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SR 478

Estuaries
The case for research into morphology and processes

Report SR 478
July 1997

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Contract

This report describes work funded by the Ministry of Agriculture, Fisheries and Food (MAFF) Flood and Coastal Defence Division, the Environment Agency (EA), the Engineering and Physical Sciences Research Council (EPSRC), the Natural Environment Research Council (NERC) and English Nature. The Team undertaking the Scoping Study comprised HR Wallingford (HR), Cambridge Coastal Research Unit (CCRU), ABP Research and Consultancy (ABP R&C), Southampton University Department of Oceanography (SUDO), MAFF Directorate of Fisheries Research (MAFF DFR) and Michael Owen. The drafting team for this report comprised R L Soulsby (HR), J V Smallman (HR), I H Townend (ABP R&C), Michael Owen (consultant) and M Postle (Risk and Policy Analysts Ltd).

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Date ....29 July 1997....

Executive Summary

Estuaries

The case for research into morphology and processes

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Since earliest times estuaries have offered many benefits to man. They have provided: safe harbours for coastal and international vessels; river access into the interior; lowest crossing points for rivers; a reliable food supply of fish and shellfish; flat, fertile land for agriculture and housing; and, more recently, economically important ports and cost-effective sites for industry. Consequently, many of Britain's greatest cities are founded on estuaries (e.g. London, Glasgow, Cardiff, Plymouth) as well as many major industrial centres (e.g. Merseyside, Tyneside, Teesside, Humberside). The economic importance of estuaries is demonstrated by the fact that £122 billion of trade passes through Britain's estuaries annually, estuarine sited industrial and commercial activity generates a turnover of roughly £26 billion per annum, and 11.5 million people live within one kilometre of the shore of an estuary.

But these and other pressures have affected the health of estuaries. A combination of sinking land levels, rising sea levels, and worsening wave climate poses an increasing threat of flooding to the surrounding built-up areas. Toxins from industry and agriculture have, over centuries, become locked in the estuarine sediments, and water quality has suffered. This in turn damages the delicate ecosystem of the estuary. The legitimate aspirations of industry, commerce and navigation to further wealth creation through expansion could possibly have a deleterious effect on the quality of life in and around estuaries. For example, a port expansion, marina development or barrage could alter the morphology of the estuary leading to increased flood risk; dredging at former industrial sites could uncover polluted sediments; agricultural run-off or an industrial process plant could release pollutants. Whilst offering significant economic benefits, any of these could adversely affect the ecosystem and habitats. Decisions must be taken which comply with the legal and social requirements to minimise threats of flood risk and to habitats and conservation, while not unnecessarily hindering economic development.

However, at present we do not have the necessary tools to make predictions of estuarine behaviour with sufficient accuracy and reliability to inform the decision making process. The kind of tools needed to remedy this are predictors of short-term (up to one year) and, most particularly, long-term (one to 100 years) estuarine morphology, water/sediment quality, and ecology. These need to be combined into an *Estuary Impact Assessment System* with the ability to forecast the effects of a proposed development scheme on the key issues of flood defence, navigation, water quality and conservation. When further combined in a management framework with social, economic and legislative factors this would yield an *Estuary Management System* that would be used operationally to make holistic decisions about the development of individual estuaries.

Traditionally the research emphasis has been largely directed at a process-based approach leading to "Bottom-up" prediction methods/models, which are good at making short-term predictions but impractical to apply for long-term predictions.

In parallel, more limited research has been done on descriptive, qualitative and quantitative aspects of the whole-estuary or systems approach, which has provided "Top-down" prediction methods/models. These methods are better suited to broad-based long-term predictions, but they are very varied and some rely on incompletely tested hypotheses. There is, in consequence, extensive scope for the development and validation of these techniques. This potential will be further enhanced by the approach adopted in the present programme, namely to bring together the best of both the Bottom-up and the Top-down approaches in Hybrid models, and, further, to cross-fertilise the hydrodynamic, morphodynamic, water quality and ecology models.

A flexible phased programme of research is put forward to achieve this. The research is based on Science Projects on Morphology, Water/Sediment Quality, Ecology and Anthropogenic Influences, cross-linked by user-driven Working Groups on Flood Defence, Navigation, Water Quality and Conservation. In view of the pivotal role of long-term morphology, approximately half the total effort would be directed at this science project. The programme is divided into three main phases, with incrementally improved Estuary Impact Assessment Systems (EIASs) delivered at the ends of Phases I and II, and an Estuary Management System (EMS) delivered at the end of Phase III. In order to meet the immediate needs, a stop-gap suite of prediction tools is delivered within the first year using existing methods.

Phase I is largely concerned with testing and comparing existing prediction methods, Phase II with improving and combining the methods, and Phase III develops new, cross-fertilised methods resulting from a major injection of basic research. The programme is underpinned by data collection and continuous monitoring. The science base encompasses physics, civil engineering and geography (for morphology), chemistry (for water/sediment quality), and biology (for ecology), as well as mathematics, oceanography, geology, IT and economics.

Options are offered to allow a trade-off of the time, cost and quality/confidence of the tools to be chosen for each phase. If the full programme is taken to deliver a product with a quality of 100, then Phase I will optionally last from 1 to 2 years, cost from £0.6M to £2.6M, and deliver an EIAS of quality 15 to 30; Phase II will optionally last from 3 to 5 years, cost from £1.6M to £5.1M, and deliver an EIAS of quality 40 to 60; and Phase III will last roughly 5 years, cost from £5M to £10M, and deliver an EMS of quality 80 to 100. Re-alignment and re-funding can take place between phases.

Direct economic benefits outweigh the cost of the research by a factor of between 3 and 6. There are also considerable intangible benefits in terms of conservation and recreation improvements. As well as management tools, the programme delivers: improved scientific knowledge and techniques that are applicable across a much wider area than just estuaries, a national inter-disciplinary research network, training of young scientists and engineers, and an enhanced UK skills base to sell estuarine expertise overseas.

The programme is timely because legislation, industrial and infrastructural development, the accumulation of past impacts, and climate change are all conspiring now to put unprecedented pressure on our estuaries.

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Appendix Breakdown of activities into research tasks

1 Introduction

1.1 The Scoping Study

A Scoping Study to establish a programme of research and development for developing techniques to predict large scale, long term morphological changes within estuaries has been commissioned by a group of funders. This group comprises the Ministry of Agriculture, Fisheries and Food (MAFF) Flood and Coastal Defence Division, the Environment Agency (EA), the Engineering and Physical Sciences Research Council (EPSRC), the Natural Environment Research Council (NERC) and English Nature. The team undertaking the Scoping Study comprises HR Wallingford (HR), Cambridge Coastal Research Unit (CCRU), ABP Research and Consultancy (ABP R&C), Southampton University Department of Oceanography (SUDO), MAFF Directorate of Fisheries Research (MAFF DFR) and Michael Owen (Consultant).

1.2 Terms of reference

Main objective

To investigate the possible lines of research and/or development towards the goal of developing techniques to predict large scale, long term morphological changes and the resulting sediment related impacts within estuaries (including water quality aspects) and assess their consequences for estuarine management.

Sub objectives

Investigate and report on possible lines of research to:

- quantify the external forcing factors including ecological and physical factors;

- identify the important internal processes responsible for estuary change, physical, biological, chemical and anthropogenic;

- identify the impact of changes on the estuary environment, including the impact of contaminants;

- identify the potential benefits of the proposed research or development, including improved approaches to design for flood defence and other estuarine structures.

1.3 Approach to the Scoping Study

The scoping study consisted of three main tasks. The first of these was a review of current and previous research relevant to the morphology and major sediment processes of tidal estuaries. In parallel with the review a consultation exercise was undertaken to establish the user requirements for such techniques. The consultation was mainly conducted through questionnaires and guided interviews with organisations with an interest and/or responsibility for estuary management. The results of the first two tasks are presented in a separate companion report, Reference 1, hereafter referred to as "the Review".

In the final task the outcomes of the review and consultation process were used in combination to formulate the future research and development requirements. These requirements and the justification for undertaking the proposed research and development programme are presented in this document.

1.4 Structure of the report

The report comprises five further chapters. In Chapter 2 the background to the scoping study is given. This provides the context of research and development for estuary morphology and processes, and summaries of the state of the art and the user requirements as identified in the review and consultation (see Reference 1). The economic and scientific justification for the research and development programmes are presented in Chapters 3 and 4 respectively. The timeliness of the research and development programme is given in Chapter 5, with discussion of the programme options in Chapter 6. Chapter 6 refers to a table of options for research and development which is presented in the Appendix.

2 Background

2.1 Perspective

Estuaries are a focal point for the full range of human activities. Throughout history man has settled near to the coastline and has used estuaries and rivers as a transport artery to inland areas. At first estuaries were places of relative shelter and also provided a source of food and means of transport. 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 systems.

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. The observation of the natural environment is increasingly viewed by man as a recreational pursuit. In addition to this estuaries are also used for other recreational activities such as sailing, fishing etc. The conservation and recreational requirements for estuaries clearly need to be considered in conjunction with the effects of economic and social developments when planning for and managing estuaries. The natural environment also plays an important role in flood defence, for example, saltmarshes can provide natural protection. The issue of *sustainability* must be addressed in management decisions, for all these reasons.

It can be seen from the foregoing that estuaries in the UK play a pivotal role in the nation's capacity for wealth creation. They are the location of the main gateways to international trade, industries of national importance and major centres of population. They make an enormous contribution to overall quality of life through their national and international importance to conservation (particularly in hosting sites of international importance), heritage, landscape and recreation. As demonstrated by the NERC LOIS programme, they carry significant fluxes, including contaminants, from the land to the sea. They provide a unique challenge to managers and decision makers who are concerned about the long term consequences of their decisions related to flood defence, conservation, water quality, navigation, recreation etc..

Estuary management tools would enable more confident prediction of the effect of the management decisions which need to be made. These decisions cannot be avoided, because a decision to "do nothing" in a changing estuarine environment is as much a management decision as any other. The development of management tools is also fundamental to ensuring that estuaries remain at "favourable conservation status" and will, in future years, be of a quality that fulfills our commitments under the EC Habitats Directive.

Unfortunately, no tools currently exist for evaluating the long term consequences of anthropogenic action against a background of the long term estuary evolution in the absence of such action.

2.2 State of the art

The Review examined the different physical influences which contribute to the morphological development of estuaries. It also summarised the techniques which are presently available for prediction of large-scale, long-term morphological changes within estuaries.

The review demonstrated that with present understanding and the use of available data and modelling techniques it is possible to predict with a reasonable degree of accuracy:

- Short-term changes in water levels, currents and wave patterns due to new or historical developments.

- Short-term changes in water levels, currents and wave patterns during extreme storm conditions.

- Short-term changes in patterns of erosion and deposition associated with new or historical developments.

- The impact of thermal or other discharges on water quality in the estuary environment.

- Some of the effects of biological and chemical activity on estuary developments.

The review demonstrated that without further research and development there are large uncertainties in the prediction of:

- Long-term impact on estuary form associated with either natural variation or construction works.

- The feedback between ecological and chemical processes and estuary form.

- The feedback between evolving estuary form and water quality.

These are all key areas in establishing the impact of developments for long-term planning and management of estuaries.

2.3 User requirements

A wide range of estuary users were consulted as part of the Review. This involved sending a consultation document and questionnaire to individuals within organisations involved in estuary use. The consultation document provided a statement of present day capabilities, the terms of reference for the scoping study and a summary of estuary processes. It was aimed at supporting the questionnaire and evoking a response. The questionnaire requested both factual information, and an identification of the further knowledge and innovative requirements which were necessary to meet future needs. Overall the response from consultees was very positive with a response of about 60% from the 107 organisations consulted by the study team.

In general the responses from the users reflected their responsibility for particular issues and activities within their estuary. The main requirement of users was for tools for the future management and planning of estuaries. The need for these tools is largely driven by legislative requirements. Specific requirements mentioned by users were:

- Improved predictive techniques/models for estuary management with suitable verification and data to assess applicability.

- Improved understanding and prediction of the long-term estuary response to engineering developments.

- Evaluation of beneficial use opportunities for dredged material with respect to flood and coastal defence.

- Improved knowledge of environmental issues with respect to dredging activities.

- Guidelines for good practice in the dredging of contaminated sediments.

Users also requested that dissemination of these tools and their capabilities, and communication between estuary users should be improved. Many of the users acknowledged that the provision of such tools required improved collection and collation of data and identified the following specific points:

- More continuous monitoring of (estuary) inputs and water quality to verify models.

- Continuation of the existing long term field measurements and analysis for the long term picture of estuary behaviour.

- Development of new instrumentation and improvement of existing instrumentation.

- Improved collection, storage, access and dissemination of data, particularly for input to predictive techniques and model verification.

- Optimise and improve use of remotely sensed data.

Users also identified that the following advances in the understanding and prediction of physical processes were required:

- Understanding the long term evolution of estuary hydrodynamics and morphology due to both natural and human induced change.
- Reliable quantitative prediction of the movement of fine sediments.
- Establishing the interaction between fluvial, estuarine and coastal processes in the long-term.
- Understanding estuary processes and parameterising links between hydrodynamics, morphology, water quality and ecology in the long term.
- Understanding saltmarsh and mudflat processes and their interaction with the estuary system.

The timescales over which tools for estuary planning and management were required varied between users. Many estuary users required tools that can start to be used now or within the next 1-2 years as they have areas of concern which must be resolved in the immediate future. Others were prepared to acknowledge that it may be advantageous to wait for better tools to be available in 2-5 years time with an overall aim of continuing to improve these over a 5-10 year period.

3 Economic justification

3.1 Economic importance of estuaries

With over 581,000 hectares of estuarine intertidal mud and sand, the UK's estuaries constitute approximately 28% of the intertidal area of northwest Europe. These areas form a focal point for a considerable share of the economic activity within the UK. In terms of foreign trade, for example, of the £290 billion worth of imports and exports in 1992, about £177 billion was moved through ports. Given that 69% of this was shipped through estuarine ports, their significance in facilitating trade and sustaining economic activity is great. Furthermore, it has been estimated that activities within the coastal zone generate a turnover of roughly £51 billion per annum, accounting for approximately 4.8% of Gross Domestic Product (GDP). Examination of a breakdown by different sectors indicates that roughly 50% can probably be attributed to activities carried out on estuaries alone. These include the shipping and port related activities noted above, ship building, industrial activities (chemical, oil and gas, general equipment supply, etc.) and environmental protection.

In addition to their importance to trade and industry, the UK's estuaries are extremely important as centres of economic activity, for recreation and from an ecological perspective. Roughly 11.5 million people are estimated to live within one kilometre of an estuary in Great Britain. However, the total population which can be associated with estuaries will be much greater. For example approximately 850,000 live within one kilometre of the Mersey Estuary and over five million within the Mersey basin. As a result of such high levels of historic development in the land areas surrounding estuaries, there are also significant costs associated with the provision of tidal flood defences. Work undertaken by the Environment Agency indicates that there are roughly 2,150 km of tidal defences, with the continued protection of these areas relating to costs of capital and maintenance works in the order of £48 million per annum.

Estuaries have great economic importance as spawning and nursery areas for commercial seafisheries and shellfisheries. For example, the value of shellfish landings in 1994 was roughly £128 million. Estuaries are also important sites for recreational angling. They provide passage for migratory salmonids which are of significant recreational value to freshwater anglers and provide key sites for sea angling (which has some 2 million participants aged 12 years plus). They are also important spawning and nursery areas for some of the more highly prized species such as sea bass and flounder. Survey work undertaken in the late 1980's found that sea bass anglers were willing to pay over £25 per annum (mean value) to prevent the closure or loss of a fishery. Multiplying this by the estimated 490,000 bass anglers in England and Wales indicates a value associated with the protection of this recreational fishery alone of over £12 million.

It is more difficult to attribute a value to the recreational activity associated with estuaries, however, data from the Sports Council and UK Day Visits Survey provide a good indication of the importance of the coast in general. For example, some 105 million day visits per annum are made to the UK coast, with a large proportion of these being associated with recreational activities such as walking, boating/sailing, going to the beach and sightseeing. A significant proportion of these can be attributed to activities based at estuaries. Others have estimated that the value of leisure and tourism at the coast is around £7.9 billion per annum; a significant part of this will correspond to estuaries given that they are the focus of many coastal holiday destinations.

From a conservation perspective, estuaries provide unique areas of habitat, containing a range of rare species. Roughly 80% of estuaries contain at least one Site of Special Scientific Interest and they are exceedingly important habitat areas for overwintering bird populations. It has been estimated that some 1.7 million wading birds overwinter on the UK's estuaries, accounting for about 40% of the northwest European overwintering population.

Because the morphology of each estuary is a function of a unique and complex interplay between the anthropogenic and the natural factors, developing a holistic understanding of the consequences of management decisions is important to avoid detrimental effects to the above uses of estuaries. The construction of flood defence works, dredging of shipping fairways and berths, aggregate extraction, training walls and docks all interfere with the dynamics of estuarine morphology. This, in turn, affects ecological processes, environmental quality, water quality (in terms of flushing of contaminants), commercial and recreational fisheries. For example, the RSPB estimate that 79 UK ports have jurisdiction over 44 sites of international importance for birds, yet the influence of the dredging of 30 million tonnes of sediment from UK ports (in 1993) on morphological and fluvial dynamics and hence on intertidal ecosystems is still not well understood.

The sustainable management of estuaries and the shoreline as a whole demands a more strategic approach towards the assessment of development proposals and current activities, with regard to both the costs and benefits to industry and the environment. Such assessments must rely on the use of past experience, but also on sound predictions of both the short and long-term effects of alternative actions. In order to avoid damages to industry and the environment, while at the same time ensure a cost-effective use of government and private sector finances, better tools which afford a higher degree of certainty are required than currently exist. There also needs to be an improved and wider dissemination of best practice.

3.2 Economic benefits of the research

The four main areas identified as benefiting from the proposed research are flood defence, water quality, conservation and navigation. The economic benefits of the research may be realised in a number of ways, with the most important being

- a reduction in the uncertainty surrounding scientific predictions of estuary behaviour and thus greater confidence in model outputs

- an increased availability of information to allow for more timely decisions to be made in respect of changing environment

- more cost-effective use of available resources for maintaining and managing assets within estuaries due to a better understanding of cause and effect.

The previous section provided some global indications of value for different assets or activities associated with estuaries. In order to be able to assess the benefit of the proposed research, these need to be recast into some measure of expenditure. This is most easily done for those activities for which there is a direct annual revenue or expenditure. For many activities the expenditure is not readily quantified. Whilst we know that imports and exports worth some £125 billion each year are transported via estuaries, this is not a direct revenue and it merely provides a measure of the importance of estuary ports to trade and hence GDP. Similarly, populations living around estuaries derive a number of intangible benefits from the estuary. The table below provides some estimates of annual revenue or expenditure, where these are known, and the percentage of estuary based use for a number of activities or interests (Reference 2)

Directs		Intangibles or Unquantified	
Activity	Annual cost or value (£m)	Activity or Interest	% estuary based
Sea defence	48	Human population	21
Navigation dredging	75	Imports/exports (by value)	69
Aggregate winning	57	Power generation	57
Water treatment	650	Oil refineries	81
Commercial fishing	130	Recreation - marinas	41
		- sailing clubs	24
		- leisure fishing	30
		- visitors	20-30
		Bird population (i)	40
		Conservation areas	80 (ii)

Notes (i) % of northwest European overwintering population
(ii) % of estuaries containing some form of designated site

The components that make up the programme have been costed and confidence factors assigned, based on the probable contribution to a comprehensive management capability (see Table 5 and Section 6.5 for further details). Components have been grouped to form three phases, which provide a progressive improvement in predictive tools and management capability. These are incremental, in that they build on the results and methodology of previous phases. Taking the higher bound cost for each phase, the costs, timescale and confidence levels are as follows:

	Cost (£m)	Duration (yrs)	Confidence (%)
Phase I	2.6	2.0	30
Phase II	5.1	5.0	60
Phase III	10.0	5.0	100

In any one phase, the research produces benefits which have an area of influence and a potential saving (or loss). Subsequent research may

- improve the confidence with which those same benefits can be delivered
- extend the area of influence and/or the savings (losses) associated with these same benefits
- give rise to new benefits, which have a different area of influence and savings (losses).

Using sea defence as an example, the benefits might be:

Phase I	realignment opportunities
Phase II	design improvements, plus extended influence of realignment opportunities
Phase III	reduce impacts due to defence works.

Consequently, influence and costs may, or may not, be independent from one phase to the next, depending on the nature of the benefits.

An estimate of the benefits required, as a consequence of the research, can be estimated by simply considering the annual return required to cover the investment. Assume we seek a payback within 10 years of completion of the research and use a discount rate of 6%. The annual savings resulting from each phase must then be approximately equal to or greater than:

Phase I	£360k/annum
Phase I+II	£1000k/annum
Phase I, II, and III	£1800k/annum

To determine whether this order of saving is likely, it is necessary to consider the specific activities in more detail. For instance it is noted above that sea defence expenditure in estuaries amounts to some £48 million/annum. Some fraction of this expenditure involves a planning or management decision which could be influenced by the new tools provided by the research; for example, where there is an option to abandon one line of defence and there are choices on where to set the new line. If poor (low confidence) tools exist then the engineer will overdesign or take some precautionary approach to cater for the lesser certainty of long-term behaviour. This implies either a greater than necessary cost, or some compromise which would incur higher maintenance costs to "hold the wrong line of defence". A poorly informed decision may also lead to secondary impacts, such as coastal squeeze. As a consequence, the proposed research holds the potential to improve understanding and so reduce at least some of this expenditure. In order to consider the benefit that is likely to accrue from the research, it is necessary to estimate the percentage of the current expenditure that could be influenced by improved knowledge and techniques and, of this portion, the probable saving that may arise. For sea defence, identifying opportunities to realign defences could influence 20% of the total expenditure but other compensatory works may mean that only half of this results in savings (a gain). Thus, the potential saving is:

£48 million x 0.2 x 0.5 = £4.8 million

If in addition, we apply the confidence level for the phase, we obtain a probable saving in sea defence works at the end of Phase I of £4.8m x 0.3 = £1.4 million. Thus an estimate of the annual benefit accruing to a particular activity as a result of the research can be calculated from the algorithm:

Benefit = Annual Value x Influence x (Gain/Loss) x Confidence

The extent of influence and the gains or losses vary with each phase. Thus, again using sea defence as an example, the more refined tools from Phase II are likely to influence a greater range of defence design parameters but the savings are likely to be less substantial. The design tools are likely to provide the greatest direct cost savings in the cost of maintenance and replacement works. In consequence the output from Phase III is more likely to provide some limited refinement but the main benefit will be more intangible, the emphasis moving to a more sustainable balance with other interests. Some indicative figures for Phases I, II and III are given in Table 6.

This line of reasoning has been extended to the other annual revenues and expenditures for the activities listed in the table above. The percentages for the 'influence' and 'gain/loss' are based on an assessment of the ways in which each activity is likely to be influenced by the proposed research programme. The resulting values are summarised in Table 6 and it must be stressed that these are no more than rough estimates. Some of the intangible benefits likely to accrue, with respect to the other activities or interests, are also noted in Table 6. Summing the 'benefits' provides a total annual benefit for each incremental phase of the programme.

Assuming, as above, a payback is required within 10 years of completing the research and a discount rate of 6% is used, the cost and benefit streams can be reduced to net present values (NPV's) and a benefit-cost ratio calculated. This has been done, using the costs and durations noted above and the benefits given in Table 6 and results in the following estimates:

	Phase I	Phases I + II	Phases I + II + III
NPV of costs (£m)	2.4	6.2	11.8
NPV of benefits (£m)	7.9	30.4	78.5
Combined NPV (£m)	5.5	24.8	61.7
Benefit-cost ratio	3.3	4.9	6.2

This indicates that, based on the savings in direct annual costs alone, there are worthwhile returns from the proposed research. Whilst these are obviously fairly crude estimates, it must also be recognised that the ability, resulting from Phase III, of being able to move closer to a truly holistic approach to sustainable management within estuaries, is likely to give rise to significant intangible benefits, which should not be under valued. As an example, a properly planned flood defence scheme making use of predictions from computational models in order to comply with the Habitats Directive could avoid costly corrective measures which might otherwise become necessary.

It is clearly more difficult to make a calculation of all the future benefits deriving from a programme of research than it is to calculate the benefit from a specific engineering scheme at a specific site, and there is no recognised method of making such calculation. The method used here is as comprehensive an approach as possible. The values used in Table 6 for "influence" and "gain/loss" are believed to be best estimates, although it is not possible to quantify them precisely. Even if a certain latitude is allowed in these values, each phase still gives a worthwhile Benefit-cost ratio, especially if some monetary value is also attached to the intangible benefits.

4 Scientific justification

4.1 The scientific challenge

Estuaries provide an interchange between the open sea and the land drainage network. Each estuary is a unique result of geology, climate, marine and ecological conditions and the accumulative effect of a number of man made works. Also each estuary has a unique sedimentology, fluvial, tidal and wave input. 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 both tides and freshwater flows. This provides for a wide diversity of communities and an area that is biologically highly productive.

The complete morphology of an estuary is difficult to define, as there are many properties which can be used to describe it. The plan shape of an estuary is an obvious part of the morphology, but it also includes other forms such as the long profile and cross sectional shapes, the upstream meandering channels, the deltas, spits and bars at their mouths. At a much smaller scale, bedforms such as ripples or dunes, or even sediment grain size characteristics, must also be seen as components of the system.

Most estuaries are in, or close to, some form of natural regime or dynamic equilibrium, which is perturbed by tidal, seasonal and episodic fluvial and meteorological events. Maintenance dredging and exploitation of the estuary's physical and biological resources may be part of the existing regime. The morphological regime state of an estuary is a dynamic equilibrium between sediment deposition and erosion, where the balance occurs over a number of cyclic periods, such as tidal cycles, seasons, or even a number of years. Over a short period, in geological terms, of a decade or so, an estuary might be seen to alter significantly. This will be manifested by changes in the position of ebb and flood channels and erosion or deposition of material on sand and mud banks. These changes may be due to episodic or continuous processes. However over a longer period the estuary may often be considered to be stable, with neither a gain nor loss of material within the estuary. In this case the estuary can often be considered to be in dynamic equilibrium.

Any engineering works which alter tidal propagation, gravitational circulation, water quality or the supply of sediment will cause a corresponding change in the pattern of sediment transport. This in turn feeds back on the hydrodynamics so that the estuary converges asymptotically onto a new regime. A natural large episodic event, such as a storm or flood or ice formation, may trigger a non reversible pattern of sediment transport and hence cause a change in the estuary regime. Similarly long-term trends in input conditions to the estuary, such as those caused by sea level rise for example, may mean that the estuary never actually achieves its regime state.

A fundamental difficulty in predicting the behaviour of estuaries is encountered in the synthesis of the system elements into a functional framework. The relationship between process and morphology in estuaries, unlike that in most other landforms, does not exhibit a clear cause-effect hierarchy. Estuary tidal discharges are dependent on estuary morphology, which is in turn modified by tidal currents: no clear distinction can be therefore be made between dependent and independent variables. Predicting estuary response thus involves complex spatial and temporal relationships, with feedback between hydrodynamic, sediment and ecological processes and the estuary morphology being fundamental to the system.

The hydrodynamic processes of tidal movement, wave action and fluvial inflow are relatively well known and documented. However the interaction between these processes is less well defined, particularly in terms of their influence on sediment transport. These forcing processes, together with the influence of sea level rise and human activity, and the interaction with morphology, ecology and geology are ultimately responsible for the evolving estuary state via the related movement of material within the estuary. To determine the rate at which evolution will occur it is therefore necessary to understand the factors influencing the relevant transport mechanisms.

Estuaries generally contain a wide range of sediments, ranging from granular materials such as sand and gravel through to cohesive sediments such as silts and muds. Cohesive sediments in particular show a very intricate behaviour, depending on the physico-chemical properties of the sediment itself, on the chemistry of the water, and on ecological processes. Each of these factors varies spatially and temporally within an estuary, leading to extremely complex patterns of sediment transport and distribution. Little is known about many of these processes, particularly in the long-term, large scale context of estuary morphology.

Ecological activity influences the changing shape of an estuary by modifying the stability of the sediments, impacting on the nature of the sediment-water interface, and by affecting the movement and impact of water on the sediment surface. Significant ecological modifiers occur at all scales from micro to macro, and include bacteria, macroalgae, higher plants and surface living and burrowing animals. In a similar way, the temporal scale at which individual organisms operate is relatively short, but communities can act over much longer timescales. A particular feature of most biological activity is a clear link to temperature and light cycles which suggests that much of the temporal interest in the link between ecology and morphology may be modified by seasonal cycles.

Essentially an estuary is a mixing zone through which a river discharges to the sea. The zone of mixing is not static however, but moves in position according to factors such as the state of the tide and freshwater flow. Consequently water quality in estuaries usually exhibits marked spatial and temporal variations. Many estuaries are highly dynamic, with a high intrinsic capacity for dispersion and dilution. These attributes have been exploited extensively by man in the discharge of waste effluents into estuarine systems. Such discharges can have a profound influence on the water quality profile of an estuary, which through its effect on ecological processes could significantly affect the development of estuary morphology. In turn, the morphology of the estuary, by dictating water flow patterns, will exert a considerable influence on the dispersion and dilution of effluent discharges and hence the water quality profile of the estuary.

4.2 Linkage with other science programmes

For almost all the mechanisms influencing estuary morphology, much is already known about individual, short-term, local processes. This has been achieved through a number of research programmes, including recent studies under the EU MAST and Environment Programmes and the NERC LOIS (Land-Ocean Interaction Study) Programme (including the LISP and RACS sub-programmes). However this knowledge is not in itself sufficient to be able to predict the evolution of an estuary, either in its natural state or as influenced by man's activities. To achieve this, it is necessary to understand and quantify the interactions between different processes, to identify the important factors governing the dynamic equilibrium state, to describe and quantify those factors, and to combine all this information into a system which describes both the short-term, local changes and the long-term, estuary wide evolution of the estuary. The advancement of a comprehensive systems approach such as described would enable links to be developed with various existing and proposed global and regional research programmes such as the GOOS/EUROGOOS (Global Ocean Observing System) and GER (Global Environmental Research) programmes.

4.3 Scientific benefits

Given the extremely complex nature of all estuaries, the research programme proposed here represents an exceptionally challenging task for scientists and engineers from a wide range of disciplines. The programme will therefore deliver improved scientific knowledge and techniques concerning the multifarious interactions between hydrodynamic, sediment, chemical and ecological processes, information which in many cases will have applications over an area much wider than just estuaries. At the same time the programme will lead to the development of a national inter-disciplinary research network, will contribute to the training of young scientists and engineers, and will generate an enhanced skills base to sell UK estuarine expertise overseas.

5 Timeliness

Developments within estuaries have, historically, been examined individually and studies have generally focused on the local impacts. The presumption has been that if the local effects are small, the impact on the wider regime will be negligible. This view has come under increasing pressure for three reasons:

- recent environmental legislation has placed the onus on developers to demonstrate that new works will not have a deleterious effect on important habitats (such development includes the provision of flood and erosion protection works and other infrastructure works such as roads, jetties, quays, etc)

- there is a growing consensus that even quite small changes to the estuary form, may influence the wider equilibrium of the estuary

- whilst individual schemes may have only a minor impact, the cumulative effect of a series of developments may be more significant

The situation is potentially exacerbated by sea level rise and the attendant problem of "estuarine squeeze". In some cases an estuary is topographically squeezed and habitats, such as salt marshes, are only temporary natural features in geomorphological terms. In other estuaries, the presence of the sea defences prevents landward movement of the intertidal area, so preventing the natural system from adjusting to the changing environment. Separating out what is happening naturally, from what is being induced as a result of anthropogenic change, is essential if appropriate management decisions are to be made. The recent report of the IPCC scientific committee reinforces earlier predictions of global change and serves to emphasise the immediacy of this aspect of the problem.

Existing sea defences around many of Britain's estuaries are under threat from "estuarine squeeze", and the option of managed re-alignment of defences is being increasingly considered. A reliable interdisciplinary estuary management system would be a powerful tool in the decision making process, by providing predictions of the long-term development of the estuary morphology and ecology resulting from a range of set-back scenarios.

Users needs are also changing. Demographic shifts and changes in shipping patterns are increasing the intensity of use in certain estuaries. The relatively recent switch to containerisation (last 20 years) is heightening the requirements of ports for sheltered water, a deep water approach and substantial areas of land immediately adjacent to the waterside. At the same time container ships are increasing in size to what are known as "post-Panamax". This is leading to pressure for approach channels to be dredged in order to accommodate these larger vessels. Recent changes to the Conventions for the disposal of dredged material have resulted in the requirement to identify feasible alternatives to disposal at sea. As with other types of activity, there is a need to better understand the implications of such management actions in the wider regime, if unwanted knock-on effects are to be avoided.

The demand for ever-increasing navigable depths and the consequent increase in maintenance dredging volumes indicates a need to consider both capital and maintenance dredging operations within an holistic, estuary wide context. Beneficial use of capital dredgings is already realistically achievable in beach recharge schemes. However an holistic approach to estuary management would also enable the development of new approaches to maintenance dredging which would aim to realise the greatest overall benefit whilst minimising overall costs.

The stated objective of the Netherlands Ministry of Transport, Public Works and Water Management (Rijkswaterstaat) is to retain the maintenance dredgings within the estuary in order to realise flood defence, water quality, conservation and amenity benefits whilst minimising the cost of the dredging to the port authority. The latter is an essential objective because any additional costs would immediately be reflected in increased port charges which would discourage trade and thus inhibit wealth creation.

Unfortunately, as here in the UK, progress towards achieving these objectives is inhibited by the present lack of reliable tools for predicting the long term consequences of the options under consideration. Tools which allow the reliable prediction of long term estuarine morphology will enable evaluation of the consequences of various dredging strategies for flood defence, water quality and conservation as well as for port operation.

Our scientific capability to study these problems, rather predictably, reflects the same historic focus. There is a wide array of tools available to study short term, local problems. The basis for using these same tools to extrapolate in time and so examine longer term changes is highly dubious. Equally, however, work with a more holistic view, seeking to model the system as a whole, has received only limited attention; much of the literature dates from the 50's and 60's! The current understanding of estuary evolution is limited and in consequence our predictive capability is extremely primitive.

This inability to study the problem is already causing delay and constraining development. There is therefore a highly focused demand, from a wide array of users, for tools which enable the concerns of the planners and conservationists to be adequately addressed.

As already noted, the extensive research effort into detailed physical processes to underpin the current capability has not been matched by work on the systems and long term approaches. There is therefore an opportunity to make full use of past and current research, to support a programme which takes a fresh look at estuary behaviour. The emerging environmental research agenda and, in particular, the systems approach being adopted within national programme for Global Environmental Research (GER), are consistent with such an initiative and collectively should be mutually supportive and provide a coherent long term direction to the various research programmes.

6 Options

6.1 Framework

The formulation of the programme is subject to the following considerations:

- address the needs of statutory bodies to respond to proposed schemes
- ensure strong linkage of user needs to scientific programme
- develop stop-gap tools as soon as possible, followed by progressively improved products
- offer a phased programme
- offer options to funders to choose those strands of the programme which meet their needs, and to choose activities within strands
- offer options to trade off time, cost and quality of products
- indicate costs and benefits of options

6.2 Products

The main products of the programme are tools with which to guide management decisions about estuaries. The tools should be capable of making accurate predictions of the impact that a proposed development scheme would have on the estuarine environment. In the absence of such tools (the “Do nothing” option), decisions could be taken to restrict potential wealth creation through commercial and infra-structural development because it <u>might</u> lead to an (unquantified) reduction in quality of life in terms of endangering habitats or an increased risk of flooding of built-up areas. The more accurate the prediction tools, and the greater the confidence that can be assigned to them, the greater the ability to inform the decision-making process to obtain an optimum balance between wealth creation and quality of life.

The main issues that have to be addressed by statutory bodies are:

- flood defence
- navigation
- water quality
- conservation

The tools must therefore be directed at aiding predictions of these three issues. The issues require prediction methods for:

- estuarine morphology
- water/sediment quality
- ecology

Some issues may be relatively short term (up to one year), such as the effect of a toxic spillage, or the effect of a major storm or flood event. Many issues will have to be considered over a longer time-scale (one to 100 years), such as building a barrage, extending a harbour, deepening a navigation channel, building a marina, constructing a power station.

Present prediction methods can be broadly divided into "Bottom-up" predictors for the short term, and "Top-down" predictors for the long term. Taking the example of Estuarine Morphology, Bottom-up predictors are numerical models based on equations describing the detailed physical processes of tidal flows, waves, sediment transport and sediment budget, while Top-down predictors are qualitative-descriptive methods, empirical methods for extrapolating past behaviour to the future, and regime methods, that deal with the response of the estuary-system as a whole without considering individual processes.

The Bottom-up predictors have the problem that computer-time becomes prohibitive for direct long-term simulations (e.g. at least 10 years of continuous computing would be required for a 100-year prediction). Even then it is not known whether continuous integration of short-term processes will give correct predictions of long-term behaviour, because of incomplete representation of processes and accumulation of errors.

The Top-down predictors are simple and quick to use but have the problem that many are based on unproven hypotheses and they do not as yet yield the time-scales of changes. Also past performance of estuaries is not necessarily a guide to the future, especially if major changes (e.g. a barrage) are planned.

The shortcomings of the Bottom-up and Top-down predictors have suggested the development (still in its infancy) of Hybrid models in which a Top-down method is essentially calibrated (either at intervals in time, or probabilistically) by a Bottom-up method. The Hybrid approach appears to offer the optimum way forward for improved prediction methods.

For Water Quality, the short-term, Bottom-up, prediction can be addressed by using a flow model (possibly the same flow model as for the Bottom-up morphology methods) combined with diffusion and water chemistry models. In the long-term, an important factor is the locking up of pollutants in bottom sediments, which may be released slowly through pore-water exchange, or rapidly when the bed is dredged or eroded at a later date. A Hybrid approach would combine these two methods.

Conservation issues require predictors for all aspects of the ecology of the estuary. This in turn requires an understanding of the behaviour of the individual plant and animal species, especially their response to changes in their environment. Such studies can be regarded as the traditional (short-term) biological approach, where short-term here means roughly the life-time of an individual plant or animal. For long-term predictions, computer models of population dynamics have been developed. These are based on hypotheses relating populations of species to factors such as food supply, predation and environmental factors. A Hybrid approach would combine these two methods, and would necessarily also have to be linked to the predictors for flow, morphology, and water/sediment quality. In turn, there would need to be feedback from ecology to the other models (e.g. saltmarsh vegetation damps waves and slows currents; algal mats and mucus secretions bind sediments; burrowing organisms mix polluted sediments deeper into the bed).

Further details of the present methods and their deficiencies can be found in the Review: Section 2 for Morphology, Section 3 for Hydrodynamics, Section 4 for Sediments, Section 5 for Ecology and Water Quality.

The most important, and possibly most difficult, problem for all three of the main issues is the prediction of long-term estuarine morphology. The development of a robust, validated Hybrid morphological model is perceived to be the key to the whole programme. A concept diagram for a programme of research to achieve this is shown in Table 1.

The set of tools, which can include descriptive as well as quantitative methods, to predict short-term and long-term impacts on Morphology, Water Quality and Ecology can be described collectively as an *Estuary Impact Assessment System.* The products of the first few years of the proposed programme of research are progressively improved versions of an Estuary Impact Assessment System.

However, ultimately the pressures on an estuary come from the anthropogenic influences of the developing social, economic and legislative framework (see Section 6 of the Review). Present methods include local (micro) socio-economic analyses (equivalent to the Bottom-up scientific methods), and institutional framework/macro economic models (equivalent to the Top-down scientific methods). A combination (Hybrid) of the two is required to make long-term socio-economic forecasts.

The anthropogenic influences are an essential part of the management process, which when melded together with the scientific predictors (the Estuary Impact Assessment System) can form an *Estuary Management System.* This is the ultimate goal of the proposed research programme.

The definitions of the Tools, Models and Methods detailed above are summarised in Table 2.

6.3 Work programme

A flexible phased research programme is proposed to deliver the above products, summarised in flow-chart form in Table 3, which expands on Table 1. In the boxes the words "Methods", "Models" and "Tools" should all be interpreted as being subdivided according to the scheme in Table 2. The words "Combine methods" should be interpreted as combining Bottom-Up with Top-Down to form

Hybrid methods, as well as combining elements of Morphology, Water Quality and Ecology methods.

The programme is divided into three main phases, with Phase I subdivided into IA and IB. There is a pressing need for a suite of tools *NOW*, to tackle today's issues in as informed a manner as possible with the methods currently available. Hence in Phase IA, the existing methods to predict each of the quantities in Table 2 are collated and reviewed in terms of scientific justifiability and in terms of the degree of testing against data performed by their originators. The Mark IA Estuarine Impact Assessment System (EIAS) comprises this collation with recommendations for which methods are suited to which kind of problem in which kind of estuary. In this and subsequent tests and recommendations, a method of judging must be used which minimises subjective bias (e.g. a double-blind system could be used).

In parallel in Phase IA, existing data-sets for testing each type of predictor are located, selected, obtained (subject to overcoming problems of ownership, confidentiality and cost), and processed into a suitable form for testing the prediction methods. In Phase IB these data-sets are used to make uniform and objective tests of the prediction methods, the results are reviewed, possible minor improvements and re-calibrations are performed, and new recommendations are made to provide the Mark IB EIAS.

It will become apparent in Phase IA that there are gaps in the existing data-sets; possibly no data of a particular type can be located at all. In Phase IB a programme of gathering new data, especially the setting up of long-term monitoring programmes where necessary is initiated.

The newly acquired data will be analysed and interpreted in Phase II to develop a better understanding of both the short-term processes and the long-term behaviour of estuaries. This feeds into the existing Mk IB methods, modifying them and adding new methods, and some cross-fertilisation and combination takes place both between methods for different time-scales, and between methods for different disciplines. The old and the new data are used to test the new methods, and recommendations made leading to the Mark II EIAS.

Data gathering continues and intensifies in Phase II, and basic research into the various scientific disciplines and the socio-economic factors commences, following lead-ins in Phase IB to monitor ongoing activities worldwide and identify the important areas for research.

In Phase III, the basic research (including new methods such as systems approaches) and the development of new understanding from data intensify and cross-fertilise between theories, hypotheses and models and the new data. New, fully-interactive, and cross-fertilised methods are developed, taking account of the work on social, economic and legislative factors and built into a management framework. After testing and further refinement, this delivers an operational Estuary Management System.

At the ends of Phase IB and Phase II there will be a need to review the achievements so far, take account of new requirements, and re-focus and adjust the plans for the next phase. It would therefore not be wise (or possible) to be too prescriptive about the form of Phase III at the present time.

A more detailed breakdown of the activities corresponding to the numbered boxes in the flowchart (Table 3) into individual research tasks is given in the Appendix.

6.4 Coordination

Although this is not a managed programme of research, it is necessary to maintain a strong coordination to ensure that the focus remains on the user needs, and that researchers in each discipline do not simply plough their own furrows. A matrix system is proposed (Table 4), in which the various scientific disciplines are arranged as Science Projects, and these are cross-linked by user-driven Working Groups. The members of the Working Groups will draw out from the Science Projects those aspects which their area of interest requires, and will promote the cross-disciplinary exchanges to produce the overall suite of tools to address their needs. Leaders of the Science Projects will be scientists involved in the research, while leaders of the Working Groups will be representative of the funders or users. A Coordination Panel, comprising the leaders of the Science Projects and the Working Groups, will ensure the cohesion of the whole programme.

Because of the importance of predicting long-term morphological development, approximately half of the total effort is directed at this project, with the other three projects sharing the remaining half.

6.5 Times, costs and quality

As in all walks of life, a trade-off must be made between the time taken to achieve a goal, the cost of achieving it, and the quality of the product. In the present programme, various activities must be undertaken to achieve a viable end-product, but the level at which they are undertaken is optional (e.g. should two, five or ten estuaries be monitored?). Other activities are not essential but would greatly enhance the quality of the prediction methods, and the confidence that can be placed in them, if they were included.

Table 5 shows a list of activities with estimated costs and durations for each, and shows some of possible ways in which they could be combined. The total cost, duration and quality of the output of each option are shown. "Quality" is measured by assigning a score of 100 to Option 18, which is the most likely to deliver a robust and comprehensive management system, and scoring the other options on a relative basis to reflect the degree to which they fall short. The score provides a measure of the quality of the product, and the confidence that can be placed in it, attributable to the various options.

It is seen that Phase I costs £0.6M to £2.6M, lasts 1 to 2 years, and delivers tools of quality 15 to 30. Phase II costs £1.6M to £5.1M, lasts 3 to 5 years, and delivers tools of quality 40 to 60. Phase III costs £5 to £10M, lasts very roughly 5 years, and delivers tools of quality 80 to 100. The costs for Phases II and III are on the basis that the earlier phases have been funded following a similar option.

Table 5 provides a basis for making decisions about the implementation and funding level of the programme, and allows the decisions to be re-assessed between phases.

6.6 Dissemination

It is essential that the scientific knowledge and the management tools generated during the programme are disseminated as widely and quickly as possible. This applies to transfers within the scientific community working within the programme, and also to making the management tools widely available among potential users. Although the greatest emphasis will be to disseminate the various marks of tools at the end of each phase, it is desirable to maintain a more continuous information flow throughout the programme. This will be achieved through guidelines, workshops, seminars, training courses, articles in appropriate publications (e.g. MAFF Flood & Coastal Defence, New Scientist, Nature, New Civil Engineer), television and radio programmes, scientific reports, journal papers, presentations at conferences, and software packages.

7 References

1 Estuary morphology and processes: a review of recent research and user needs. HR Wallingford, Report SR 446, 1997.

2 Perry, C S. Human activities in UK estuaries-a study of their relative social and economic importance. MSc dissertation, Bournemouth University, 1996.

Tables

Table 1 Concept diagram

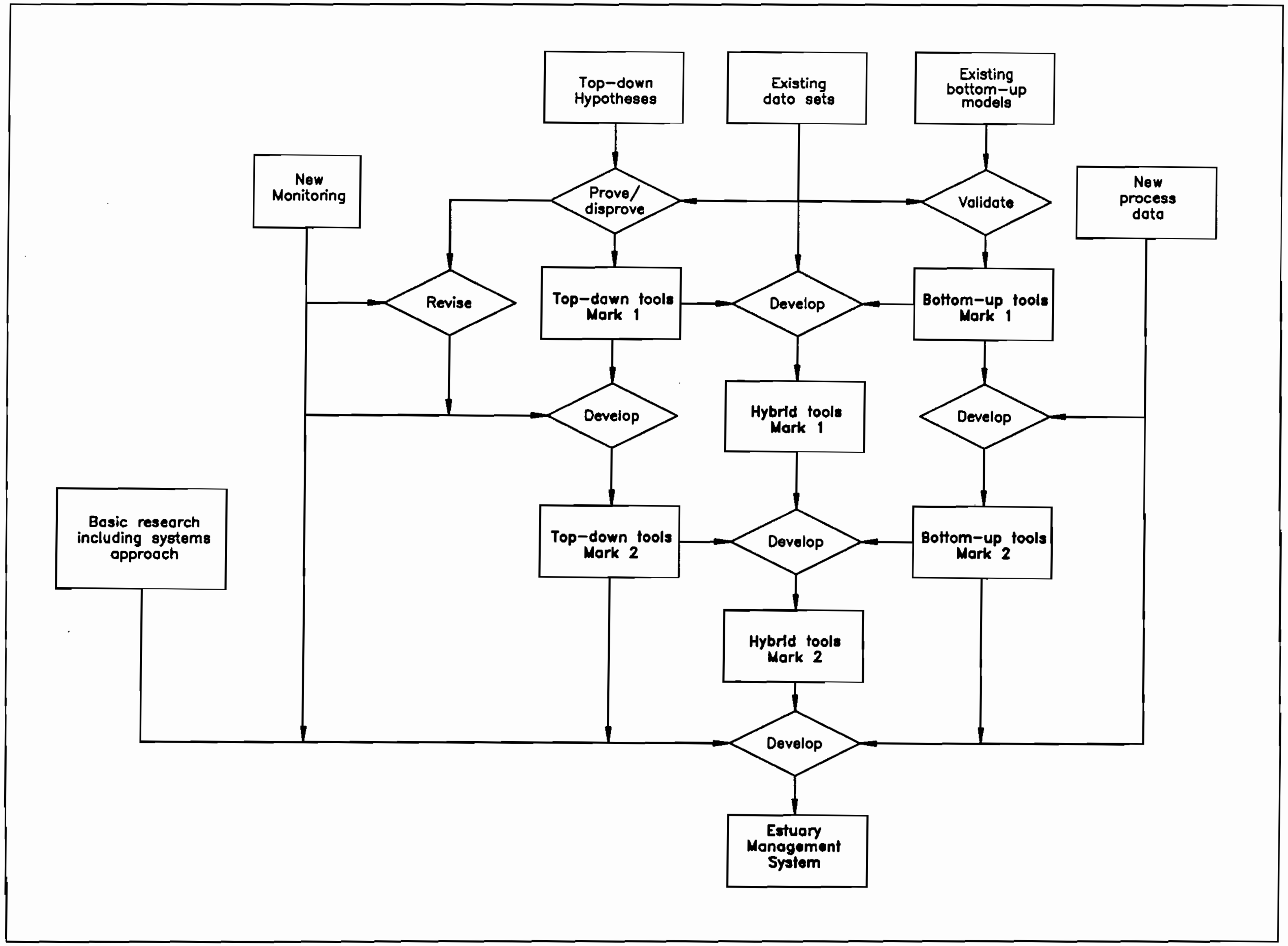

Table 2 Types of methods, models and tools

	Estuarine Morphology	Water/sediment Quality	Ecology	Anthropogenic Influences
Bottom-up (Process-based, Short-term) Methods	Physics-based numerical models	Flow-plus-chemistry water quality models	Plant and animal biological understanding	Local socio-economic analysis/methods
Top-Down (Estuary-system, Long-term) Methods	Qualitative, empirical and regime methods	Sediment-pollutant models	Population dynamics models	Institutional framework / macro-economic models
Hybrid (Bottom-up Plus Top-down, Short to Long term) Methods	Long-term, physics - calibrated, morphological models	Long-term water/ sediment quality predictors	Long-term ecological development predictors	Long-term socio-economic predictors
Estuary impact Assessment System	Collection of the above tools			
Estuary Management System	Interlinked combination of all the above tools			

Table 3 *Programme flowchart*

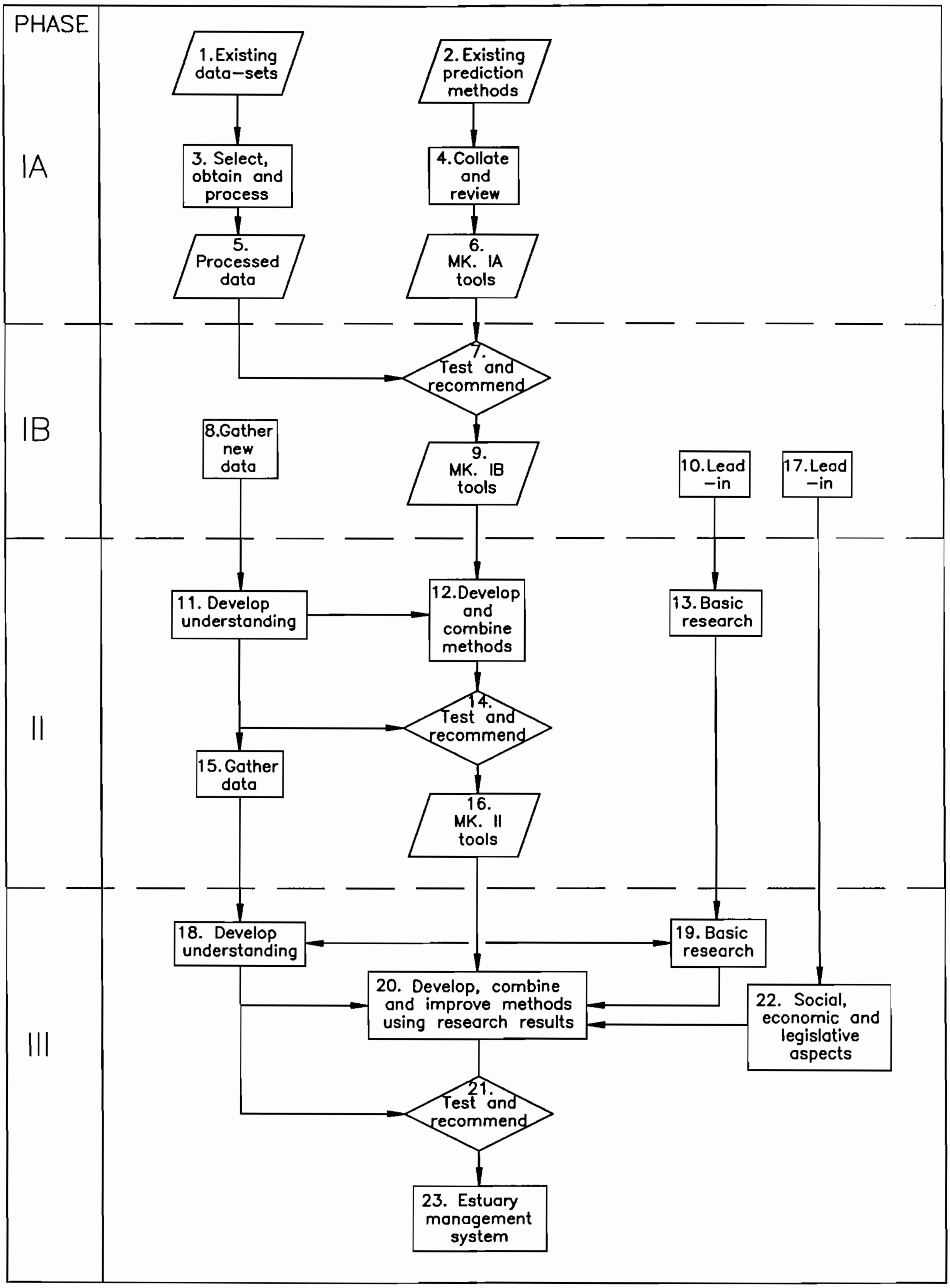

Table 4 User/science matrix

Science project		1	2	3	4
Working Group		Estuarine Morphology	Water/ sediment Quality	Ecology	Anthropogenic Influences
A	Flood Defence	X		O	X
B	Water Quality	O	X	O	X
C	Conservation	X	O	X	X
D	Navigation	X	O	O	X

Key: X Primary importance
O Secondary importance

Table 5 Some options for coherent programmes

		Cost £M	Time yrs	Pre-requisites	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
					Some possible options																	
					PHASE I					PHASE II								PHASE III				
1 Data	a. Existing but raw	0.1	0.5		X	X	X	X														
	b. Existing and processed	0.4	0.5	1a		X		X						X	X	X						
	c. New + monitoring	1.0	5+	1a,1b					X								X	X	X	X	X	X
2 Conceptual development	a. Existing hypotheses	0.2	1	1a	X	X	X	X														
	b. New hypotheses	0.4	2	Present research						X	X	X	X	X	X	X						
	c. Basic research on systems approach	2.0	5+	Present & planned programmes														X	X	X	X	X
3 Develop Whole-estuary tools	a. From existing methods	0.3	1	2a	X	X	X	X														
	b. From new methods	1.2	3	2b, 3a						X	X		X	X		X						
	c. As a result of new basic research	?	5	1c, 2c														X		X		X
4 Develop Process-based tools	a. From existing methods	0.2	1	2a			X	X			X											
	b. From new methods	1.2	3	2b, 4a								X	X		X	X						
	c. As a result of new basic research	?	5	1c, 2c															X		X	X
5 Develop Hybrid tools	a. From existing methods	0.4	1	2a			X	X			X											
	b. From new methods	1.3	3	2b, 5a								X	X									
	c. As a result of new basic research	?	5	1c, 2c																X	X	X
OUTPUT					Variants of EIAS MK I					Variants of EIAS MK II								Variants of EMS				
TOTAL COST (£M)					0.6	1.0	1.2	1.6	1.6 -2.6	1.6	2.2	2.9	4.1	2.0	2.0	3.2	2.6 -5.1	5 - 10				
TOTAL DURATION (YEARS					1	1	1.5	1.5	1.5 -2.0	3	4.5	4.5	4.5	3	4.5	4.5	4 -5	5				
QUALITY/CONFIDENCE (%)					15	20	25	30	15 -30	40	45	45	50	50	55	60	40 -60	80	80	90	90	100

Notes:
1. Monitoring (options 5 and 13) can be added to any of the options 1-4 and 6-12 to give a long term perspective.
2. Many of the activities within a phase can be pursued in parallel.
3. Total costs for Phases II and III are on basis that earlier phases followed similar options.
4. Quality/confidence are scored subjectively by the amount they fall short of the most comprehensive option 18.

Table 6 Potential Annual Benefits

Activity	Annual Value (£m)	Phase I				Phase II				Phase III			
		Influence %	Gain/ Loss %	Confidence %	Benefit (£m)	Influence %	Gain/ Loss %	Confidence %	Benefit (£m)	Influence %	Gain/ Loss %	Confidence %	Benefit (£m)
1. Sea defence	48	20	50	30	1.4	30	20	60	1.7	10	10	100	0.5
2. Navigation dredging	75	10	20	30	0.5	20	10	60	0.9	50	10	100	3.8[1]
3. Aggregate dredging [2]	57	10	(100)	30	(1.7)	5	(100)	60	(1.7)	5	(100)	100	(2.9)
4. Water quality[3]	650	1	50	30	1.0	1	50	60	2.0	1	50	100	3.3
5. Fishing	130	0	0	30	0	0	0	60	0	1	100	100	1.3
6. Ports, shipping	124k	Unquantifiable loss to economy if developments are unnecessarily constrained											
7. Recreation	Undefined	Limited intangible benefits due to reduced impacts from activities 1 - 4				Clear intangible benefits from being able to quantify the impacts of other activities				Significant intangible benefits as estuary wide management seeks to identify sustainable balances between the various interest groups			
8. Conservation	Intangible												
Additional increment due to improved confidence in benefits of earlier phases					0				1.2				3.5
Total incremental benefits for each phase of research[4]					1.2				4.1				9.5
Cumulative benefit					1.2				5.3				14.8

Notes:

(1) Some of the benefit is likely to be achieved by greater recycling of dredge material within the estuary. This may, in turn, give rise to far higher savings in sea defence works than indicated.

(2) It is assumed that, whilst there will be new opportunities identified, additional constraints will give rise to a net reduction in estuary won landings.

(3) Direct savings are taken to be limited but improvements will provide a substantial contribution to intangible gains in Activities 5, 7 and 8.

(4) Benefits for Phases II and III are incremental over those from previous phases.

Appendix

Breakdown of activities into research tasks

To be read in conjunction with Table 3
Numbered activities and outputs correspond to the numbered boxes in Table 3.

Activity/Output	Comments/Benefits
1. - Identification and review of estuary data sets. - Establishing an initial framework for analysis and utilisation of the data. - Production of a simple directory of data	The objectives are to identify those specific data sets which can be used in Activity 3 and to produce an inventory of other data. The benefit of this item is that it identifies existing information which can be used in subsequent parts of the research and also provides a framework for future analysis and utilisation of the data.
2. - Compile inventory of existing Bottom Up, Top Down and Hybrid methods and models. - Define framework for evaluating the available techniques.	The benefit of this item is that it will provide an effective framework for a group of techniques to be investigated together under Activity 4.
3. Establish data sets for selected estuaries using the framework from Activity 1. - Collect all available geomorphological, historical and contemporary data relevant to estuary processes and morphology. - The data sets should typically include information on bathymetry, hydrodynamic and sediment regimes, ecology, water quality and anthropogenic activity. - Collate data and store efficiently so it can be used for subsequent analysis and verification of models. - Identify additional data requirements for future model testing.	Key estuaries will be selected on the basis of known 'good' data sets which will be identified in Activity 1. Quality rather than quantity is important. The main objective is to have good useable data sets for future verification. It is anticipated that of the order of six estuary data sets will be collected and collated in this way. It is recognised that there may be confidentiality difficulties in acquiring the data. It will be important to capitalise on existing data through a co-ordinated approach to the various data collection agencies.
4. Evaluation of existing methods for predicting long-term large-scale estuary morphology. - Evaluation of different influence/response relationships for estuary morphological predictions. To include influence/response relationships between water quality, ecology and morphology. - Evaluating the effect of selection and sequence of events for probabilistic morphological modelling. This will need to include the possible impacts of sensitivity to changes in the forcing factors (e.g. increased storminess). - Evaluation of the hybrid approach to morphological modelling.	To achieve the maximum benefit this item needs to be carried out as a single study involving researchers who have already developed these techniques. Work within this item will include a range of approaches, for example 'top-down', 'bottom-up' and hybrid. It will also build on MAST work carried out under G6M and G8M projects.
5. OUTPUT: A suite of existing data-sets processed into a form suitable for testing of prediction methods/models.	The benefit in establishing these data sets is that they will provide verification data for the various prediction techniques; add to the knowledge base for improved understanding of processes and morphology, and provide direct information for dissemination.
6. OUTPUT: EIAS Mk.IA A suite of tools for predicting morphology, water quality and ecology using existing methods, with recommendations regarding reliability and range of applicability based on published tests.	Gives an immediate benefit to practitioners in that the best present technology in estuary management and planning tools will become available to them. This has a direct benefit in satisfying user need at an early stage in the R&D Programme.

Activity/Output	Comments/Benefits
7. - Test the existing methods collated in Activity 4 against the processed data in Activity 5. - Make improved recommendations based on these uniform objective tests. - Review existing models and establish research framework for development of techniques which show most potential.	Includes Bottom-up, Top-down and Hybrid methods. Benefits include guidance for development work in Phase II.
8. - Identification and recommendations for future data collection methods and sites to enhance and expand existing long-term data sets for future verification data. - Use of DGPS for mapping intertidal and saltmarsh areas. - Use of remote sensing for bathymetric data collection. - Use of models in combination with data collection to allow both temporal and spatial extension of the data sets and to optimise the data collection strategy. - Data collection at selected sites to continue to build up future long term data sets. - Guidance on estuary data collection and potential use of data which will allow practitioners to plan their monitoring in the most effective way. - Should include guidelines for the choice and measurement of chemical, biological, ecological and water quality parameters in addition to bathymetric, current, wave and sediment data.	Recommendations to be made on best practice for future data collection. These will need to be sufficiently flexible for both specific data collection exercises and for simple and practical extensions to existing routine data collection, eg by ports. It will be important as part of this item to provide a mechanism for better co-ordination of data collection by different agencies operating in an estuary, e.g. Ports, EA, EN, etc. This should seek to avoid duplication and make maximum use of the available resources. The benefits of this item are: direct to users in identifying best practice for future data collection both in terms of individual and co-ordinated activities; building on emerging technologies for large scale data collection; establishing long term data sets to be used in Phases II and III; information on available data and data collection being accessible to practitioners. This guidance can be used directly in the effective management and planning of estuary developments.
9. OUTPUT: EIAS Mk. IB An upgrade of the Mk IA suite of tools, based on existing methods, with more robust recommendations regarding reliability and applicability based on uniform, objective tests against existing data.	Enables practitioners to upgrade their estuary management tools at a relatively early stage in the programme.
10. Monitoring of new technologies and developments in modelling (e.g. systems approach) which may have the potential for future application in estuary processes and morphology.	Identifying present 'blue skies' research which could be developed further in Phases II and III.

Activity/Output	Comments/Benefits
11. Development of techniques for understanding and parameterisation of estuary processes. - Use of remotely sensed data for examining estuary sediment characteristics. - Multi-functional use of the EA's monitoring programme of air-borne CASI images of estuaries. - Development of techniques for understanding and parameterisation of estuary processes, through analysis of estuary data sets. - Development of data analysis techniques for improved understanding of long-term evolution and estuary morphodynamics. - Analysis of data in A2 to identify factors influencing morphological form and change. - Use of cores for identifying historical changes to sediment patterns through the Holocene. - Use of spatial data (e.g. water quality, suspended sediments and ecological) as an indicator of estuary processes.	Directed towards improved understanding and parameterisation of estuary processes. This makes good use of emerging technology, e.g CASI, SAR, and builds on work in LOIS and JoNuS. The CASI programme for 1996/97 will have a greater focus on estuaries. Fifteen key estuaries have been selected for coverage using CASI. This item uses existing data with new methods to examine morphology and/or long-term evolution. Builds on work underway with CASI, on the dispersion of water quality tracers, and under the LOEPS project. This item should also consider the use of data from key locations within an estuary as monitors for determining change and therefore planning of developments. This will be of direct benefit to estuary users in providing a simple cost effective tool. The benefit of this work will be improved knowledge and understanding to be used in Activity 12.
12. Review of development of existing models, establish research framework for development of techniques which show most potential. This should include the further development of techniques such as entropy methods, land form models and any more esoteric approaches which arise. Development of existing methods and new techniques for long-term large scale morphological predictions. - Application of improved understanding and parameterisation of physical processes to develop existing influence/response relationships for estuary morphology. - Modelling biogeomorphological development of estuaries - Implementation of revised influence/response relationships in morphological models. - Implementation of parameterisation of physical processes to improve deterministic models of sediment transport. - Development of probabilistic models to use results from improved deterministic models. - Development of the hybrid approach to modelling based on improved regime and deterministic models. - Improved integration of hydrodynamic, sediment transport and water quality models to represent all important effects on morphology.	The benefit of this research is providing improved tools in the medium to long term for the morphological prediction of estuary behaviour. It will also provide direct information to users on methods available for long term prediction. The results of this work will also provide an insight into those areas requiring further development under Phase III.

Activity/Output	Comments/Benefits
13. Improve as necessary understanding and parameterisation of process, short-term and local/and how these influence long-term estuary wide developments including: - Saltmarsh and mudflat processes - propagation of waves and currents, conditions for existence, effects of creeks and improved modelling of sediment transport processes. - Cohesive sediment transport - transport processes on slopes, influence of minerology and organic content on settling velocity, effects of temperature and salinity on suspended sediment, modelling of consolidation and fluid mud processes. - Improved modelling of wave generation and propagation in estuaries. - Modelling the transport of mixed sediments. - Parameterisation of the interaction of biological processes and sediment stability and dynamics. - Understanding mechanics for the absorption, transfer and release of contaminants from sediments. - Evaluation of the processes by which organic carbon is deposited into sediments, modified and released. - Evaluation of the processes by which sediments and suspended solids can exert an oxygen demand on the water column.	Research as required to support long-term, estuary wide understanding and parameterisation. Will build on JoNuS, MAST, (e.g. INTRMUD and coastal morphodynamics), LISP and ECOS work and use data from the Tollesbury site. The direct benefit to estuary users is in providing improved methods for evaluation of short-term impacts of developments. There is an immediate benefit in terms of an understanding of the effects of water quality on sediment transport and in the modelling of water quality processes. This work will also assist in the definition of sediment quality in estuaries and could contribute to the EA GQA schemes. There is benefit in providing improved understanding and methods for predicting the impact of placement of dredged material, e.g. in beneficial use schemes.
Improve understanding and parameterisation of processes long-term and estuary wide including: - Identification of factors influencing the distribution of fine sediments and suspended solids within an estuary. - Influence on estuary transport of ebb/flood dominance, density flows, extreme events, pollutants and water quality. - Effect of geological constraints on estuary shape. - Direct and indirect influence of water quality changes, trophic (nutrient) status and contaminant load on sediment properties.	This will provide the fundamental scientific information required for the development of improved Top-down and Hybrid models.
- Development of sediment transport relationships which can be used in long-term predictions.	Most of the established relationships are for short-term impacts. A different or modified parameterisation is required for long-term predictions.
14. - Test the new and combined methods developed in Activity 12 against the processed existing data from Activity 5 and the new data from Activity 8. - Make recommendations about the reliability and range of applicability of these methods. - Identify most appropriate models for further development and combination.	Includes Bottom-up, Top-down and Hybrid methods. Benefits include guidance for development work in Phase III.
15. - Continue monitoring programmes started in Activity 8. - Make selected measurements at selected sites to further understanding of processes.	Benefits include the accumulation of long-term data, and information to guide the basic research in Activity 19.

Activity/Output	Comments/Benefits
16. OUTPUT: Estuary Impact Assessment System Mk. II. A suite of new tools for predicting morphology, water quality and ecology, with recommendations regarding reliability and range of applicability based on tests against old and new data.	Gives a step benefit to practitioners by providing them with new up-to-date purpose-built and tested tools.
17. - Produce a summary of existing legislation for estuary developments. - Identify social, economic and legislative issues to be addressed in Activity 22. - Monitor changes in legislation and anthropogenic pressures.	Gives rapid start on investigation of anthropogenic issues in Phase III. The intention is to provide users with a summary of the issues which may need to be addressed and who they need to contact to understand legislative requirements. This item provides a direct benefit in addressing a clearly stated user need.
18. - Continues Activity 11. - Interlinks with Basic Research activity.	Provides the new understanding from data which will lead to more advanced prediction methods.
19. - A considerable expansion of the Basic Research in Activity 13. - Interlinks with understanding from new data. - Interdisciplinary studies (physics/chemistry/biology/geology) will be important.	Provides the innovations and new theories which will lead to more advanced prediction methods.
20. - Review of progress on operational oceanography and progress in developing a systems approach to Global Environmental Research (GER). - Develop opportunities for linking local process/morphological models with regional and global models being developed as part of the operational oceanography initiative. - Exploit results of initial monitoring (from years 1-5) to advance process studies and refine predictive capability. - Linking with the operational oceanography initiative and the GER programme develop more integrated approaches which consider all components of the system; physical, chemical, biological and human. - Emphasis now is on Hybrid models. - Models and methods to be linked in a fully interdisciplinary super-model. - Models and textual information to be built into a management framework including social, economic and legislative issues.	Opportunity to revise and re-focus the research requirements to build on work in Phases I and II and take advantage of newly emerging scientific developments. Since operational oceanography requires local data and the estuary models make use of external forcing, closer links between these initiatives will be mutually beneficial. Benefit is in ensuring that an early return is achieved from the monitoring programme which is to be established under Phase I. This item provides a major challenge to the research community but only if it is tackled with vigour will we begin to be able to identify, explain and predict the consequence of human actions within the estuary environment.
21. As Activity 14, but now including tests of the management and anthropogenic aspects.	
22. - Develop local (micro) socio-economic analysis/methods. - Develop institutional framework/macro economic models. - Develop long-term socio-economic forecasting tools.	Provides the socio-economic/institutional framework needed to house the modelling methods in Activity 20.

Activity/Output	Comments/Benefits
23. OUTPUT: Estuary Management System	
A completely integrated system combining prediction and modelling methods for morphology, water quality and ecology within the hyper-text setting of a management framework. Includes (inter alia): - Guidelines on existing best practice for planning and design of estuary developments. - Identification of techniques for establishing geomorphological, historical and natural variability. - Methods for determining long-term effects of discharges and abstraction. - Methods for determining impact of dredging and placement and storage of dredged materials.	These items were all identified as user requirements. The information required to address these issues will come through Phases I and II and also capitalise on work underway on the beneficial use and properties of dredged material. Dredged material provides a resource which, if it can be used in an effective and economical manner, has a large potential benefit to estuary users. By disseminating this information there will be a direct benefit to those involved in providing improved techniques for estuary management and planning.
- An estuary management manual.	This is intended to be an incremental manual. In Year 1 introductory text describing estuary processes, morphology and methods for assessing short-term impacts of works will be included. Year 5 will see an additional section on estuary management pactice based on the outcome of Phases I and II. Revision in Year 10 based on information from Phase III. This is seen as providing education for practitioners and those who affect estuaries on the history, behaviour and the implications of sea level rise.

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