Properties of cohesive sediments are known to vary seasonally associated with meteorological conditions and biological activity. Measurements of sediment properties such as thresholds for erosion and settling velocity need to be considered in the light of experiences at other sites.

Box 7 – Confidence building for application of 'bottom-up' methods

- Expect site specific calibration and validation of key variables (eg water levels, flow speed and direction, suspended sediment concentrations, salinity, etc). Ask for the accuracy of this to be quantified (for example as rms errors rather than just plotted as a graph)
- Seek to understand differences between model and measurement. Don't assume either is necessarily right, they both contain uncertainty
- In some situations data may exist to calibrate or verify sediment transport models against sedimentation patterns
- In some situations data may exist to compare the results of sensitivity testing with hydrodynamic and sediment transport models against observed variability in estuarine form

The process of calibration will require sensitivity testing to examine different parameterisations of variables within the method to obtain the best calibration and to understand the effect of varying uncertain parameters within their possible range. This might be considered by some to be a critical aspect of the calibration of any predictive method. Undoubtedly from a scientifically rigorous point of view this is the case, but all too often this aspect of sensitivity testing is curtailed to move on to predictive scenario testing work. From the estuary managers point of view, investment in this first aspect of sensitivity testing will pay off in terms of certainty in the final solution. Note that there are problems with assigning values to the various parameters in mud transport modelling. Sensitivity analysis will uncover a huge range of outcomes, with no real methodology of selection other than experience or field observations.

Comparison of a model against field data during the calibration stage may demonstrate previously unrecognised uncertainty or errors in the field observations. The process of building confidence is iterative. It may be necessary to collect further data to generate the confidence required.

At some locations within an estuary system, reliable bathymetric records of large scale sedimentation may exist. This type of data can be used to provide a local calibration/validation and add to confidence in the conceptual model that is being developed. This type of local calibration/validation is often more important in the design stage. Extrapolation of the model away from this local area of calibration is only applicable if the processes are unchanged in different areas of the system and their relative importance is included within the model.

Box 8 - Confidence building for application of 'top-down' methods

- Unlikely to be possible to undertake site specific calibration, possible that generic applicability may be demonstrable
- Ensure that there is a plausible physical basis for the predicted changes
- Are the results consistent with those for other estuaries?
- Are the results consistent with accepted geomorphological development (e.g. for sediment infilling due to flood dominance until storage volume is reduced to the point where the system switches to ebb dominance)
- Be aware of the scope for error in the method

Top-down models are usually concerned with large-scale and longer-term morphological changes. Unfortunately the historic data associated with these types of changes is usually sparse and incomplete and therefore calibration and/or validation of this type of model is often difficult to achieve in the normal way. It is still important, however, to establish that the model can reproduce estuary evolution in an acceptable fashion, so that there is confidence in the model predictions. There are a number of ways in which model performance can be evaluated which are listed below. Note, however, these activities will not clarify the scope for error within the model as well as calibration against site specific data.

It is imperative that a physical basis for the evolution predicted by the top-down model be established. This "story" behind the prediction will vary as to its complexity under different circumstances but without this underlying foundation, the model prediction should be considered sceptically.

The top-down model could have been demonstrated to have been effective for a different situation where sufficient data was available for validation. This validation will be even more useful if the situation was of a similar type and location to the problem in question.

Confidence in the top-down model can be enhanced through undertaking a number of sensitivity tests to the main assumptions inherent in its methodology.

Box 9 - Confidence building for application of hybrid methods

- A flexible combination of a process-based model with 'top-down' method(s) may be perceived as a generic approach to predicting morphological change.
- It is likely that the approach will vary from one estuary to another dependent upon site specific data and the nature of the development or strategy being considered
- The concerns of using these methods are identical to those of both the 'top-down' and 'bottom-up' approaches

Resolution and accuracy

The resolution adopted within a predictive method is a critical aspect of the application of the method. This is perhaps most obvious in the application of 'bottom-up' models. A 3D flow model will not adequately represent the vertical flow structure unless sufficient layers in the vertical are used. A 2D flow model will not represent the detail of horizontal eddies and exchange unless the horizontal resolution of the cells in the model is sufficiently small. The effects of a dredged channel, or flow through a harbour entrance will not be resolved unless a cell size, typically less than five times the width of the feature of interest is utilised. With 'top-down' techniques the issue of resolution is less apparent. Many of the methods require as input the results of a 'bottom-up' model.

A common situation is the use of a 1D flow model. Here the number of cross-sections used to define the model may be an issue. There may only be a limited number of measured sections. However, to run the model it may be necessary to interpolate between these measured sections to provide the model with smaller reaches over which to perform its calculations. The interpolated data used within the model may be significantly different to that in nature. Such interpolations need to be compared with the known form of the estuary.

In cases where the predictive technique is to be applied many times, such as in a strategic study, it is worthwhile optimising the precise manner in which the tool is applied for computational efficiency.

The reliability of any validated predictive technique is only as good as the data available for calibration and validation. Where only limited data exist then the reliability of the technique must be questionable.

A combination of comprehensive field studies and appropriate models can enable short term, small scale change in morphology to be predicted to an accuracy of better than about 10% of the existing long term average annual rate, in the case of a change to an existing well documented regime (e.g. changes to rates of siltation, where the present rate of siltation is high and requires regular, frequent maintenance dredging). However, prediction of short term large scale rates of change is unlikely to be accurate to within a factor of better than two (i.e. 50% to 200%) if less data is available. If the system is complex, or the changes are longer term then the accuracy is likely to be less.

5.2 Examining change and variability

Sensitivity analysis

The predictive methods described in Chapter 4 provide a rigorous basis for the investigation of change and variability within an estuary system. Once the method has been set up and the calibration/validation established, the significance of small changes can be considered. This process is known as sensitivity testing. Analysis of the results of sensitivity testing can be used to add confidence to the conceptual model of an estuary system.

If a parameter in the model can vary by a factor of ten but the results of the method vary only by a factor of two, reasonable confidence in the predictions from the method may be expected. If on the other hand the results of the method vary by a factor of one hundred because of the uncertainty in the parameter then results of the method should be treated with less confidence.

Some parameters, such as viscosity, can reasonably be expected to remain fixed or uniform throughout the application of the method, others, such as an erosion threshold for a muddy sediment that might be associated with biological parameters, may vary over the area represented or may vary with time during the period of application.

Sensitivity testing may include consideration of the following parameters:

- bed friction
- sediment properties (grain size, bulk density, thresholds for erosion and deposition, settling velocity)
- regime relationship parameters

Scenario testing

Once a predictive tool has been calibrated for a particular situation, often in this case an instant in time, the tool can be used to explore the magnitude of changes associated with other previous known scenarios or events. Where an estuary demonstrates episodic changes, perhaps associated with storm events and the approximate morphological envelope within which the change occurs is known from a series of bathymetric records, 'bottom-up' models that can represent the processes occurring during the event can be used to explore the impact of different episodic forcing conditions[13].

Other scenarios that might be considered are:

- changes in tidal range,
- changes in fluvial flow,
- different mean water level,
- different wave conditions (direction, height, period),
- historical representations of bathymetry:

A predictive flow model might be calibrated for mean spring tide conditions. It could be employed to consider the energy distribution during the largest range spring tides or during a period of high freshwater flow. Alternatively the model could be re-run with exactly the same tidal forcing but with a historic bathymetry to determine the significance of changes in flow associated with a different morphology. 'Top-down' analysis of the differences between the results could then be employed to consider the significance of observed change. If the predictive process model suggested that currents are reduced over areas where the bed levels were seen to increase then the mechanisms for deposition might reasonably be inferred.

Another simple sensitivity test to undertake with any of the predictive methods is an increase in mean water level by 0.1m in the model. This test serves to demonstrate two things: the significance of a small amount of relative sea level rise on an otherwise static morphology and the significance of the accuracy of the bed levels represented in the model. If significant differences are predicted as a result of this test, for instance areas which were predicted to erode become areas where accretion is predicted, then considerable caution must be applied in making decisions based on the absolute values of the predictions.

5.3 Use of model outputs

Conceptual model

By employing a mix of techniques to explain documented changes within an estuary system, it is possible to develop a conceptual model of how the system functions. This conceptual model must be coherent and provide a self-consistent summary of how the estuary functions.

[13] For example, channel switching around Reeds Island, see Paper 7, Reference 4.

The conceptual model is more than a sediment budget because it also includes the concept of how the components within the sediment budget vary and interact[14]. The conceptual model that is developed must be able to provide a plausible explanation for the variety of issues that the estuary manager encounters such as:

- patterns of erosion and deposition
- dredging and disposal (including sand winning)
- changes to inter-tidal areas and levels
- marine import/export of sediment
- fluvial import of sediment
- migration of channels
- vessel operations

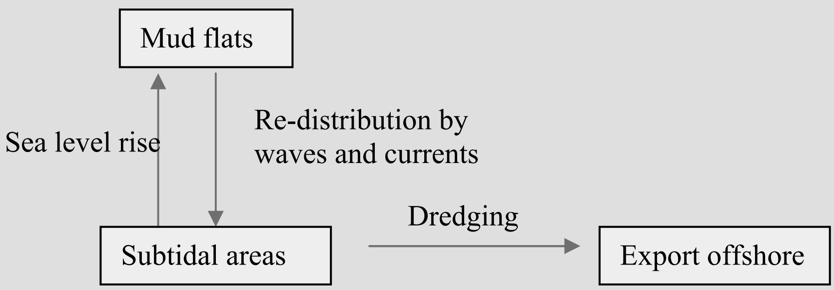
Note that not all of these issues can be adequately represented in the techniques described in Chapter 4.

Development of the conceptual model should utilise all available data for the estuary. Through this process it may become necessary to consider certain contradictory data sources. If the contradictions can not be reconciled, the data should be presented to demonstrate uncertainty in the observed functioning of the estuary. There are so few data available that to disregard any of them may be considered a shortfall in the study methodology.

The process of developing the conceptual model can be time consuming[15]. It requires synthesis of available data with the results of the different baseline predictions and sensitivity testing of the various techniques applied. The manner in which the conceptual model is presented will vary from one situation to another. In most cases the conceptual model will be a written description illustrated with results from the different techniques applied accompanied by schematic figures and flow diagrams. It is unlikely that the format of output available from a single technique will be suitable for fully describing the conceptual model.

An example conceptual model:

An estuary has been demonstrated to have no marine or fluvial input of sediment and therefore sediment transport results from a source within the estuary, (probably mud flats), that is re-distributed by tidal and wave energy on a regular basis. Salt marshes have been observed to be eroding horizontally and accreting vertically, (reducing in plan area), and mud flats steepening, all of which are consistent with sea level rise. Since there is no sediment input to the system the maintenance dredging (and disposal offshore) of material from navigation channels and berths may be resulting in net export of sediment from the estuary.



[14] For example of development of a conceptual model see Paper 5, Reference 4.
[15] The synthesis task, in some cases, will require as much effort as the data analysis and modelling.

'What if?' testing

Once a conceptual model has been developed, that model can be used to establish how the system will respond to a given change associated with a development or activity. In order to achieve this one or more of the methods used to develop the conceptual model will be rerun with a representation of the 'What if?' scenario. This may require setting up the detail of a new port development and dredged areas, it may require including a set-back scheme, it may be a case of raising mean sea level by 50cm. Certain 'What if?' scenarios will not be possible to represent in some of the available methods (see Section 4.9)

Often the estuary manager can pose questions concerning the relative merits of different options rather than ask for absolute predictions. The issue of accuracy is obviously significant when considering impact and the requirements for mitigation. If a flood defence strategy seeks to identify optimum sites for managed realignment, then predictive techniques can contribute significantly to this decision making – potentially providing good reasons why Option A is better than Option B or C. Alternatively, if the strategy requires accurate quantification of the rate of loss of saltmarsh throughout the system the use of tools would be different and the result is likely to have many qualifying statements attached.

On a 60km long estuary some aspects of the significance of positioning an upstream barrier across the estuary at three positions between 45km and 50km from the mouth might reasonably be expected to be predicted by a 'top-down' method. However, confidence in the results of the same method would be less if the significance of a barrage 10km, 30km and 50km from the mouth were tested, as the processes occurring at these different sites might vary considerably.

Where improved confidence is required, the use of a number of different techniques can help as in the case of the GEO II studies for the Humber Estuary (Reference 6). However, this again is more appropriate to situations where the relative merits of different options are being considered and a general understanding of the system is required rather than the prediction of absolute impact. If a number of different methods all gave rise to the same ranking of different options then reasonable confidence in decision making is achieved. If two different techniques give different predictions of an absolute impact (say patterns and rates of siltation) one is left with a degree of uncertainty which has to be moderated by efforts to determine which best represent the dominant processes.

In most cases predicting the morphological change in a form that is usable for making decisions requires further assumptions to be made.

If a technique predicts a volume of accretion or erosion then some assumptions about the pattern of distribution may need to be made. This may come down to an assumption of an average estuary wide amount of erosion or deposition. To convert this into a change in area will in turn require some assumptions about gradients of the bed in an estuary. If an inter-tidal area has an average slope of 1:100 between highest and lowest astronomical tide levels a vertical erosion of 10mm represents a horizontal movement of 1m on the slope. If the wetted perimeter of the inter-tidal area were 20km in length then the erosion would represent a loss of 2ha of inter-tidal area. Supposing the slope of inter-tidal is non-uniform and inter-tidal exposure was important (hectare hours) then the calculations become correspondingly more complex.

Presentation of results

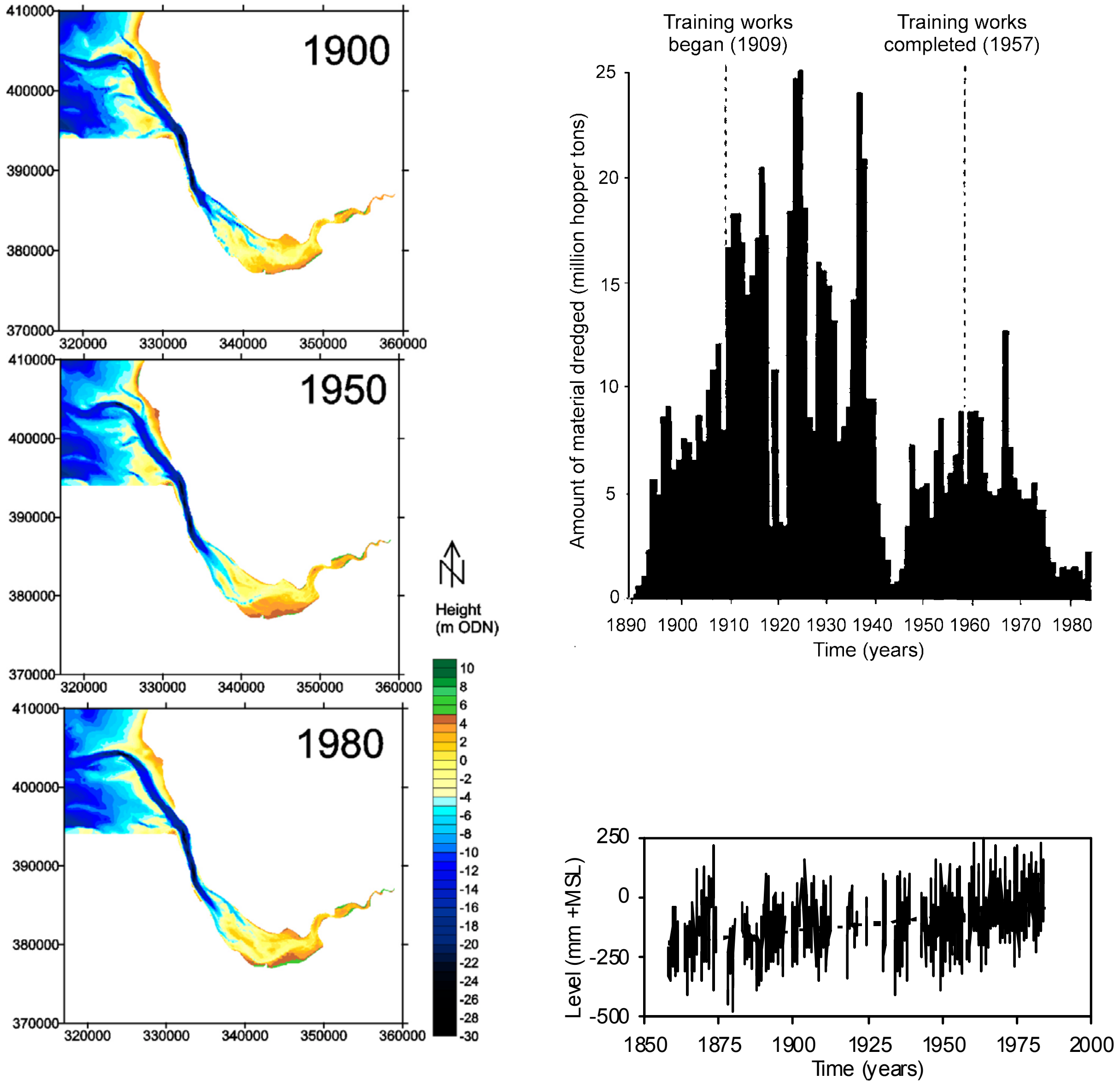
The critical issue in presenting results from the predictive techniques described in Chapter 4 is to adequately present the conceptual model of estuary functioning first and to use this as the basis for building the credibility of the results. Where a predictive technique is unable to reproduce observational evidence an explanation must be provided and the level of certainty in the results of the technique discussed. Inevitably, there will be some situations where the techniques appear to apply well and there will be situations where they do not. This does not necessarily prevent informed decisions from being made, provided some measure of the associated uncertainty in the results is taken into account.

The predictive techniques outlined in Chapter 4 will provide output in different formats. Whilst there are a variety of techniques that can be used to post-process data and insert data into other interfaces for presentation purposes, an important aspect of the different techniques is the nature of the raw output from the method. If a one-dimensional flow model lies at the heart of a hybrid model then it is impossible, without further parameterisation, for the output from that model to be processed, for example, to include spatial variability in the flow across the cross section. Simple algorithms can be applied to determine the flow distribution across the cross section but it will not be possible to demonstrate back eddies arising in the model such as could be produced from a depth-averaged two-dimensional flow model. A one dimensional model assumes the channel is straight or moderately sinuous. On a large spatial scale a one dimensional network system can represent some ‘2D’ features like flat/channel area and widening of main channels. Similarly a depth-averaged model will not reproduce the effects associated with density driven currents in the vertical.

The important factor to consider is whether the predictive tools being applied will provide the level of information required for making decisions as a direct output from the technique without the requirement to reprocess the results..

6. SUMMARY OF GUIDANCE

Chapter 6 provides a brief summary of the guidance contained in this report. The Guide has aimed to demonstrate the present recommended approach that can be adopted to investigate and predict morphological change in estuarine environments.



Bathymetric surveys of the Mersey Estuary and accompanying information on dredging activity and sea level rise during the period
(Source: Papers 14 and 15, Reference 4)

The ability to predict morphological change in an estuary environment is a critical input to many decisions concerning estuary management. Understanding morphological change and the factors that influence such change is an important element of the many different plans and initiatives for management strategies. Management strategies include flood defences and water and ecological resources as well as consideration of specific development and operational proposals.

This guide has aimed to summarise an effective and systematic approach that can be adopted for investigating and predicting morphological change in estuarine environments. In this chapter the key points of this guidance are summarised.

1. Estuary functioning can be considered as the processes within, and interactions between: hydrodynamics; sediment dynamics; morphology; water quality; ecology and human activities. Morphology is the arena within which other processes take place and therefore can be used as the common link. Consequently it is often at the centre of many of the management issues associated with the functioning of an estuary system.

2. Development issues can be strategic and estuary wide or can be specific localised developments. *Cumulative impacts* must be considered under the Habitats Directive.

3. A series of morphological questions have been identified (Box 3) which can be asked on a range of spatial and temporal scales. Scales of interest (Tables 1 and 2) cover operational (local area - months to years) to strategic (estuary wide – decades).

4. The starting point for an investigation is a detailed analysis of historical information relating to morphological change for the estuary of interest that is relevant to the nature of the project.

5. The next step in considering morphological change associated with a project is scoping of the likely effects of the project on estuary morphology, both as a direct impact and as impacts via the other process areas (hydrodynamics, sediment dynamics, water quality, ecology and human activities).

6. Further data requirements should be *self evident* following the historical analysis and scoping but will relate to forms of data from which morphological change can be inferred (Table 3) and data required to calibrate/validate the predictive methods used.

7. Selection of methods for considering any morphological change should include consideration of previous investigations into the estuary, precedents for use of methodology for other sites, the key morphological concerns for the estuary and design and operational issues associated with the project.

8. No single method has been identified which can adequately answer all questions over all spatial and temporal scales. The choice of scales of interest should be made in consultation with the appropriate regulators.

9. 'Bottom-up', 'top-down', and hybrid methods for prediction of change have been identified. 'Top-down' methods are most appropriate for long term, large scale issues, whilst 'bottom-up' models are likely to deliver useful information for design and operational issues but will generally require application of additional 'top-down' methods to deliver information concerning changes over longer timescales. A number of these hybrid approaches exist which combine aspects of both 'top-down' and 'bottom-up' methods.

10. In many cases application of more than one methods to address the same question will be helpful. This is most likely to be for complex strategic studies. The certainty in the answer comes from developing a credible understanding and conceptual model of the morphological processes within

the estuary. This understanding will be based on observational evidence. Use of more than one technique will not necessarily lead to greater certainty in the answers but is likely to lead to a better understanding of the estuary system and its functioning. The different methods build on the same observational evidence in different ways.

11. All of the methods are only as good as the data relating to morphological change that they are founded upon. This highlights the importance of the data collation and an appropriate level of field work.

12. It is rare for there to be adequate data for calibration and validation of morphological prediction methods. Because of this, the credibility of the methods used must be developed by building upon the understanding of the estuary functioning that can be developed through analysis of historical data. This will entail use of a variety of data sources. The quality of such data sources should be considered.

13. The selection of appropriate sensitivity tests to be performed with predictive tools is important. This helps to establish the level of uncertainty in the model itself and also how the outcomes may vary under a range of scenarios.

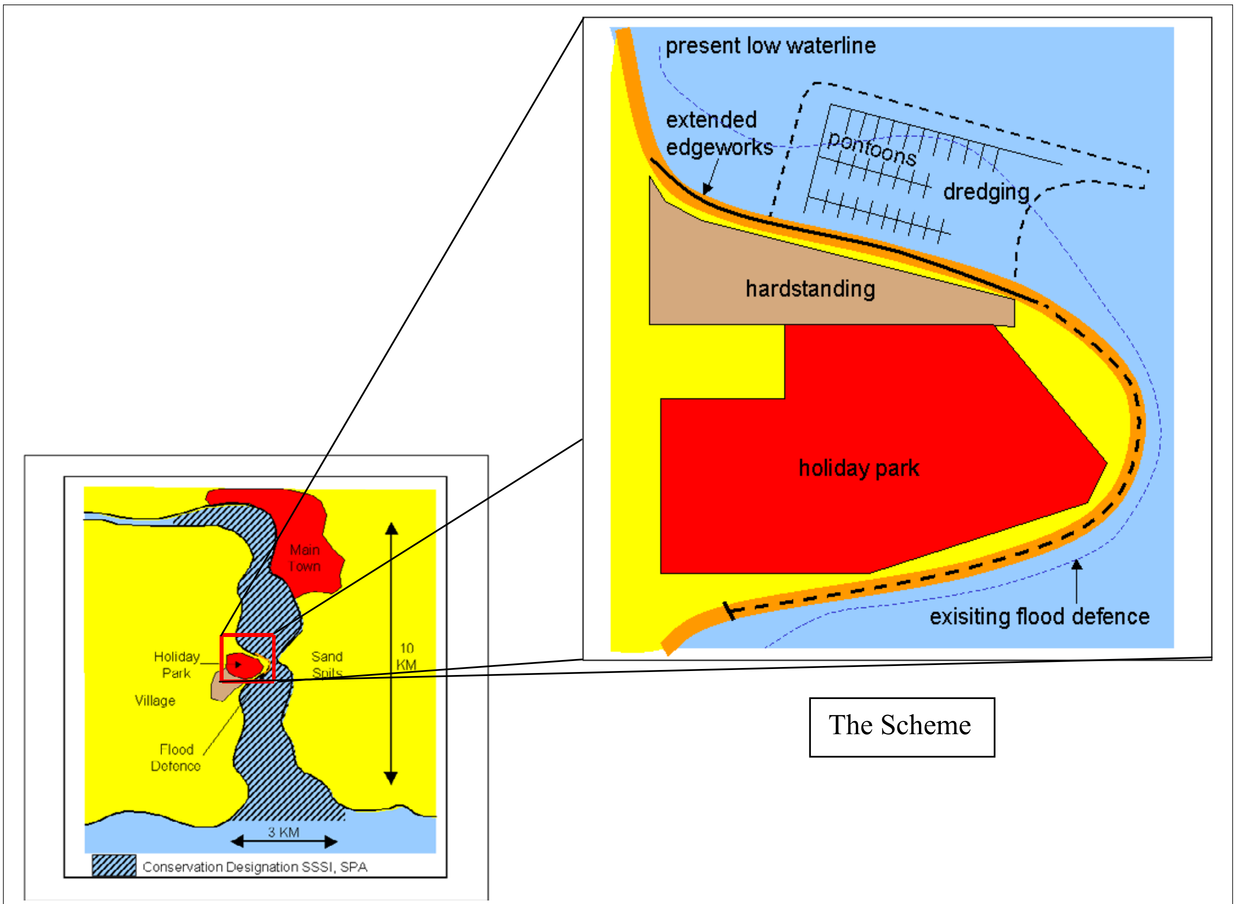
14. Evidence for calibration and validation of the tools used must be presented. Where the methods applied are unable to reproduce all features of the observational evidence then the differences must be clarified. Where more than one method has been applied intercomparison of results should be undertaken and differences examined.

15. On completion of the application of the methods a synthesis of the results integrating the historical data and the results of the different techniques should be undertaken in order to produce a credible analysis of baseline and predicted change and to develop a conceptual model of the estuary functioning.

16. In applying predictive methods to understand morphological change it is important to note that other predictive methods may be required, such as water quality modelling. If this is the case then ‘bottom-up’ process-based modelling can have duplicate uses.

7. WORKED EXAMPLE

The worked example that is described in this chapter has been selected to illustrate some of the issues outlined in the guide. No single example can demonstrate all aspects. In this example firstly the estuary is briefly described, then the guidance in this report is applied to a hypothetical project. Where assumptions are made the range of options associated with alternative assumptions are presented.



The Scheme

The Estuary

7.1 The Estuary

- The layout of the estuary is illustrated on the previous page. The estuary is relatively small, with the tidal limit some 20km from the mouth. The main feature of the estuary is that about 5km from the mouth the estuary is constrained by two sand spits. The tidal channel between these spits is relatively deep and flows are relatively high. Seaward of this point the channel is constrained to the western side of the estuary with the bulk of the estuary comprising an inter-tidal sandy area. Landwards of the spit the channel meanders northwards between sand flats. About 10km from the mouth the channel becomes more defined with relatively steep inter-tidal slopes with the foreshore comprising mixed sediments.

- The sand spit to the west has had flood defences constructed in recent years. The works comprise placement of rock. The reason for the defence work is to protect a holiday park which has developed on the spit.

- Within the inner estuary there are many moorings for small craft. Recreation is an important activity on the estuary and is significant for the economics of the area.

- The estuary is designated as an SPA for its important inter-tidal habitats which provide a feeding and breeding resource for many birds.

- There is a naturally maintained navigable channel for 15km of the estuary.

- There is a town about 10km from the mouth on the eastern side of the river. There are associated discharges from the town into the estuary.

- The estuary is subject to relatively short duration fluvial flood events because of the mountains upstream in the catchment.

- Sediment supply is both fluvial and marine but most sediment movement is associated with redistribution of sediment existing within the system.

- There have been no previous morphological studies undertaken for the estuary, although an Estuary Management Plan and a Catchment Management Plan exist.

7.2 The hypothetical scheme

- It is proposed to construct a dredged basin and approach channel in the lee of the western sand spit to enable pontoon berths for 70 vessels to be created.

- Adjacent to the dredged basin an area of hard standing and waterside facilities will be constructed.

- The existing flood defence will be extended around the spit to contain the marina and water side facilities.

7.3 Scoping

This guide is focused on provision of advice on matters associated with morphological prediction. In this section we discuss other issues such as conservation and water quality where there is a clear link to morphology. However, with any scheme of the type described in the previous section there are clearly numerous other issues that would have to be considered. Usually it is clear where the primary and secondary linkages between different process areas are. However, through the consultation process associated with environmental assessment any linkages that have not been considered are likely to be pointed out.

For example, the scheme proposed is for a 70 berth facility. For the conservation objectives of the area it may be important to consider whether the scheme is for 70 new vessels to come to the area or whether it is to reduce the number of moorings in the inner estuary by 70, with vessels being relocated to the new facility. This is clearly an important issue from the perspective of the local economy, and from the point of view of water quality and disturbance to wildlife. From a morphological point of view it is only likely to be important if vessel movements (propeller scour and boat wake) are important in maintaining the present form of the estuary.

In the following sections discussion of the stages of the investigations required are provided:

- Direct Issues (Section 7.4)
- Analysis of existing data (Section 7.5)
- Selection of methods and requirements for new data (Section 7.6)
- Development of conceptual model and selection of methods to use (Section 7.7)
- Scenario and 'What-if' testing (Section 7.8)

7.4 Direct Issues

The direct issues that can be identified from the proposed scheme and the description of the estuary fall under the following headings:

1. Capital dredging
2. Disposal of dredged material
3. Maintenance dredging
4. Dispersion of fine material
5. Changes to local hydrodynamic regime
6. Destablisation of existing morphology with estuary wide impacts
7. Potential for impact on estuary wide habitats
8. Mitigation for habitat loss
9. Cumulative impacts
10. Local flood defence scheme
11. Meandering Channel in Inner Estuary

Further detail is supplied under these numbered headings below:

1. Dredging – dredging creates an immediate morphological change to the estuary. The estuary will respond to the dredging through changes in form local to the dredging and possibly on a wider scale if the dredging destabilises the dynamic equilibrium of the sand spits.

2. Disposal – dredging is accompanied by a requirement for disposal. Dredging in shallow water is often undertaken using plant that most economically discharges material by a pipeline. Generating a requirement for a local disposal or placement operation.

   For any site which does not presently have a nearby MAFF licensed disposal site for material of a similar nature and quantity there can be significant issues. Many of these issues will be associated with the potential for morphological change associated with the disposal/beneficial use options.

3. Maintenance – For any scheme involving capital dredging there is likely to be a requirement in the future for subsequent maintenance dredging. Such dredging will prevent short term re-establishment of any previous equilibrium and will eventually become part of the future equilibrium that might be achieved at a site.

Consideration must be given to the manner in which maintenance dredging might be undertaken. Will it be by agitation techniques or will it require use of the site used for disposal of capital dredged material? Will future maintenance dredging represent removal of material from the estuary system to an offshore disposal site or will it be recycling of sediment within the estuary?

4. The short term effects of dredging and disposal in terms of loss of fines into the water column and increased suspended sediment concentrations may need to be considered, particularly if there are any sensitive fisheries nearby.

5. The works although minor in extent will cause changes to the local hydrodynamic regime. These changes will reflect in changes to the local morphology. This may be associated with changes in local wave conditions because of dredged areas and reflections from structures or it may be because of changes to the tidal flow patterns.

   Minor changes in hydrodynamics may cause more significant changes in water quality at some locations.

6. Because of the nearby sand spits in this estuary consideration must be given as to whether the proposed project has the potential to destabilise the spits with consequential estuary wide impacts. *This is an issue unique to this site. In many situations there is no such local feedback mechanism for small schemes and it would be reasonable to consider only the local and cumulative impacts of the scheme.*

7. The potential for large-scale change represents a risk to the existing make-up of the inter-tidal habitat of the estuary. Understanding the present day and historic distributions of saltmarsh and flats will be important in terms of setting a context in which to consider any potential impacts.

8. The scheme entails removal of a small area of inter-tidal habitat. It is therefore likely, given the SPA designation of the site that some form of mitigation will be required to offset the impact on the conservation status of the site. Consideration must be given to the morphological impact of any such scheme.

9. The estuary is an SPA, therefore it will be necessary to consider the potential for cumulative impact of the proposed development and other planned projects for the estuary.

10. The scheme is adjacent to an area which has had a local flood defence scheme constructed. In order to understand the potential for the scheme to impact with the functioning of that flood defence the history of change before and after construction of the flood defence should be considered.

11. The development is being constructed in an estuary which is known to have a meandering channel in its inner part. Whilst it may be impossible to develop a full understanding of the manner in which the channel migrates consideration of historical changes in the position of the channel is important since this will have a bearing on future maintenance of the basin and dredged approaches in addition to the potential for undermining and damage to structures.

In the remaining sections the same numbering system is adhered to relating to the issues identified in Section 7.4.

7.5 Analysis of existing data

Building on from the scoping exercise available data sources should be reviewed to identify where possible the basis for concern over particular issues. The comments below relate to the same numbering system as the previous section:

1. The volumes to be dredged should be established. The magnitude of naturally forced change should also be estimated. This will be possible if a number of historical surveys are available. The magnitude of change after a severe flood or storm event is less likely to be quantifiable.

2. A variety of data sources will need to be considered for identifying a disposal site. Consultation with MAFF and CEFAS will be required.

3. An estimate of future maintenance dredging requirements will be needed. In other estuary systems this might be based upon sedimentation rates at other nearby facilities. In this example evidence from natural changes in morphology and siltation will be required. Any evidence relating to reports of sediment accumulation (particularly rapid) is of relevance. This could include fouling of fishermen's gear to changes in the levels of inter-tidal flats on a seasonal basis.

4. Any measurements of background suspended sediment concentrations will be relevant as information against which to compare the impact of change.

5. Evidence of the magnitude of tidal currents, ebb and flood dominated channels and areas where wave action is severe/weak should be considered.

6. The history of the sand spits should be explored. In particular the basis for introducing the flood defence scheme and the evidence of change following introduction of the scheme should be documented.

   If the spits can be shown to highly stable through history and the impact of the flood defence scheme on the eastern spit minimal then there is a strong case for suggesting that no delicate equilibrium exists a between the two spits and consequently the risk of the development destabilising the spits and estuary might be considered negligible.

7. As for any estuary designated as an SPA for inter-tidal habitats the available information relating to change in areas of habitat type should be analysed.
   It is most likely that virtually no bathymetric data exists for the inter-tidal areas of this estuary.

   The estuary is small with no commercial port operation. However, there are likely to be some aerial photographs and possibly more recently CASI and LIDAR data. These sources could be explored through consultation with the Environment Agency.

8. The significance, in terms of habitat value, of the area of the inter-tidal to be removed because of the project needs to be established. Consideration of the value of other areas within or adjacent to the estuary should also be carried out.

9. Any other schemes or projects that will require consideration as cumulative impacts should be identified.

10. The history of the flood defence scheme and its construction should be reviewed. The methodologies and plant involved and the rates of construction may be important when it comes to considering the short term impacts of the proposed development.

11. The history of channel migration needs to be documented and the envelope within which the channel is known to have meandered identified.

In addition to the above the local Environment Agency and English Nature/Countryside Commission for Wales and any other relevant authorities should be consulted with regards to the proposed development. This will identify any specific morphological concerns for the estuary that the regulators are already aware of.

7.6 Selection of method and collection of new data

The selection of the method comes down to identifying which of the 11 issues identified above, and any further issues raised by interested parties, requires further investigation to resolve to a level at which an acceptable degree of confidence can be applied to the decision. In considering the selection of methods for resolving the issues, it is necessary to also consider what additional data may be required.

1. All of the 'top-down' equilibrium methods can be applied to this system. However, it will be necessary to provide some evidence for the assumption that the system is in a form of equilibrium. It is possible that the meandering channels govern the gross functioning of the estuary form. If this is the case less confidence is likely to be gained from equilibrium methods which include no representation of this process. Estuary wide 'bottom-up' modelling may be required to demonstrate the sensitivity of the system to changes in the meandering channels and subsequently the impact of the development on this process.

2. The requirements for study will depend upon MAFF, the Environment Agency and the Local Water Authority. It is possible that 'bottom-up' flow modelling and dispersion studies for the area of the disposal site and that modelling of the impact on water quality will be required.

3. As a minimum a desk based assessment of sedimentation in the dredged areas will be required. This may need collection of further field data relating to tidal currents, water levels, bed sediment type and suspended sediment concentrations.

4. If no data exists on suspended sediment concentrations in the areas of proposed dredging and disposal this data should be collected. 'Bottom-up' flow modelling and dispersion studies will be required to predict impact.

5. The potential for local change will require application of short-term 'bottom-up' models of flow and waves as a minimum with sediment transport modelling also being required if it appears particularly complex to assess the results of the hydrodynamic modelling. Setting up these models and calibrating and validating the flow models will require data.

6. Field data concerning the spits needs to be analysed. A variety of data source might be used. These could include: bathymetric charts, aerial photographs, CASI, LIDAR, archaeological data, ecological data. Information on fluvial flows and any water abstraction would be helpful.

7. See item 1 above.

8. Discussion of mitigation options with the relevant stakeholders will be required. Options include: creating new areas of inter-tidal by managed retreat or foreshore recharge; restoring area of inter-tidal that for some reason are below grade. The mitigation may need to consider the effects of both the capital project <u>and</u> subsequent maintenance dredging. If areas are identified that are suitable for works then further field investigation will be required at these locations. If 'bottom-up' methods have been established to address other issues they could be applied to investigate, design and optimise the mitigation scheme(s).

9. Cumulative effects of other schemes will need to be considered. This can be done by representing all proposed schemes and re-running the models used or it may be sufficient to argue, on a physical basis, that the impacts of the schemes are independent of one another and therefore the

cumulative effect can be established simply by adding the impacts of each scheme. If the schemes are some distance apart and relatively small this is likely to be acceptable. Where there is an obvious mechanism for interaction then a new simulation will be required. Sufficient data relating to the other schemes will need to be obtained. In some situations it may be necessary to consider the cumulative effect of further development at the site of the project if this is a possibility. In this case that might be a future expansion of the dredged basin or improvements to the navigation channels in the estuary.

10. It is likely that engineering design studies were carried out for the flood defence scheme. These should be sought. If they include methodologies for considering the effect of the development on the flood defence scheme these could be utilised. If they do not it may be necessary to consider the wave and flow conditions adjacent to the scheme with and without the development in place and determine whether there is likely to be an impact on the integrity of the defence.

11. See item 1 above.

7.7 Development of conceptual model and selection of methods to use

From the preceding sections it can be seen that this estuary is not a simple case. The meandering channel may be significant in the overall functioning of the estuary. It is possible that the estuary presently functions in three sections.

i) The outer estuary seawards of the spits perhaps being controlled by incident wave energy from offshore and the tidal discharge from the upstream estuary.
ii) The middle/inner estuary being dominated by the meandering of channels, perhaps controlled by high fluvial flows or local storm waves.
iii) The upper estuary is likely to be controlled by fluvial flows and large tides which help to maintain the channel.

An initial hypothesis for a conceptual model might include the following with the commentary in italics helping to confirm the issues and refine the conceptual model.

- An onshore/offshore exchange of sand with the outer estuary occurs due to wave conditions and fluvial/tidal flow
  Cross-shore profiles may help to demonstrate this.
- There is exchange of sediment between the outer and inner estuary.
  Comparison of historical surveys may help with this. Field measurements showing sand moving between the spits could also be useful.
- Redistribution of sediment within the inner estuary is related to local waves, large tides and fluvial events.
  Frequent observations before and after different events could help here, surveys, aerial photographs, photographs from higher ground.
- Muddy sediment from upstream of the town is washed out of the estuary during large tides and fluvial floods.
  Measurements of suspended sediment concentrations will be required to establish if this is correct.
- Channel meandering in the inner estuary is responsible for the present position of the spits. Is there a delicate balance with ongoing erosion? Or is it more robust with both spits being relatively stable?
  Analysis of historical data, possibly including short cores may help to build up a history of evolution of the spits. New field measurements to determine present rates of change will complement this but will not be sufficient information on its own.
- The upper channel is dominated by fluvial flow in winter (with erosion down to a stable bed) and by tidal flow in the summer (with corresponding accretion in the upper channel).
  Flow and bathymetric measurements in the upper channel will be required to establish this.

Depending upon the analysis of information associated with the meandering of the channels and the stability of the spits it may be possible to argue that expert geomorphological interpretation is sufficient to consider all aspects of this development. However, if there is inadequate data available it is likely that it will be necessary to resort to some 'bottom-up' modelling of tides and waves. It may be possible to then use desk based analysis to interpret sediment movement and morphological change. However, it may be necessary to consider application of 'bottom-up' modelling of sediment and even morphological updating.

If there appears to be some evidence of stability, 'top-down' techniques could be applied to consider the longer term evolution of the estuary. However, given the complexity of the site and the lack of existing users in the estuary it is unlikely that adequate data will exist to make such an approach worthwhile.

7.8 Scenario and 'What-if?' testing

In this case the main application of models will be to try and develop an understanding of how the system functions. Various scenario tests might be envisaged: effects of tides of different ranges, effects of local and offshore generated waves, effects of high fluvial discharge, consideration of evidence for stratification (perhaps pilot modelling with a 3D flow model), examination of the meandering channel in previously known positions.

Based on the results of this sensitivity testing the conceptual model can be refined and then the tests for the predictive model run determined. It should not be necessary to repeat all the scenario tests with the proposed development in place. If the conceptual model is robust it should be possible to identify a few tests to be undertaken with the development in place that will adequately provide a basis form which to draw conclusions about the scheme.

Depending upon the requirements of the stakeholders it may also be necessary to undertake tests with the same tools specifically to address their needs. These might include: dispersion of fines during construction and disposal; impact of mitigation schemes.

If there are no significant discharges to the estuary it is unlikely that it will be necessary to consider water quality the possibility of the requirements for a water quality study should be recognised. If the development were to house 70 new vessels then the potential for discharge from the new development might become an issue.

7.9 Summary

The example provided here has demonstrated that even a relatively modest scheme may require considerable investigation in order to satisfy the requirements of the present legislation. The particular case is complicated by presence of morphological forms that are relatively large scale within the estuary. The inclusion of meandering channels in the scheme provides an added complication that presently state-of-the-art 'bottom-up' predictive morphological models find difficult to address; especially where the channel switches course periodically. In such a situation resorting to data analysis and collection is a route to build confidence in the conceptual model. Realistically analysis of existing data is unlikely to yield the required results because of the likelihood of only limited data being available. Accordingly data collection will be required. It may be required over a timescale of many years to capture a channel switching event and before the effects of large storms and floods on the system can be determined.

For this scheme providing the decision makers with all the answers relating to morphology will take time. The developer will certainly need to establish a good dialogue with all stakeholders.

Irrespective of the outcome of the morphological studies other factors not considered here may prevail. There could be fishery concerns, conservation interests, economic drivers and political will that simply dominate the proceedings. The outline above provides the basis for a well argued analysis of the potential for the proposed development impacting the morphological functioning of the estuary.

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Appendix 1:
A brief summary of techniques available for prediction of water quality within estuarine systems

Appendix 1: A brief summary of techniques available for prediction of water quality within estuarine systems

Natural processes, discharges from anthropogenic processes and the presence of man-made compounds in non-target areas, such as estuaries, will impact on the existing water quality. The change in water quality is important due to both the impact on natural ecological processes but also due to the impact on man's use of these environments. Reductions in fish stocks, contamination of shell fisheries, reductions in wildlife levels and the quality of associated resources, such as surrounding waters and vegetation, are becoming recognised as a result of man's influence. In the context of estuarine morphology, the major affect of water quality is related to their impact on sediment properties and key biota. These impacts affect the ecological system, thereby affecting the physical system with consequent changes to sediment transport. A main question raised and discussed in the initial scoping study with respect to the impact of contaminant and pollutants was "can contaminants present at environmental concentrations affect estuarine communities to the extent that subsequent changes result in a negative impact on the estuarine ecosystem so as, in turn, to affect the estuarine morphology?" (Reference 1). When considering water quality more generally the question "What affect will water quality have on the morphology of an estuary?" is important. While the "How will morphological change affect water quality?" is of direct interest from a legislative viewpoint and when considering the management of estuaries.

This appendix gives a brief summary and overview on the techniques available for prediction of water quality within UK estuarine systems. Consideration is given to the key water quality issues, relevant variables and the processes that contribute to and are impacted by water quality. Water quality prediction approaches are presented. The importance of sound and sufficient data for model calibration and validation is discussed. The challenge for designing a modelling system that links long-term morphological change modelling to water quality models is considered.

A1.1 Introduction

Estuaries are biologically productive bodies of water with a wide number of uses (fisheries, shell fisheries, recreational, industrial, shipping). The various uses of an estuary place conflicting demands and burdens on water quality. Predictive models and techniques serve as an aid in assessing these conflicting demands and in developing protective management strategies. Water quality concerns of importance in UK estuaries include the problems associated with nutrients, urban waste water (concerns with gross organic contamination and nutrients), contaminant inputs (point and diffuse; pipes, groundwater, ships, etc) and contaminants stored within the system. Water quality covers a wide range of issues from local reductions in parameters like dissolved oxygen and local changes in pH and salinity resulting from point discharges to the impact and distribution of toxic contaminants such as tributyltin. A wide range of legislation exists in the UK for the management of water quality and is summarised in a previous report from this study (Reference 2).

The interactions between water quality and morphology involve a complex interplay of processes and there are a large number of parameters of interest. This scientific area includes some uncertainty when predictions are being undertaken. It is also important to be mindful that a change in the quantity of one parameter can then result in subsequent changes to quantities of other parameters with feed back mechanisms and interactions. Water quality models are aimed at representing the mechanisms and processes of importance to predicting changes in water quality occurring in estuaries generally from natural processes or as a result of some human activity. Different models will represent estuarine processes to different levels of complexity. Models require data from field surveys to calibrate them and involve inputting description of certain parameters and processes. Not all models incorporate all water quality parameters.

A 1.2 Water quality mechanisms and processes in estuaries
The mechanisms and processes controlling water quality in estuaries are outlined below and include both natural and anthropogenic processes.

Natural;

- Fluvial flow and freshwater runoff
- Tidal flow and tidal propagation
- Sediment supply
- Change in wave climate
- Bioturbation
- Biostabilisation
- Atmospheric deposition

Direct anthropogenic influences;

- Point source industrial and sewage wastewater discharges
- Non point source agricultural run-off
- Urban/industrial/port run-off
- Dredging
- Atmospheric deposition
- Accidents; Oil spills, collisions
- Shipping/boating activities
- Reclamations
- Construction of structures such as barrages

At one level an estuary can be regarded as a mixing zone through which a river discharges to the sea. A number of mixing mechanisms occur and change with time. The degree of mixing is a function of river flows, tidal action, wind and other factors. The differences between the chemical characteristics of the freshwater and seawater inflows can affect the relative densities of the water layers and the resulting degree of mixing. Contaminants and nutrients will be distributed within the water column and processes occurring at the sediment/water interface, the freshwater/ salinity interface (turbidity maximum zone) and the atmosphere/water interface will be important. Seasonal processes such as algal blooms will also occur. Water quality in estuaries therefore normally exhibits marked spatial and temporal variations.

In turn the influence of morphology on an estuary, by dictating water flow patterns, will exert a considerable influence on the hydrodynamics in an estuary and therefore on the dispersion and dilution of contaminants and nutrients. The prediction of the impact on water quality arising from both domestic and industrial waste water discharges is of particular interest in estuarine management.

Sediment behaviour and sediment water exchange also play a major role in controlling estuarine water quality.

As the morphology, hydrodynamics and sediment regime of an estuary changes, parameters like the position and intensity of the turbidity maximum position and residence time of particles in the estuary will all change which in turn affect contaminant transport.

The morphology of an estuary affects the dilution and dispersion of discharges and storage of particle reactive contaminants. Historically deposited contaminated sediments that are presently buried can be exposed and redistributed due to erosion induced by shifts in estuarine morphology arising from natural and man-made influences. Release of such contaminants can impact water quality and ecology.

Biogeochemical interactions are an integral part of the functioning of an estuarine ecosystem. Estuarine ecosystems are dependent on a supply of the major biogeochemically active elements and are affected by the surrounding water quality.

Nutrient loading due to inputs from agriculture and from urban wastewater is not only a major water quality concern but may be a significant factor influencing the development of estuary morphology. Nutrients play a major role in ecological processes. The effect of changing the supply of nutrients on morphology, as has happened in many estuaries, is poorly understood but could have a significant impact on the ecological processes that both stabilise and destabilise sediments. A review of these processes is given in the initial Scoping Study report (Reference 1).

Phosphates which are removed from the water column onto sediments in estuarine low salinity regions may be stored temporarily in inter-tidal flats. Once transported into higher salinity/low phosphate coastal zones these species can be desorbed and released into the water column. Sediments act as a store for phosphate where the extent of phosphate removal depends on sediment accumulation.

Nitrate is removed from the water by uptake during primary production or it may be utilised by bacteria in inter-tidal areas (denitrification). Sediments will act as a nitrogen modifier and sink with the extent of nitrogen removal depending on estuary shape (morphology) and positioning of inter-tidal areas with respect to sources (nitrate concentration). Silicon is also removed from the water column by diatom primary production however, suspended particulate matter levels modulate the retention of silicon via light availability to diatoms.

Estuarine morphology, particularly the location, extent and nature of wetlands and inter-tidal areas, is a critical factor determining the nutrient budget of estuaries. Morphological changes do not only affect inter-tidal areas. For example, an improved light regime with increased storage will promote water column utilisation of nutrients and possible stabilisation of sediments by algal growth.

Water quality is also strongly influenced by local discharges/ inputs and underlying sediment quality. Contaminants may be several orders of magnitude higher in sediments than in the water column. Upon release via resuspension/disturbance the impact on water quality will depend on how contaminants are transported and associated speciation effects. Accumulation and decay of organic matter in sediments can result in a significant sediment oxygen demand. Disturbance of organic rich sediments can cause significant local reductions in dissolved oxygen due to the chemical oxygen demand of the by products of decomposition present in the pore water.

Feedback mechanisms on water quality and morphology can occur. For example organic micro-pollutants can condition particle surfaces thereby affecting deposition and storage of contaminants. Increased contaminants can compromise benthic organisms and their stabilising effects on sediment. For example, tributyl tin and polychlorinated biphenyls can impact on invertebrate populations which not only modify sediments but, through the action of bioturbation, effect oxygen transport into sediments and denitrification processes.

The main parameters of importance to the use and functioning of estuaries which may be included in a water quality model and which are influenced by the processes discussed above, include;

For water;

- Dissolved oxygen
- Biochemical oxygen demand
- Chemical oxygen demand
- Suspended solids
- Temperature
- Salinity

- Ph
- Organic matter content (doc)
- Nutrients (carbon, nitrogen, phosphorus and silicon)
- Chlorophyll-*a*
- Ammonia (ammonium)
- Sulphide
- Metals (copper, cadmium, mercury, zinc etc)
- Organometals (tributyl tin)
- Organic contaminants (hydrocarbon oils, herbicides, polyaromatic hydrocarbons etc)
- E. Coli
- Microbial population

For sediment;

- Pore water chemistry
- Particle size distribution
- Organic matter content
- Redox
- Ph
- Temperature
- Contaminants
- Microbial population
- Macrofauna (suspension feeders and bioturbators)
- Nutrients
- Metals (copper, cadmium, mercury, zinc etc)
- Organometals (tributyl tin)
- Organic contaminants (hydrocarbon oils, pesticides, polyaromatic hydrocarbons etc)

A1.3 Approaches to modelling water quality
A number of techniques for water quality predictions exist.

Initially, for water quality modelling, data is needed to set up the required hydrodynamic processes. Data on the quantities/concentrations of individual parameters being investigated is also needed over suitable time scales so that models can be calibrated and validated for a given use. In addition, models are based on empirical information and relationships and so data is required to calibrate the model with respect to empirical relationships if values are not well known. The data requirements for a water quality model are likely to be more involved than for a hydrodynamic model.

Models have widely different spatial and temporal scales, reflecting the different goals for which they were originally developed. The spatial range varies from regional and estuarine scale with a spatial resolution (kilometres) to resolve steep concentration gradients, to no spatial variability (e.g. chemical equilibrium model). Temporal variability also covers a range from no temporal variability (i.e. steady state) to temporal resolution within a tidal cycle.

The time resolution of the external forcings also affects the temporal variability of the models. Typically water quality models need to include hydrodynamic processes like tidal forcing, advection/ diffusion, sediment transport, fluvial and boundary inputs. The temporal scale of this forcing ranges from long-term average conditions, to actual meteorological (hourly, daily) data.

Estuary water quality models are developed to address a number of generic and more specific issues including the following:

- Dispersion and dilution (dissolved species) so that environmental concentrations can be determined and compared against regulated standards or even potentially linked to impacts.
- Impact of remedial measures.
- Impact of changes in hydrodynamics (regulating freshwater flow, dredging, construction works, etc)
- Particle reactive contaminant transport and fate.
- Impact of development (e.g. Dredging) on water quality parameters(e.g. Suspended particulate matter, dissolved oxygen).
- Biological parameters (production, nutrient utilisation, dissolved oxygen).
- Understanding of dominant processes within a system.

Existing water quality models have different focuses and strengths in terms of physical (hydrodynamics), chemical and biological/ecological processes. In terms of hydrodynamics, some models have a detailed three-dimensional computations of flow while others are two- dimensional (depth averaged). Some have true meteorological forcings of short time scales, while some use monthly average conditions, or are steady state (no time variation). A critique of 1-, 2- and 3-D estuarine models of the Mersey, indicating their capabilities and limitations for predicting tidal propagation, salinity and sediment intrusion is included in the modelling report (Reference 3).

For the processes relevant to water quality, models also incorporate very different degrees of complexity. Models range from chemically simple models where the contaminants are treated as conservative substances which are transported through the system according to the large scale flow pattern. The more chemically complex models include a wide range of processes and detailed reactions including contaminant adsorption/ desorption, particle sedimentation and resuspension, species oxidation and reduction reactions and volatilisation and degradation.

Predictive time scales of water quality are limited and can not be directly coupled to long term predictive morphological models. They will need to be applied separately to an already changed morphology. Also they may have different resolution.

Water quality models may be complex coupled transport/ biological models or combined to hydrodynamic models. Simpler models for water quality prediction exist which could be applied to morphological models in the future.

The water quality models of interest in the UK which deal with nutrient/primary production and contaminant transport include:

- ECOS
- MIKE 11, MIKE 21
- CSERAM
- TELEMAC
- SULIS
- QUESTS
- DELFT 3D
- ISIS
- POLEST
- COHERENS from MUMM
- DIVAST
- SCAMP (partitioning/ speciation model)
- Partitioning models
- others (LOIS modelling, conceptual models e.g. Holocene nutrient behaviour in the Humber, biogeochemical modelling in the Wash).

In relatively shallow high tidal range estuaries, depth-averaged one-dimensional and two-dimensional (in plan) models are usually adequate whilst deeper, lower tidal range estuaries usually require two-dimensional (in the vertical) or three-dimensional models in order to represent the gravitational circulation (landward at the bed and seaward at the surface) which controls the position of the turbidity maximum and the dispersal of pollutants. Gravitational circulation can be a significant problem, even in the absence of stratification, being driven by the longitudinal salinity gradient and the mean sea level slope.

Most water quality models (e.g. MIKE-11, ISIS, TELEMAC, QUESTS, DELFT 3D) are designed to look at the short to medium term i.e. weeks to months. A number of models have been developed specifically to look at longer term effects. These include NORPOL (a 3D model of heavy metals in the North Sea). SULIS (a 3D model or 2DV water quality model). CSERAM a 2D model for medium term transport of radionuclides in the Irish Sea.

A1.4 Selection and validation of tools
The choice of model to use for a particular estuary will depend on the questions to be answered and the following:

- The need to simulate lateral variation in either hydrodynamics or water quality.
- The need to simulate vertical variation (as a result of stratification or gravitational availability in a deep estuary).
- The range of water quality variables to be simulated (oxygen and nutrient balance, particulate contaminants, toxic pollutants etc).
- The available time scale for study.
- Available data.
- Scale of works in relation to the estuary system.

Selecting the spatial and temporal for a water quality model to be used in a particular study should be based on the resolution of the physical, biological and chemical processes that control the system rather than the models output's scale.

Estuaries are quite irregular and irregularities tend to trap contaminants in backwater areas as tides move in and out (a feature of models but not necessarily reality). Few water quality models can incorporate all aspects of water quality modelling i.e. inter-tidal areas, sediment transport, biology, contaminant transport.

Some models will be better adapted to looking at impacts of, for example, new structures, dredging, sea level rise, one-off flood, discharge (impacts inherently different). The model used needs to be matched to the time scale of impact required after these impacts (tide, days, weeks) and also criteria interested, or questions which need to be answered. For example the physics, nutrients, contaminants, inter-tidal erosion, dissolved oxygen/ suspended particulate matter, dispersion, bioavailability.

For calibration of contaminant transport many water quality models strive to reproduce salinity and pollutant concentration trends in the estuary. These property/salinity plots can give indications of controlling processes in various areas. However, at present sediment transport models may not be good enough to trace implicitly contaminant transport upon release via sediment erosion.

A1.5 Linkages with morphodynamic tools
A paper designed to present the linkages from the physical process/ morphological modelling to the requirements of water quality and ecology can be found in the modelling report (Reference 3). The issues relevant to modelling water quality are discussed briefly here.

Water quality models are used primarily to investigate processes as a result of legislation and regulations or to improve scientific understanding. The present use of water quality models, both in consultancy and academia, involves answering questions which are not related to predicting long term changes in estuary morphology.

Process based water quality models are not capable of directly simulating the impacts of long time (decades) scale changes induced by factors such as the effect of sea level rise. They have to be used in a series of steps. Water quality models can be applied either to outputs of top-down or hybrid models (morphology, hydrodynamics, SPM concentrations and transport) but the success and outputs of these models have yet to be seen or need to be applied to different set-up scenarios. Testing of sensitivity on these new scenarios is then possible.

For shorter-term/immediate impacts such as structure building, dredging impact and flow events the water quality modules can probably fit directly onto the hydrodynamic, sediment transport models in existence and several that include water quality and chemistry already exist.

With some models which predict processes over inter-tidal areas it may be possible to adapt them for the assessment of nutrient removal and then test the sensitivity of a system with respect to inter-tidal area positioning and managed realignment strategies for example.

There are two approaches for coupling flow and water quality models. The direct approach, where the flow and water quality simulations proceed concurrently and the hydrodynamic and water quality algorithms are contained within the same computer code and run simultaneously. The indirect approach where the flow simulation is run separately and simulations used as input to a water quality model. There are advantages and disadvantages to both which primarily result from tradeoffs between computer storage requirements and computational time. Generally, the direct linkage approach requires increased computational time while the indirect linkage method may require quite large computer storage.

When linking it is important to consider that there are different time scales associated with circulation and water quality variations and the assumptions on which many water quality models are based. For example, many hydrophobic and particulate reactive contaminants will strongly sorb onto sediments. Most toxicant models assume that this sorption process is at equilibrium (using partition coefficient Kd to describe this). Sorption kinetics are assumed to be fast in relation to the time steps of the water quality model so that an equilibrium condition is achieved during a time step. The assumption of equilibrium sorption may be reasonable when using time steps of days or longer but probably is not appropriate for time steps on the order of seconds to minutes. There is, therefore, problems modelling changes to this resolution. Additionally there is the problem of reconciling and modelling processes which change on timescales which are different from morphological change.

Most water quality modelling for contaminants at present is not coupled to sediment transport and contaminant uptake, however, CSERAM is one exception to this. For many contaminants, which have the potential to affect water quality and ecological functioning, the transport of the sediments is of primary importance in determining contaminants fate and distribution throughout an estuary. Presently sediment transport models may not be accurate enough for determining sites of erosion/deposition and sediment movement around the estuary. Present models force contaminant concentrations using salinity, SPM, pH relationships to reproduce property/salinity plots to give insight into processes affecting contaminant within the estuary.

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Appendix 2:
A brief summary of techniques available for prediction of ecology within estuarine systems

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A brief summary of techniques available for prediction of ecology within estuarine systems

Estuaries are physically and chemically demanding environments which support a range of resilient biological communities and habitats. However, while the organisms which make up a habitat show a tenacious grip on their particular niches it is not known to what extent the biota create, rather than simply occupy, their niches. In the initial scoping study the question "is the role of the ecosystem of primary importance in the morphological development of estuarine systems or only of secondary importance in modifying certain key properties?" was asked (Reference 1). This previous review covers those aspects of the function and behaviour of estuarine organisms that have the potential to make a significant impact on the morphological development of estuaries and concentrates on the affect of ecology on sediment stability. In addition, when considering ecology and the morphological development of an estuary the question "How will birds affect morphological change" is important. While the question of "How will morphological change, with its subsequent effect on vegetation and invertebrates, affect the numbers of birds?" is a direct interest from a legislative viewpoint and for the management and conservation of estuaries.

This appendix gives a brief summary and overview on the techniques available for predicting ecology and biological processes in estuaries. Consideration is given to the key ecological issues, relevant variables and the processes that contribute to and are impacted by the ecology of an estuary. Prediction approaches for estuarine ecology are presented. The importance of sound and sufficient data for model calibration and validation is raised. Some examples of possible linkages with morphological predictive tools are given which can be used to improve our understanding and prediction of long-term morphological changes, whether they are as a result of natural processes or due to human induced perturbations to the system.

A2.1 Introduction

Estuaries are biologically productive bodies of water where the ecology is not only of value to man as a resource (e.g. fisheries and shell fisheries) but also many estuarine habitats and species are of recognised conservation value. Maintaining these environments and estuarine biodiversity is important because of legislative commitments but is also important since the ecology will have an influence on the estuary morphology.

It is known that the biota in an estuary play a vital role in the hydrodynamic and sedimentation processes and are therefore an important influence on estuary morphology. Significant ecological modifiers occur at spatial scales from macro to micro and include microorganisms, microalgae, higher plants and surface living and burrowing animals and birds (Reference 1).

It is also known that the biological processes and their subsequent impacts on morphology will fluctuate seasonally. For example, most birds are in UK estuaries from September through to April, with many fewer in summer. Birds can affect sediment stability in three ways: (i) By consuming, and thus reducing the abundance of, the vegetation and invertebates that themselves have an effect on stability. Herbivorous birds regularly eat out all the surface fronds of *Zostera*, for example; invertebrate consumers (waders and ducks) regularly eat 40-60% of the standing crop biomass present in autumn. (ii) By changing the behaviour of the prey. Surface-active invertebrates, such as *Corophium* which comes to the surface to forage - may do so less often when birds arrive, as an anti-predator defence. By consuming less surface diatoms etc, they may then have less affect on stability. (iii) The birds own paddlings, bill-snuffling, pecking and probing when feeding may physically disturb the sediments. Imagine the surface area roughed-up by 1000 shelduck feeding for eight hours over an exposure period.

Most studies on the impact of ecological processes on estuary morphology involve small scale influences of the ecology on the sediment movement and stabilisation. For example, sea grass meadows and mussel beds have a major impact in reducing current velocities at sediment surfaces, thus creating conditions of sedimentation. A number of studies and predictive models are developed for predicting the effect that forecast morphological changes in estuaries would have on the local and World abundance of the waders and wildfowl. These predictive models are based around the need to understand the impact of changes, such as developments causing subsequent habitat loss, on bird populations and species diversity as this is the focus of more recent legislation and policy. Although in their early phase of development, it will not be long before these models can be parameterised for one or more species in a single site or for single species in many sites throughout the entire non-breeding range. Ecological modelling is quite advanced for some terrestrial ecosystems and some of these methodologies and concepts may be applicable to estuarine ecological modelling.

The morphology of an estuary depends on the hydrodynamics, underlying geology, sediment supply and properties, ecology and water quality. Hydrodynamics, sediment properties and water quality affect the ecology present at a site. In addition, feedback mechanisms will occur whereby the ecology will in turn influence the hydrodynamics, sediment properties and water quality.

The ecology (habitats and selected species) in estuaries are managed to an extent through legislation and regulations. Legislation for Environmental Impact Assessment (EIA) and the requirement for dredged material disposal licences are also of importance and requires that the techniques used for predicting the influence of ecology on morphology are improved. An overview of the existing legislation in the UK that potentially has implications with regard to morphological change within estuary systems is given in a previous report as part of the EMPHASYS project.

A2.2 Ecological processes in estuaries

Biological activity will influence the changing shape of an estuary by modifying the stability of the sediments, the nature of the sediment/water interface and the impact of water movement on the sediment surface. There is strong evidence that the ecology of an estuary acts as a significant modifier of sediment properties. The biota play a fundamental role in the supply, retention, stabilisation, and the erosion of sedimentary material. However, little is quantitatively known about the feedback of the biological and ecological processes on the morphology. Data may exist for specific processes or sites but the applicability of information to a wider scale or across sites is uncertain.

Habitats, such as salt marshes and mud flats, are an integral part of temperate estuarine morphology. Habitats encompass a wide range of species all contributing to the ecological activity of the surrounding estuary. Habitats and selected species are therefore of importance to the morphology of an estuary and with respect to regulations and legislation.

Habitats and species of interest include:

- Salt marshes
- Mud flats
- Eel grass beds
- Sand/ shingle banks
- Saline lagoons
- Sheltered muddy gravels (inter-tidal)
- Micro-organisms
- Mussel beds
- Fisheries and shell fisheries
- Birds
- Marine mammals

The physical and biogeochemical mechanisms and processes within estuaries which are important in determining the ecology and habitat quality are outlined below and include both natural and anthropogenic influences:

Natural

- Sea level rise
- Change in wave climate
- Temperature
- Salinity
- Suspended particulate matter (SPM)
- Geological constraints
- Fluvial flow
- Sediment supply
- Ecological succession
- Physical processes (tidal propagation etc)
- Freshwater run-off
- Bioturbation
- Birds
- Biostabilisation
- Biogeochemical processes

Direct anthropogenic influences

- Impacts from man's activities (construction, shipping, recreation, pollution etc)
- Habitat creation schemes

In addition, the ecological models will involve biological processes to predict population sizes in the forecast morphological environments. Models involved in predicting species populations may include processes such as:

- Foraging efficiency
- Predation

and which predict in the birds the rate of:

- Emigration
- Mortality

And thus either local or global population sizes in forecast new morphological environments.

Indicators for the functioning and possibly quality of an ecological system may include:

- Species density
- Species biomass
- Survival rate
- Body condition
- Growth rate
- Fecundity
- Biodiversity

Since the processes and the ecology are occurring on a variety of temporal and spatial scales, it is important to specify the spatial and temporal scale which any predictive technique addresses. For example:

What are the time-scales to be considered?

- Sea level rise (centuries)
- Bed level changes (decades)
- Sediment composition (months/years)
- Human intervention (years)
- Weather (days)
- Climate (years/ decades)
- Hydrodynamics (hours-days)
- Population dynamics of species (years)

- Succession of vegetation (years/decades)
- Migration patterns (months)

What are the spatial scales that should be considered?
- Long term morphology (estuary scale)
- Short term morphology/hydrodynamics (mud flat scale)
- Benthos (sub mud flat scale)
- Birds/fish/mammals (sub mud flats scale and estuary wide spatial distribution habitats)
- Human interventions (all scales)

A2.3 Approaches to modelling ecological processes
Ecological models of use for predicting estuarine morphology generally address the following:

- The influence of biota on sediment properties
- Microbial processes in sediments
- The toxicity of contaminants
- Bird population size

Models may be:
- Based only on empirical relationships between environmental factors (such as shore level) and the biological determinand (such as invertebrate abundance), and are often of the regression type.
- Dynamics models based on the mechanisms and processes thought to determine abundance

It will be important to be able to predict distribution, species composition and densities (biomass) of species from given abiotic conditions (sediment type, drainage, tidal inundation, current velocity, wave energy, depth, salinity).

However, it has been reported that there is a weak relationship between abiotic factors and species biomass, so further research to improve model predictions is required.

Predictive systems need to address how does the biology interact with morphology and hydrodynamics (vegetation, roughness, siltation, stabilisation).

Within the consortium team ecological predictive techniques of interest include:

- DELFT Eco-morphology methodology/approach, where biological indices are linked to changes in environmental conditions and abiotic factors (empirical data driven models).
- 'NICHE' type model, in which the effect of changes in shore-level, salinity and sediment particle size on invertebrate biomass densities are predicted using regression-type models.
- PML BIOTIDE model of accretion and erosion of inter-tidal mud flats and salt marshes, in response to physical factors (current velocity, tidal height, offshore, SPM) and biotic factors (bioturbation by *Macoma* and biostabilisation by microphytobenthos).
- ITE single-site Oystercatcher and multi-site Brent goose behaviour-based population models; models based on game theory, the choices made by one competing individual as to where to feed over a low tide period are contingent on those made by its competitors.
- models based on game theory, the choices made by one competing individual as to where to feed over a low tide period are contingent on those made by its competitors.
- "carrying capacity" concept, the application and interpretation of this term needs to be carefully undertaken.
- BIRD-POP. Designed to predict the effects on bird populations arising from any predicted changes in invertebrate abundance and exposure time of the inter-tidal flats.

When developing and using predictive models it is important to recognise that the loss in quantity of a habitat, for example resulting from a development such as a reclamation, may not be a good indication of the impact on the ecology, biodiversity or a selected bird species. The quality of the habitat will also be important. The quality of the habitat for birds depends largely on the abundance of their food species (vegetation and invertebrates). The abundance of these following morphological change can be predicted from NICHE-type models. The effect the predicted changes in food abundance have on bird numbers is then predicted from the ITE-type behaviour-based population models.

The scientific understanding of the influence of a perturbation on individual species and perhaps subsequent impacts on populations is complex. Also, if a population is wiped out the importance of that on the functioning of the ecosystem, and of interest here, the changes to estuary morphology are not presently possible to predict. The direct and indirect impact of the ecological processes on sediment properties is only recently being realised. The processes involved, feedback mechanisms and implications are not well understood. Methodologies have to be based on a generic approach using site specific data.

Large data bases (in both space and time) are needed for these models. An important issue in using models developed for one site at another site will be to determine if they are still valid.

At one extreme, shorebird models deal with a single wintering season. At the other, they deal with many sites over many seasons. The multi-site and long-term models enable better representation of disadvantaged birds moving to other estuaries where they might do better, and allow the long-term population consequences of estuary morphological change, and of the birds' responses to it, to be forecast.

The RIKZ are undertaking a study (Zeekennis Project) using information and data from the Western Scheldt estuary. Presently they use a range of models that describe and predict the physical (currents, morphology, sediment composition) and chemical characteristics (oxygen, nutrients, pesticides). Using these results, predictions on biological effects are made using a number of NICHE-type models based on the outcome of such modelling exercises and a range of habitat modelling techniques.

As a part of their study they will produce a report which will discuss hydrological, morphological and ecological models available to RIKZ within the context of scale and problems associated with scale-up. Ultimately their project should lead to a better understanding of the possibilities and limitations of making predictions on benthic macrofauna and birds at estuary scale.

A2.4 Selection and validation of tools

Given the stage of development of the science, application of tools is very much dependent upon availability of data. If data are not available for site specific validation then the application of predictive techniques from one site may not be appropriate at another.

Application in the future of ecological predictive techniques without requirements for such extensive validation data sets will require an improved understanding and description of the ecological processes in an estuary at the scale of the estuary. This should enable a better link to be made between estuarine ecology and estuarine morphology for predictive modelling.

A 2.5 Linkages with morphodynamic tools

Presently the results from hydrodynamic and morphological models are used to drive some ecological models. For some processes, for example algal growth, it may be possible to use the ecological model to feed back into the sediment properties for a sediment transport model.

Although the main purpose for the bird population models is in their use for ecological predictions based on the conservation value of birds, the bird population models can be used to predict the effect of the birds on vegetation and invertebrate abundance and then relate this to impacts on hydrodynamic and sediment properties and the morphology of estuaries.

A more complete discussion of the links of morphodynamic tools with ecological models is included in the modelling report (Reference 2).

References

1. Estuary Morphology and Processes. A review of recent research and user needs. Report SR 446. HR Wallingford, UK. September 1997.
2. EMPHASYS Consortium (2000). Modelling Estuary Morphology and Process. Final Report. Research by the EMPHASYS Consortium for MAFF Project FD 1401. Report TR 111. HR Wallingford, UK. December 2000.

Appendix 3:
A brief summary of techniques available for prediction of morphology within estuarine systems

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A brief summary of techniques available for prediction of morphology within estuarine systems

A3.1 INTRODUCTION

The report identifies the requirement for methods to predict changes in estuarine morphology on short (up to 1 year) and long (1 to 100 years) time scales. These methods are needed to aid statutory bodies to make management decisions. This appendix identifies some of the predictive methods available, as listed in Table A3.1.

The predictive methods are classified as either:

- Top-down
- Hybrid
- Bottom-up

A top-down modelling approach involves applying a concept or overall understanding of the functioning and behaviour of a whole system, such as an estuary, to make predictions regarding its future behaviour and development. This approach often involves the use of observational data and empirical relationships, enabling a description or statistical prediction of the behaviour of the estuary to be obtained.

Bottom-up models are assembled from knowledge of smaller scale, physically based, processes to give a prediction of larger scale, longer-term change. The bottom-up model would usually be run for each identified process or condition and the resulting morphological changes summed using probabilistically determined weighting factors. The order of combination of each individual event may be important in achieving the final prediction.

The overall aim, of hybrid models, is to seek ways of integrating models that operate on, or address, different spatial and temporal scales and different processes. Since, generally, bottom-up models apply over short time scales and top-down models over longer time scales, the hybrid models are a means of connecting the two scales together and producing results that cover the intermediate weeks to years.

Estuary users need to be able to predict estuary morphology in order to provide a framework for other initiatives. It is therefore necessary for the models to be able to determine links between various estuary processes (including localised saltmarsh and mudflat processes), such as hydrodynamics, morphology, and other factors, including sediment movement, water quality, ecology and climate change. This would improve understanding of the long-term trends in estuary behaviour, and of the data that is required to in order for this to be possible.

It is unlikely that the end users requirements will be satisfied by one specific model but would rather be addressed by an integrated suite of models.

The concept of a dynamic relationship between the process areas is important to recognise. At any one time an estuary system may be responding to historical large scale forcing on one or more of these processes. When a new development is considered for the estuary, the impacts may influence one or more of the processes at a variety of scales.

Table A3.1 – Table of Morphological Predictive Methods

Model Type	Model Name
Top Down	Accommodation Space
	Expert Analysis / Sediment Budget Analysis
	Regime Theory
	Mudflat Analysis
	Rollover
	Sed Balance
	Estplan
	Estform
	POLANT/ANST/ANSE
	Historical Trends Expert Analysis
	SHAPE-SED
	NICHE
	Conceptual Estuarine Model
Hybrid	Estmorf
	Mudpack
	Hymorph
	Estent
	Estreg
	Statistical-Dynamical Method
Bottom Up	Sedtrans
	POLEST
	Estbed
	ISIS
	Telemac 2D & 3D
	DIVAST 2D / TRIVAST 3-D
	1-D Cohesive Sediment Transport Model
	CUMBSED
	Bird Population
	Mike 11/12/21 suite/3
	PISCES

A3.2 SUMMARY OF MODELS

A brief summary of the predictive methods is provided below.

A3.2.1 TOP DOWN

Accommodation Space

Approached from a geological perspective, this method utilises the relationship between changes in the amount of depositional accommodation space within an estuary and changes in estuarine sedimentation patterns. The method aims to predict long term morphological changes as a result of sea level fluctuations.

Sediment Budget Analysis

This approach utilises inputs relating to hydrodynamic forcing and sediment data to obtain a prediction of the sediment budget in an estuary. Recorded data is used to calibrate the model and future changes are estimated by considering the influence of changes in forcing on sediment transporting mechanisms. The sediment budget predictions are then used in an interpretative manner to infer estuarine morphological changes.

Regime Theory

This model predicts long term morphological change through the empirical Regime Theory relationship between estuary cross section and tidal prism. This approach investigates gross morphological change (estuary width, depth, length and planform) based on a change in the tidal prism.

Mudflat Analysis

A method relating the evolutionary morphology of mudflats to hydrodynamic forcing and sediment supply. The method provides an understanding of the dominant forcing mechanism on the mudflat and how the morphology will change in response to a change in forcing.

Rollover

Based on the Regime Theory, this method investigates the landward transgression of the estuary with sea level rise. The change in shape, elevation or position of the estuary may be predicted.

Sediment Balance Model

This model utilises the empirical relationship between tidal morphology and tidal asymmetry. The model allows changes in the gross morphological properties of either a single reach or the entire estuary to be used to predict the resulting affect on tidal asymmetry.

EstPlan

A model which predicts how channel planform will vary according to a number of hydrodynamic and morphological variables. Within the method an estuary is defined as a rigid 'strut' which will buckle at a certain point, with the degree of buckling representing the amplitude of sinuosity. This method is currently being developed further.

EstForm

A morphometric model to study creek and estuary forms. It can be used to explore the potential effect of changes (e.g. sea level rise) on the estuary form.

POLANT/ANST/ANSE

These are methods developed to complete frameworks of estuarine responses for tidal propagation, salinity intrusion and bathymetric evolution.

Historical Trends / Expert Analysis

The method involves analysis of historical changes in estuarine morphology and sediment accretion / erosion patterns through studying historical and archaeological evidence. Evaluation is also made of the current rates, trends in forcing factors, sedimentary and geotechnical properties and ecological constraints. Through this, an understanding can be gained of the morphological changes that have occurred within an estuary, along with a prediction of future changes.

SHAPE-SED

A model based on regression analysis that utilises the relationship between inter-tidal surface sediments and a number of variables relating to an estuary's physical features. The model predicts the overall sediment composition for the whole of an estuary in terms of the proportional cover of mud and sand.

NICHE

This model predicts the limits of the distribution of the major saltmarsh plants and the densities of the macro-invertebrates and shorebirds in and on inter-tidal muds and sands.

Conceptual Estuarine Model

The model uses analysis of historical trends and sediment budgets within the estuary to predict future morphological changes.

A3.2.2 HYBRID MODELS

ESTMORF

ESTMORF is a dynamic-empirical model which simulates the morphological development of an estuary on a timescale of decades. It is especially designed to predict the effect of natural developments, like sea level rise, and/or human interference's like dredging and dumping, on the morphological equilibrium state of an estuary. It is coupled to a hydrodynamic model to simulate the water flow. The empirical part of the model relates the water flow to equilibrium profiles of the channels. From this information, an equilibrium concentration field is derived. The dynamic part of the model computes a sediment concentration field and the natural morphological development of the estuary.

Mudpack

This technique predicts inter-tidal profile morphology using a balance between applied stress and the inherent strength of cohesive inter-tidal sediments.

HYMORPH

This method allows the prediction of long term morphological change, using regime theory supported by a one-dimensional flow model.

EstEnt

This is a model to predict the target, most probable states of an estuary based on entropy arguments.

EstReg

An estuary regime model to predict the restoration of an equilibrium regime state.

Statistical-Dynamical Method

This method has been applied to open coastlines and nearshore regions, but the principles should be applicable to estuarine situations. The method utilises historical survey measurement to predict long-term evolution.

A3.2.3 BOTTOM-UP MODELS.

BIOTIDE

This model is aimed at predicting the influence of biota on the net erosion of cohesive sediment and the transport and deposition along an intertidal transect.

POLEST

These models involve finite difference (rectangular grid) solutions to the momentum and mixing equations. The 3D model includes representation of both salinity and temperature and thereby density/stratification. All the models solve a mass-balance equation for sediments including a range of erosion, suspension and deposition expressions

EstBed

This model is able to make predictions of the morphological evolution of estuaries. It is based on both hydrodynamic, wave and sediment transport modelling incorporating regular bathymetric updating to represent the process of sedimentation and erosion of the bed. The model can be used to simulate morphological change in both cohesive and non-cohesive environments

ISIS

This model predicts flow patterns and sediment transport, which can be integrated to obtain morphological change. Suspended sediment transport and erosion and deposition are represented. The effects of consolidation of mud on the bed are represented in a simple two-layer model. Branched channel networks can also be represented in the model.

TELEMAC 2D
TELEMAC 2D predicts flow patterns and sediment transport which can be integrated to obtain morphological change. A depth averaged flow and sediment transport model. Different types of sediment transport modules can be used to represent either predominantly muddy or predominantly sandy sediment transport.

TELEMAC 3D
This model is similar to TELEMAC-2D, except that the water column is represented by several layers. This allows more accurate representation of the hydrodynamics in estuaries where the influence of fresh water on salinity variation is important. Also, for estuaries where suspended sediment concentration is very high, the possibility of stratification by suspended sediment exists: 3D methods offer the possibility of representing this to some extent whereas 2D or 1D methods do not.

DIVAST 2D / TRIVAST 3D *
These are hydrodynamic and sediment transport models with DIVAST 2D being depth-integrated and TRIVAST 3D being layer-integrated.
[* Models primarily used as research tools]

1D Cohesive Sediment Transport Model
This is a 1-D cohesive sediment transport method utilising the MIKE11 model. The method is of use in modelling estuarine turbidity maximum formation. The theories of erosion, deposition, settling and consolidation of cohesive sediment are incorporated into the method.

CUMBSED (Cumberland Basin Sedimentology)
This method calculates the erosion and deposition of one cohesive component and one non-cohesive component, transported by a hydrodynamic model. The method is calibrated with up to 20 ‘hydrodynamic sediment parameters’, e.g. fall velocity.

BIRD-POP
This model predicts the effect on a single estuary, or on several, of a wide variety of human activities on the body condition, overwinter survival rates and local / global population size of shorebirds (Waders and Wildfowl).

A3.2.4 COMPARISON OF MODELS

Table C2 compares the above predictive methods

TABLE A3.2 – GENERAL INFORMATION ON THE PREDICTIVE METHODS

	Model	DATA					
		1. What are the processes being measured?	**2.** What inputs are required for the method?	**3.** Where Is the input information obtained from?	**4.** Which estuary characteristics are important for the method?	**5.** Are any other key aspects required for an estuary to provide a suitable testbed?	**6.** Are there limitations to the model because of these characteristics?
H R Wallingford	Sediment Budget Analysis	Hydraulic Geological	All types of measured physical information. Process model results describing short-term behaviour.	Field measurement.	Tides. River flow. Sediment type. Sediment transport rate.	Greater confidence in results when large amount of relevant information available. Good historical data would allow test by hindcasting.	
	Regime Theory	Hydraulic Geological	Cross sectional shapes of estuary. Tidal discharge.	Bathymetric data, flow model results.	Works best for channels with approx. Uniform sediment size.		Method not applicable if estuary is undergoing response to changes in forcing.
	Mudflat Analysis		Large and small-scale mudflat topography. Sediment properties. Current speeds. Tidal range. Wave conditions. Suspended sediment data.		Significant areas of mudflats.	No.	
University of Newcastle	Regime	Hydraulic, Geological	Cross Sectional area or tidal prism.	Field measurements or chart data	Shape of estuary.		
	Rollover	Geological	Bathymetry / Cross Sections.	Field data /SLR predictions	Shape of estuary tidal curve/tidal prism.		Tidal curve may vary with SLR.
	Sed Balance	Geological	Cross-sections along estuary and tidal curves.	Field Data / charts	Shape tidal curve.		
ABP	EstPlan	Morphology Plan shape	Tidal properties. Freshwater input. Width/depth variations along estuary. Littoral drift at mouth.		See 2.	Numerous estuaries with varying plan shapes.	Only the principle geological constraints are considered.
	EstForm	Morphology Form	Bathymetry. Surrounding topography. Constraints e.g. geology. Tidal properties.		Length. Tidal properties. Geometry.	Known changes in form and sediment budget over time.	Cannot use asymmetric sections or plan shape other than straight alignment.
POL	POLANT/ANST/ANSE	Tidal response Salinity intrusion Bathymetric evaluation	Tidal amplitudes. Salinity distributions. Bathymetry.	Historical data.	None – method applicable to any estuary.	No.	Not applicable to anomalous features e.g. major sill or entrance bar.
BGS	Accommodation Space	Morphology Geological	Sea level curve. 3D form of base surface of Holocene marine deposits.	Field measurements (boreholes, seismic reflection records) sea level data.	Basin shape. Sea level history. Sediment supply.	No.	
RHUL	Historical Trends/Expert Analysis	Hydraulic Geological Environmental Human Activity	Baseline morphology. Bathymetry.	Existing field data or further measurement/ sampling.	Areas with significant sedimentary record. Plan / cross-sectional shape unimportant, nor is nature of regime.	Estuary should be dynamic, i.e. have experience significant change within last 150 years.	No, other than that a rock / floored boundary is unlikely to show any change.
University Of Southampton	Conceptual Estuarine Model	Hydrodynamic Geological Geomorphological	Sequential bathymetry, structure contour maps (elevation of upper bedrock erosion surface.) Baseline information on hydraulics and sediments.	Field measurements.	Areas with significant changes and preserved sediments.	No.	Human induced changes must be of similar or higher amplitude than the natural.

TABLE A3.2 – GENERAL INFORMATION ON THE PREDICTIVE METHODS (cont.)

	Model	DATA					
		1. What are the processes being measured?	**2.** What inputs are required for the method?	**3.** Where is the input information obtained from?	**4.** Which estuary characteristics are important for the method?	**5.** Are any other key aspects required for an estuary to provide a suitable testbed?	**6.** Are there limitations to the model because of these characteristics?
CEH	SHAPE-SED	Environmental	Bird pop. Numerical density; size-distribution and ash-free-dry-mass/length relationships for the main invertebrate prey species in different parts of the estuary in autumn; the over-wintering decrease in prey abundance due to external factors such as storms; the extend and time of exposure over each low water (spring/neap cycle); winter daily ambient temperature; autumn initial bird population size; consumption rates on any supplementary food sources; the duration and aerial extent of disturbance from a single person.	Field measurement.	Ability to access inter-tidal area of whole estuary to obtain surveys of the necessary surveys of invertebrate distributions.		
University Of Newcastle	Mudpack – Regime	Hydraulic	Long term wave/tidal elevation data. Sediment shear stress. Suspended sediment concentrations.	Field measurement or hindcast values, EA records.			
DH	ESTMORF	Hydraulic Geological Environmental	Initial-, boundary- and global-concentration field. Empirical constants for equilibrium relations. Dredged/dumped sediment volumes. Bottom subsidence. Sea level rise. Sediment transport parameters. Data for flow model. Numerical parameters.		Estuary shape. Tidal volume / discharge.	Human intervention or natural developments should be present in the estuarine system.	Require sufficient data on the historical morphological development of estuary. Strong stratification may restrict use of model.
H R Wallingford	HYMORPH	Hydraulic Geological	Tidally varying water level and river flow. Regime relationships between width, depth and peak tidal discharge.		See 2.	Ideal case: estuary in approx. equilibrium / regime at some point in time, with an intervention (e.g. barrage construction) occurring after this.	Geological constraints may limit applicability of model.
ABP	EstEnt	Morphology Hydrodynamic	Estuary hydrodynamics. Bathymetric timeseries.	Calibrated model.	Hydrodynamics.	No.	
	EstReg	Hydraulic	Estuary hydrodynamics. Form relationships.	Calibrated model.	Morphological development dominated by the tide rather than wind / waves.		
University of Nottingham	Statistical-Dynamical Method	Morphology	Historical Survey Measurements				

TABLE A3.2 – GENERAL INFORMATION ON THE PREDICTIVE METHODS (cont.)

	Model	DATA					
		1. What are the processes being measured?	**2.** What inputs are required for the method?	**3.** Where is the input information obtained from?	**4.** Which estuary characteristics are important for the method?	**5.** Are any other key aspects required for an estuary to provide a suitable testbed?	**6.** Are there limitations to the model because of these characteristics?
H R Wallingford	ISIS	Hydraulic	Cross-section topography. River flow hydrograph. Tidal variations. Sediment properties.		Importance of lateral / vertical variations.	No.	2D / 3D model may be necessary if lateral / vertical variations are very influential.
	TELEMAC 2D	Hydrodynamic Sediment transport Morphology Ecology	Boundary conditions. Initial conditions inc. bathymetry and sediment distributions. Parameters describing hydrodynamic processes. Parameters describing sediment behaviour.	Field measurement or 'typical' values.	Sediment types. Number of driving forces.	No.	More difficult to apply for non-uniform sediment and many different driving forces. Unable to represent density currents.
	TELEMAC 3D	Hydraulic	As for 2D but also: Initial and boundary conditions for salinity. Description of vertical mixing process.	Field measurement, turbulence model.	All physical processes represented.	Estuary where fresh water influences on gravitational circulation is important.	None
CEH	NICHE	Environmental	Estuary size. Fetch. Water levels. Spring tidal range. Altitude. Day/night cycles. Macro-invertebrate abundance. Sediment properties. Shore level. Shorebird abundance. Shore-width and proportions comprising sand and mud.	Field measurement.	Ability to access the intertidal areas to obtain samples and other data.	To be representative of a class of estuaries so that models apply as widely as possible.	Unable to parameterise the models without this data.
	BIRD-POP	Environmental	Site specific data required includes: Tidal inundation. Day/ night cycles. Size distribution. Ash-free-dry-mass/length relationships for invertebrates. Non-site-specific data.	Field measurement. Non-site specific data available in literature.	Size of estuary.	No.	Easier to parameterise the model for small estuaries, but is possible for estuaries of larger size.
PML	BIOTIDE	Hydraulic Geological	Bathymetry. Sea surface elevation. Bioturbator density. Functional relationships between U_{crit}, mass eroded, erosion rate and biota density.				
POL	POLEST	Hydraulic	Bathymetry. Tidal elevation constituents. Temperature and salinity at mouth. River flows and temperature.		Sediment data.		
ABP	EstBed	Hydrodynamics Morphology	Calibration data, inc.: Tidal levels, current speeds, suspended sediment concentrations, bed sediment properties.	Laboratory and field measurement.	Bathymetry. Morphology. Hydrodynamics. Sediment properties.	No.	
David H Willis and Associates	CUMBSED	Hydrodynamic Sediment Transport	All the empirical co-efficients used in the various theories				
University of Brighton	1-D Cohesive Sediment Transport	Sediment Transport	Field measurements of water level, velocity and turbidity	Field Measurement			
Cardiff University	DIVAST 2-D / TRIVAST 3-D	Hydrodynamic Sediment Transport	Sediment Type (cohesive or non-cohesive) and grain size				

Appendix 4:
List of outputs from project

Appendix 4:
List of outputs from project

MAFF PROJECT FD1401
ESTUARIES RESEARCH PROGRAMME, PHASE 1
OUTPUTS BY THE EMPHASYS CONSORTIUM

Status of this list

This list is considered to be complete at the time of compilation and printing (6 December 2000). Other papers and reports arising from the research may be written following completion of the project (end December 2000).

Obtaining the outputs listed below
If you would like further information about obtaining any of the outputs listed below please contact the project manager (email: rjsw@hrwallingford.co.uk)

KEY REPORTS

EMPHASYS Consortium. 2000. A Guide to Prediction of Morphological Change within Estuarine Systems. Version 1B. Research by the EMPHASYS Consortium for MAFF Project FD 1401. Report TR 114. HR Wallingford, UK. December 2000.

EMPHASYS Consortium. 2000. Recommendations for Phase 2 of the Estuaries Research Programme. Final Report. Research by the EMPHASYS Consortium for MAFF Project FD 1401 (Task Leader: Professor K Pye). Report TR 113. HR Wallingford, UK. December 2000.

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R L. Soulsby, on behalf of the EMPHASYS consortium. The UK Estuaries Research Programme – Phase 1. Paper submitted for 36th MAFF Conference of River and Coastal Engineers.

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Soulsby RL. Presentation of Phase 1 research at the IAHR Maritime Board meeting, Cardiff, October 2000.

Pye, K., D. van der Wal & S. Yoshida (2000).*Historical Trend Analysis and Expert Geomorphological Assessment as tools for long-term morphological prediction in estuaries.* Abstract for the British Geomorphological Research Group, 40th Anniversary, Annual Conference 2000, 12-14 September, University of Sheffield. Conference Schedule and Book of Abstracts, p. 71.

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EMPHASYS Consortium (2000). Presentation seminar of the results from the Estuaries Research Programme, Phase 1. 6 December 2000. London.

Other posters available.

OTHER ARTICLES AND PUBLICITY

MAFF Flood and Coastal Defence newsletter, Issue No 11, December 1999

- Article: "Estuaries Research Programme – Phase 1"

Project leaflet

- Version 1.0 Describing the project (July 1999)
- Version 3.0 Describing the ouptuts from the project (December 2000)

Project web site hosted by HR Wallingford at http://www.hrwallingford.co.uk/projects

Then choose "Estuaries Research Programme" under "Select project"

The Estuarine, and Coastal and Sciences Association bulletin

- Bulletin No 32 – September 1999
- Bulletin No 35 – September 2000

RELATED REPORTS

HR Wallingford. 1997. Estuaries. The case for research into morphology and processes. Research for MAFF, the Environment Agency, EPSRC, NERC, and English Nature by HR Wallingford, Cambridge Coastal Research Unit, ABP R&C, Southampton University Department of Oceanography, MAFF Directorate of Fisheries Research, Michael Owen and Risk and Policy Analysts Ltd. HR Wallingford Report SR 478, July 1997.

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