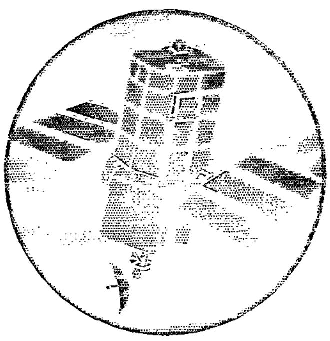
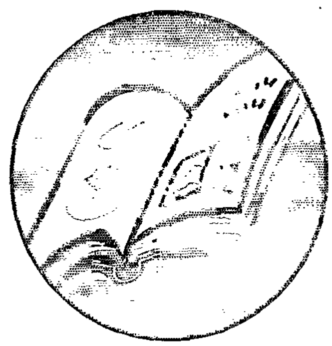
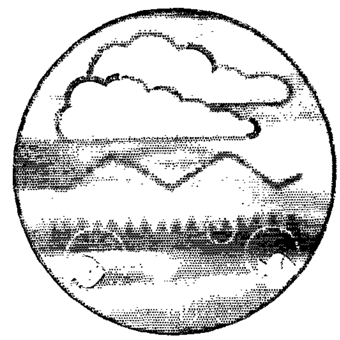
Determining the Freshwater Flow Needs of Estuaries

Research and Development

Technical Report
W113

ENVIRONMENT AGENCY

Determining the Freshwater Flow Needs of Estuaries

Technical Report W113

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This report presents a methodology for the determination of the freshwater flow needs of estuaries. The information within this document is for use by Agency staff involved in the licensing of freshwater abstractions from rivers and in the computational modelling of estuaries.

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R&D Technical Report W113

CONTENTS

EXECUTIVE SUMMARY

Scope of study

The overall aim of this study is to establish best practice, shortcomings and future research needs in determining freshwater flow needs of estuaries. In particular, the study examines the use of computational, including statistical, modelling. The study has reviewed:

- existing relevant R&D;
- estuarine processes and uses; and
- the present and possible future use of computational modelling techniques for estuarine analysis, especially in determining the minimum flow needs of estuaries.

It gives guidance on:

- a methodology for the determination of minimum flow needs;
- the general and data collection requirements of various types of models; and
- carrying out a preliminary assessment before starting a major study.

The outputs from the study are:

- This R&D Technical Report (W113) that identifies shortcomings, best practice, implementation benefits and future R&D of freshwater flow needs to estuaries; and
- A quality control manual (R&D Technical Report W168) to be used when undertaking a computational model study.
- R&D Technical Summary WS107.

Relevant R&D

Relatively little R&D has been directed towards the freshwater flow needs of estuaries and the determination of residual flows. There is, however existing or ongoing research into:

- Aspects of computational modelling, providing support to residual flow determination;
- Residual flows in rivers. The Surface Water Abstraction Licensing Policy (SWALP) procedure is designed to consistently assess applications for surface water abstractions.
- Morphology. Current MAFF research is looking at methods for the prediction of long term morphological change caused by changes in the estuary.
- Fisheries research. This includes research into minimum acceptable flows and the effect of temperature on migratory fish.
- Risk assessment. Research into risk assessment methods in management decision making and long term corporate planning. A risk assessment approach has been used in the determination of freshwater flow needs in this study.

Estuarine processes and uses

Most short term estuarine processes are well understood and can be simulated by computational models or other analytical methods. However, there are major gaps in knowledge in:

- Long term morphological change;
- The relationship of sediment and ecology; and
- Ecological mechanisms.

Present and future use of modelling techniques

Computational modelling is closely linked to the computing power available. It is certain that the power available on the average modeller's desk at low cost will continue to escalate. It will become possible to create models that are:

- more realistic, using more complex algorithms to simulate hydrodynamic, chemical or ecological functions;
- more detailed in space and longer in time;
- more integrated, with a single model being used for a range of functions; and
- simulates morphology and ecology with confidence.

Modelling is widely used in the Agency for flow and quality analyses. However, less advance has been made in the use of models to determine the freshwater flow needs of estuaries.

Methodology for determining freshwater flow needs

This report sets out a management and technical approach to freshwater flow need studies. The approach is designed to make best use of existing and emerging technology. The approach also allows the manager to use simple methods of analysis where budget dictates, although it should be stressed that the use of such simple methods should be seen as less than ideal, adding little to one's knowledge of the management or needs of an estuary than the methods used to fix the last round of Minimum Residual Flows (MRFs) a generation ago.

The management approach stresses the need for a coherent data management policy. At present data collected by the Agency may not always be easily retrievable for future studies. A policy is needed that:

- Encourages project teams to archive data;
- Creates a simple, yet comprehensive, database to allow retrieval of this data;
- Makes use of the best technology, such as geographical information systems (GIS); and
- Collects long term morphological data in advance of computational modelling developments in this field.

A technical approach for the determination of freshwater flow needs is proposed, using concepts from risk assessment. This approach is shown below:

STAGE 1	Review existing reports and check data availability.
STAGE 2	Classify estuary type and select estuary reaches.
STAGE 3	Determine external review, complete data and impact matrices.
STAGE 4	For low impact uses and processes, use simple analysis methods.
STAGE 5	If appropriate, carry out preliminary analysis.
STAGE 6	Review design standards and set out study standards.
STAGE 7	Complete risk matrix, seasonal variations and risk assessment.
STAGE 8	For each use and reach, select appropriate analysis method.
STAGE 9	Rationalise and optimise model design.
STAGE 10	Cost modelling studies.
STAGE 11	Consider joint funding of modelling, or simpler models.
STAGE 12	Set up modelling contracts.
STAGE 13	Carry out or manage modelling studies.
STAGE 14	Analyse model results and set MRF.
STAGE 15	Post-project appraisal.

Recommendations

This report recommends the following future R&D needs:

- The technical approach described should:

  a) be trialed; and
  b) its application to disciplines other than water resources considered.

- Each region should develop a strategic computational modelling plan that:

  a) indicates the management approach for each estuary, as to whether modelling will be carried out in-house, jointly, or by audit only;
  b) proposes a strategic programme for in-house modelling; and

- Data collection and management should be reviewed, then:

  a) a fully integrated and focused data monitoring strategy adopted;
  b) a consistent policy on data adopted between regions;
  c) a minimum specification database to archive estuarine data developed; and
  d) a GIS should be used for this data archive.

- An overview should be kept of advances in morphological and estuarine modelling techniques to identify any future R&D needs.

- Data collected by the Agency does not include data sufficient for the building of morphological models to predict long term changes in an estuary. The Agency should:

  a) keep the ongoing MAFF sponsored research on morphology in view; and
  b) implement a morphological data collection programme as soon as is practicable.

- Agency functional groups and policy makers should consider whether:

  a) the Agency's computational modelling budgets are adequate for the Agency to maintain its capability in computational modelling:
  b) the Agency's regulatory role if carried out through review and audit of others work alone, if modelling is no longer carried out; and
  c) whether the Agency loses its independence as a regulator if it co-operates with other interested parties in developing estuary models.

Part A - INTRODUCTION

1. INTRODUCTION

1.1 Scope of study

The overall aim of this study is to establish best practice, shortcomings and future research needs in determining freshwater flow needs of estuaries. In particular, the study has examined the use of computational, including statistical, modelling in determining these needs. Although written from a water resources perspective, it is recognised that this aim also affects a number of other functions, such as water quality, flood defence and fisheries. It is hoped that the resulting document will be of practical use across all disciplines with an interest in estuaries.

The study has therefore reviewed:

- existing water quality, resources and flood defence R&D relevant to computational modelling of estuaries and the determination of their freshwater flow needs, in order to avoid duplication of effort;
- existing R&D into quality assurance applied to computational modelling of rivers and estuaries;
- the present use of computational models in simulating the response of estuarine processes to variations in residual flows to estuaries both in the UK and abroad.
- estuarine processes and uses; and
- the present and possible future use of computational modelling techniques for determining the minimum flow needs of estuaries.

It gives guidance on

- a methodology for the determination of minimum flow needs;
- the general requirements and data collection needs of various types of models;
- carrying out a preliminary assessment before starting a major study, to identify important processes in the estuary, appropriate model type and data needs.

The outputs from the study are:

- This R&D Technical Report that identifies shortcomings, best practice, implementation benefits and future R&D of freshwater flow needs to estuaries.
- A quality control manual to be used when undertaking a computational estuary model study.

The main elements of this document are shown below:

PART A	INTRODUCTION - Scope and background of study, examples to illustrate need of study, recent relevant references.
PART B	BACKGROUND INFORMATION - estuarine processes, uses affecting freshwater flows, computational modelling techniques.
PART C	METHODOLOGY FOR ESTABLISHING FRESHWATER FLOW REQUIREMENTS - methods in use and possible future ideas.
PART D	STRATEGY FOR ESTABLISHING FRESHWATER FLOW REQUIREMENTS - proposed management and technical approaches.
PART E	SUPPORTING INFORMATION - list of consultees, bibliography, model costs and worked examples.

The reader wishing to apply the findings of this report should read Part D, which contains a proposed management and technical methodology to determine the freshwater flow needs of an estuary.

1.2 Background

1.2.1 Need for national approach

The Environment Agency has a statutory duty under the Water Resources Act 1991 to conserve, redistribute or otherwise augment water resources and secure their proper use. The determination of a minimum residual flow (MRF) to an estuary is one of the key steps in evaluating the water resource potential of a river, and in the effective management of the estuarine environment. The MRF is defined as the river flow at which a licenced abstraction ceases. River flows can therefore naturally fall below the MRF value.

Current determination of MRFs to estuaries varies between regions, and is based on protecting legitimate interests or uses such as navigation or water quality standards within the estuary defined through consultation. Quantifying the impact of different MRFs on the estuary processes is difficult, so often the observed Q95 low flow statistic, at the gauging station closest to the tidal limit, is commonly taken as the MRF to an estuary.

A recent paper by Roger Wade (1996) summarises the position as follows:

- Historically, a wide range of methods have been used to determine the MRF;
- Use of mathematical models has often been incidental to setting the MRF;
- There is a need for the Agency to use nationally agreed methods for setting MRFs (and freshwater flow needs) in estuaries.

It is true that most estuaries have their own characteristics, and that generalisation is not possible between them. Similarly, the processes and uses that dictate the freshwater flow needs of an estuary vary. For example, Wade quotes the variation in policy between the wetter west and the drier east of the UK. The west may attempt to maintain a natural flow in the river ('put and take') whilst some smaller eastern estuaries accept zero residual flow.

Despite these differences, there is a need for a uniform approach. This should recognise the different priorities and characters of different estuaries, but it should also ensure that no process or use is erroneously omitted from the process of determining flow needs.

1.2.2 Need to identify impacts

The Habitats Directive requires the Environment Agency to review authorisations (including abstraction licences) affecting specified estuarine sites. The estuarine sediment budget may be influenced by both high and low freshwater residual flows; the growing awareness of the dynamic balance in sediment budgets in estuaries has resulted in a requirement to look at the freshwater flow needs of estuaries rather than just the minimum residual flows often referred to in surface abstraction licences.

A methodology is therefore required that challenges the traditional assumptions about estuaries and ensures that this increased knowledge is applied by the Agency. Further, the importance of a variety of technical functions in determining the freshwater flow needs becomes apparent. There may be need for close liaison between those involved in, amongst others:

- water resources;
- flood defence;
- water quality;
- fisheries; and
- conservation.

Any new national methodology must reflect this inter-disciplinary approach, and simplify the interaction of the various functions of the Agency.

1.2.3 Need to quantify impacts

At present, most freshwater flows to estuaries are based on qualitative best estimates rather than rigorous scientific investigation. The use of computational models is one of the most powerful tools available to quantify the effect of variations of freshwater residual flows when applied to estuarine water quality/morphology processes. Wade (1996), however, noted that their use in determining the freshwater flow needs of estuaries was, at best, peripheral.

The reliability of the estuary model depends directly on uncertainties in measurements, model structure and parameter estimates. The type and scale of use, sensitivity of that 'use' to the setting of a freshwater flow requirement, and the form of standards that the Agency needs to achieve (eg 95%ile water quality) will control the amount of money spent on reducing uncertainty in the model results and modelling strategy adopted.

The prolonged and detailed public enquiries that are likely to accompany future applications to increase abstraction and reduce MRF in estuaries will require supportable evidence of the impact of increased abstraction. Any new national methodology must provide such quantified evidence.

1.2.4 Use of computational modelling

There are two main types of modelling techniques available to test the effect of residual flows on the estuarine transport/residence processes:

- Statistical models provide a relatively quick approach which uses linear regression analysis to relate empirically the observed values of variables. Statistical models are useful in initial studies to assess qualitatively the effects of different MRF on an estuary. Statistical models are limited in their ability to account for the high degree of scatter in field data, and need a large amount of field data. They are better suited to defining future conditions within the range of observed data. They are less reliable in extrapolating to conditions not previously observed.

- Deterministic/hydrodynamic models use mathematical descriptions of physical laws and processes, and require detailed research and carefully designed field data collection. Deterministic models can considerably improve on the prediction accuracy and reliability of the statistical regression models and can establish the quantitative effect of residual flows on the estuary. The degree of reliability required of model predictions determines how much is spent on the data needed by the model and the type of model used. Sensitivity analysis using deterministic models can establish the key areas of uncertainty and help focus where and what field data are needed. There are several deterministic models available but not all are appropriate or easy to use.

Within the industry, some are still resistant to the use of computer modelling to help determine residual flow needs. Others strongly support modelling, perhaps without proper consideration of the limitations or appropriate use of the model. There is a need for a methodology that sets out a considered and balanced use of models.

There is also a need for guidance on how reliable the model results should be, and what the most appropriate models are to answer specific queries or requirements for data. A system is needed to ensure that procedures are correctly followed and to check that the software is being correctly applied.

1.3 Examples to illustrate needs

1.3.1 The Humber

The Humber Estuary Management Strategy (HEMS) (English Nature, 1997) is a good example of the complex and diverse uses of a major estuary. It illustrates the need for a rigorous approach to the determination of freshwater flow needs.

Users or stakeholders within the Humber, with significant and valid contributions to the estuary management include such diverse groups and interests as:

- agriculture;
- archaeological and cultural resources;
- fisheries;
- flood defence and coastal processes;
- industry and commerce;
- integrated pollution control;
- landscape;
- nature conservation;
- navigation and port development;
- sport, recreation and access; and
- tourism.

These groups and interests must be matched with the following key issues for the estuary. Issues where there is possible interaction with freshwater flow needs are shown by an asterisk:

1) Creation of a strategic planning framework;
2*) Physical and sedimentary processes;
3*) Physical processes in estuary and open water;
4) Sea level rise and coastal squeeze;
5*) Flood protection;
6*) Integrating international conservation objectives with port and industrial development;
7*) Water quality;
8) Waste minimalisation;
9) Contaminated land;
10) Sustainable economic development;
11*) Recreational management;
12) Tourism; and
13) Education and information.

The complex issues of the Humber require quantitative answers to support the estuary manager's attempts to balance the demands and needs of the many users and interest groups.

In addition, some effects of the freshwater flow inputs on the sediment dynamics of an estuary can be illustrated with reference to the Humber Estuary. In the upper region, prior to training works at Trent Falls, circa 1930, the local channels oscillated from side to side depending on the relative magnitudes of the flows from the River Trent and River Ouse. The training works stabilised this movement. Further down river, in the vicinity of Read's Island, the main channels migrate back and forth across the width of the estuary in a defined pattern, but not on a regular (cyclic) time scale. The change in direction of movement can be attributed to long periods of sustained high river flows. During this process large volumes of sediments are redistributed not only in the reach of the main channel but further up and down river, thus causing changes to the depths and levels of the channels and shoals. Such episodic events can therefore develop a chain reaction along the estuary, and, in some cases, these will be noticed because they will affect the use of the estuary, eg. navigation channels. In many cases, however, the immediate effects may not be noticed but lead to long term changes in the estuary form.

In the Lower Humber detailed records of the bathymetric changes have been made on an annual basis since about 1955. These indicate a cyclic pattern in the bank and channel configuration which have been closely linked to the dredging requirements for the Sunk Dredged Channel. The changes, however, cannot be linked to the variations in freshwater flows. Siltation rates on a monthly basis in the Sunk Dredged Channel however do show a relationship with freshwater flow inputs to the estuary (ABP Research, 1991, 1993). Generally lower than average freshwater flows increase rates of siltation within the channel and higher than average flows cause a reduction, but at a slower rate per unit change in flow. These changes are superimposed on the siltation rates caused by the changes in the bathymetry of the whole lower Humber as noted above. This effect on siltation rates within Sunk Dredged Channel is illustrated in Figure 1.1, taken from ABP Research (1993). Although the data set as a whole shows no relationship, if the data is split into three sets, corresponding to the years when the dredging requirements were high, medium and low, three near parallel linear relationships between annual freshwater flows and the rate of siltation are found. Figure 1.2 plots the long term average siltation rate against the average monthly flows and this clearly shows siltation tends to be low during the wetter winter months with higher rates particularly at the end of the summer/drier months.

The analysis also indicated that when the total freshwater flow input to the River Humber reduces to below 100 cumecs the siltation rate within the channel increase markedly. This is particularly evident when these flow rates are sustained for several months over the summer period. Similar periods during winter have less effect, indicating that water temperature is another factor in controlling the siltation patterns. Moreover, Jackson in BTDB (1970) has shown that the suspended sediment content at locations in the Humber Estuary can be correlated, using a multiple regression technique, to tidal range, freshwater flow input and water temperature.

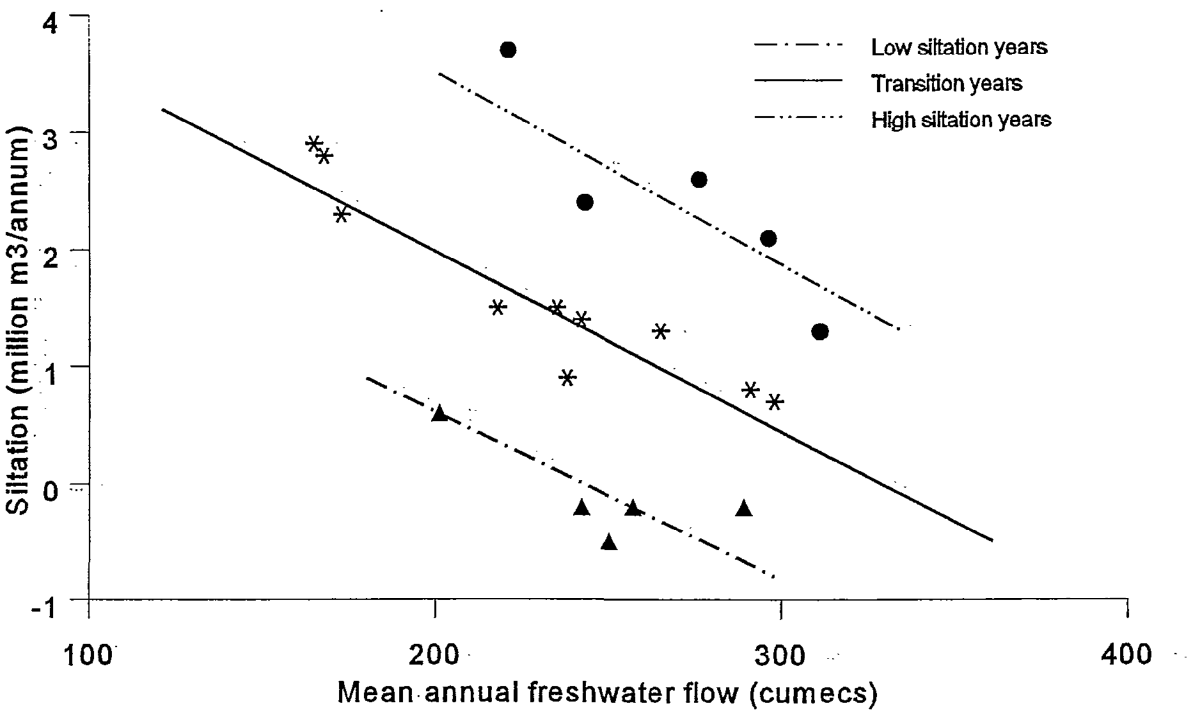


Figure 1.1 - SUNK DREDGED CHANNEL - RELATIONSHIP BETWEEN MEAN ANNUAL FRESHWATER FLOW AND ANNUAL SILTATION

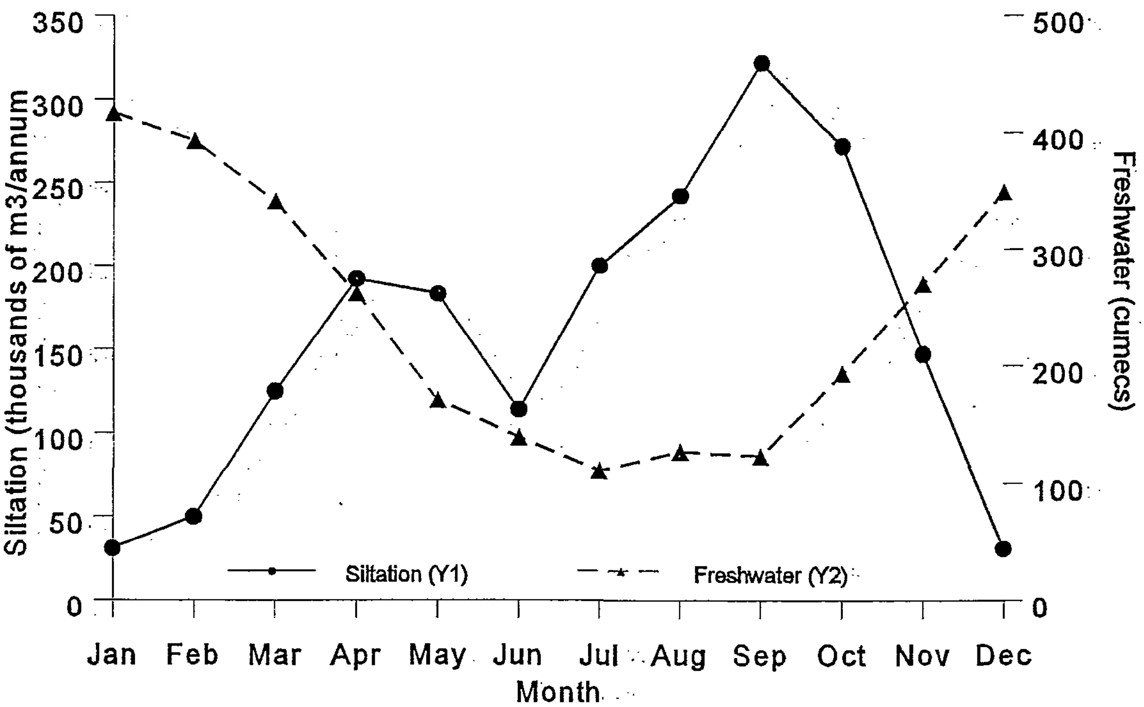


Figure 1.2 - FRESHWATER FLOW/SILTATION - MONTHLY AVERAGES 1970-1991

1.3.2 The Great Ouse and the Wash

Another example of how changing freshwater flows can affect sediment patterns in estuaries is illustrated with reference to siltation and shoaling patterns in the River Great Ouse (HR, 1993). From an analysis of bed levels and freshwater inputs between 1964 and 1988 a correlation was established between rising bed levels and reduced inflow from up river. Further down river in the vicinity of King's Lynn studies have shown that the position and heights of shoals are related to the antecedent fluvial flows. The shoals were found to increase in height after periods of low fluvial flows, below about 30 cumecs. After 2-4 months of such flows the shoals become an impediment to navigation to the docks. During periods of high fluvial flows the shoals tend to move seawards and reduce the problems to navigation. In general terms, during periods of low flow, sediments enter the estuary and deposit causing siltation either on specific shoals or more widespread further upstream. During the winter higher flow periods, the estuary is flushed creating a state of balance on an annual timescale. However, during periods of drought sediment build up occurs and if winter flows are insufficient to flush the sediment, overall bed levels increase in the river and sediments begin to consolidate. In this case, when the higher flows come they are less effective at cleaning the sediment from the estuary. In the case of the River Great Ouse the same scenario can be induced by the regulation of the flows from the various sluices and the abstraction of water. Generally the greatest abstractions are required when drought situations occur, thus the siltation rates will be accelerated. If the winter higher flows are also reduced then an overall trend towards the long term build up of sediment in the river will occur. There is evidence to suggest that this situation has already been reached.

An important function of the freshwater input to an estuary is in terms of its flushing effects. In the case of the Great Ouse the freshwater assists the flushing of sediments but in other estuaries it may be more important in mixing and flushing pollutants and contaminants. In such estuaries, reduced flushing ability could increase pollutants which change the ecology of the estuary. In time this would also have a secondary influence on sediment patterns. The fauna and flora within the sediments, both bind and break up sediments thus changing their resistance to erosion and therefore the ability for sediments to be transported. Thus pollution which kills the fauna could either cause increased stability to a former eroding mudflat, or increase the potential for erosion of a formerly stable area. In this way changes to freshwater flow inputs to estuaries have both a primary and secondary influence on the estuary form and also its function. Some effects will be seen in the short term but others may only be apparent over many years.

1.3.3 The Bure

The river Bure, in the Norfolk Broadland has serious low flow problems which results in saline intrusion caused by tidal surges extending significantly further inland. This has the following effects:

- Fish kills. Freshwater fish are driven by the salinity into minor rivers and off-river broads where they are trapped and die;
- Habitat loss. There is a loss of freshwater invertebrates and sensitive flora;
- Loss of freshwater supply. Intakes have to be shut down during surges;
- Loss of investment in the habitat restoration programme, as the treatment of eutrophic broads is compromised by saline intrusion; and
- Farmers are unable to take water from the river to maintain the high ditch levels required to qualify for ESA payments.

Here we have a less complex system, but nevertheless quantitative assessment of the problem is needed for successful management.

1.3.4 Summary

Three examples, albeit all from the east of England, show some of the mechanisms at work in an estuary (detail of the processes are described in Chapter 2) and that freshwater input is a major factor in determining patterns of sedimentation within an estuary. The natural variations in seasonal freshwater input and longer term changes in the climate will also change the sediment distribution. In many estuaries, or even locations within a particular estuary, these fluctuations will have little impact on human use. However, in estuaries used, for example, for industry, navigation, fishing and recreation, specific changes to the location of the turbidity maximum, shoals and even areas of erosion could be very important. Human use or modification to flow input could singularly or in combination with natural variations cause long term changes to the estuary mechanisms leading to serious impact on the estuary form, uses and users of the estuary.

1.4 Recent relevant references and research

1.4.1 General

The question of freshwater flow needs of estuaries has been the topic of much debate since at least the 1960s. The debate was stimulated in 1972 by Frank Law's paper to the Institution of Civil Engineers entitled "Determination of residual river flows." The paper put forward eleven principles concerning minimum residual flows in relation to abstractions and the needs of estuaries.

In 1975, the Food and Agricultural Organisation of the United Nations (FAO) published a Fisheries Technical Paper (No. 143) entitled "Determining discharges for fluvial resources." The paper reviewed the methods used, mainly in the USA but also in other parts of the world, to determine the freshwater flow requirements of rivers and estuaries, principally for fishery resources. However, the importance of rivers and estuaries in so many of Man's activities was acknowledged and discussed.

In the late 1970s, the Central Water Planning Unit carried out a detailed review of the freshwater requirements of estuaries which culminated in the publication of a report in September 1979 entitled, "Residual flows to estuaries". This is one of the most detailed reviews available of information on features of estuaries most likely to be affected by reduced river flows. It discusses ways of quantifying these effects and of assessing their importance. The report drew on the collective experience of a number of relevant UK agencies including:

- The Freshwater Biological Association;
- The Hydraulics Research Station;
- The Ministry of Agriculture, Fisheries and Food;
- The Water Research Centre;
- The Welsh Office; and
- the various Water Authorities.

1.4.2 1992 Baseline Study

In 1992, NRA completed a study of the current situation in their 10 regions (Wade, 1992). A total of 67 estuaries were investigated. 30 of these (45%) had some form of residual flow set or suggested. Reasons for setting MRFs can be grouped under 5 headings:

Water quality	-	dilution of sewage treatment works (STW) effluent
	-	to achieve/protect water quality objectives
Abstractions	-	to protect licensed abstractions that are linked to river flows
	-	to limit the ingress of saline water towards intakes
Fisheries	-	to enable the passage of migratory fish
	-	to maintain local fish populations and commercial fisheries
	-	to maintain feeding areas for shellfish
Navigation	-	to prevent excessive siltation in channels and harbours
	-	to maintain water depths for commercial shipping and recreational boating
Nature conservation issues	-	basic amenity and general ecosystem requirements

Table 1.1 is adapted from Table 2 of the NRA report and shows the wide range of ratios of residual flow to Q95. In general, 95 percentile dry weather flows were considered adequate to provide the required dilution of effluents. However, this clearly depends on the pollution load of the river which varies both with time and from river to river. Dilution of effluents is only one of several reasons for establishing minimum residual flows.

Table 1.1 - Residual flows as a proportion of Q95 in UK estuaries

Region	River	Residual flow as a proportion of Q95			
		<0.5	0.5 - 0.99	1.0 - 2.0	>2.0
Northumbrian	Tees		0.53		
	Wear		0.61		
	Tyne	0.47			
North West	Derwent		0.67		
	Lune			1.38	
	Wyre - Winter			1.91	
	Wyre - Summer				8.50
Welsh	Dee			1.00	
	Tywi		0.51		
	Usk	0.42			
	Wye			1.37	
Severn Trent	Severn - Neap tides		0.81		
	Severn - Spring tides		0.97		
Wessex	Avon (Bristol)	0.28			
	Parrett			1.00	
	Avon (Hants) - Summer			1.08	
	Avon (Hants) - Winter				3.86
South West	Exe			1.00	
Thames	Thames		0.52		
	Lee			1.33	
Anglian	Waveney		0.42		
	Yare	0.26			
	Bure	0.14			
	Ouse			1.06	
	Nene	0.24			
	Witham		0.46		

Source of data: Wade et al (1992).

1.4.3 The setting of Minimum Residual Flows

In 1975, FAO's Technical Paper No. 143 stated that,

"...the science..of determining adequate streamflow is in its infancy - born on the heels of intensive and hastily conceived water development projects."

NRA's 1992 report shows that in the UK at least, the science has not progressed all that far. A clear finding of the study was that very few MRFs have been set on a firm scientific basis. Most rely on qualitative observations or empirical rules of thumb. In some cases the rationale behind them has been lost in the mists of time. The main reason for this lack of strong scientific foundations is the lack of research into quantitative links between freshwater flow and estuary parameters such as:

- sedimentation
- water quality
- ecology

In many cases the processes involved and the part that freshwater flows play in those processes are not fully understood. The links are very time-dependent. For example they vary with the state of the tides which is constantly changing. Fishery or ecological requirements will vary seasonally.

The freshwater flow that governs a particular process may be very different from one process to another. For example, minimum flows are critical to water quality and saline incursion while flood flows may be critical to sedimentation. If the reason for setting a minimum residual flow is different for different estuaries, the resulting minimum residual flows are not strictly comparable.

Many processes will be estuary-specific to a greater or lesser extent. It may therefore be difficult to transpose the results of research on one estuary to another, although there might well be underlying principals that are more or less universal.

1.4.4 Estuarine computational modelling

There has been extensive research into computation modelling over the past two decades. Most of this research has been directed towards better, that is faster and more accurate, algorithms for the computation of flow, quality and sediment transport. Although the techniques described are applicable, and are used, in the determination of freshwater flow needs of estuaries, few references directly consider these needs.

One particularly helpful reference is a report by Cooper and Dearnaley for the Department of the Environment (1996), that gives guidelines for the use of computational models in estuarine studies. These guidelines have been adapted or quoted in places in this report.

Recent research has begun to concentrate on the long term changes in estuaries due to man's influence. In particular, the morphological changes due to changes in freshwater flow, or shipping channels are perceived as a major long term concern in our estuaries. At present, it must be accepted that we cannot predict the long term future and we should therefore be very cautious of any changes made to an estuary.

MAFF have recently started major research initiatives into morphology and its simulation, with emphasis on the science of coastal processes. A scoping study, described in Chapter 6, has been commissioned by MAFF/EA/EN/EPSRC/NERC on research into long term estuary morphology. The aim is to understand the long term processes and effects of changes on estuaries. HR Wallingford are heavily involved in this scoping study, and a useful early output is their review of recent research into estuary morphology and processes (HR Wallingford, 1996). It is expected that this ongoing research programme will provide new data for the simulation of morphological processes. These advances will need to be incorporated into management strategies for estuaries and the computational models used in their analysis.

1.4.5 The setting of Residual Flows in rivers

Although the determination of estuary freshwater flow needs has not been greatly researched, the calculation of minimum flows in inland rivers has been the subject of Agency research. The Surface Water Abstraction Licensing Policy (SWALP) procedure (NRA, 1995) was designed to create a unified approach between regions in the way in which applications for surface water abstractions were assessed. The R&D work included:

- a review of current approaches to license determination in England and Wales;
- a review of research and development work;
- development of a methodology for license determination, building on best practice and recent R&D, that was both flexible and robust;
- trialing of the methodology; and
- preparation of an R&D note.

The methodology includes:

- an environmental weighting system;
- rules to govern new abstractions;
- a standard approach for the derivation of a hands off flow (HOF); and
- an upper limit on licensing.

The procedure as presented gives a consistent approach to licensing policy, and has been a useful comparison with the methods presented in this study for determining estuary minimum flows. In general, an estuary is a more complex environment than an upland river, with more processes and uses sensitive to, or causing, changes in freshwater flow. It was therefore considered that the SWALP procedures could not be transferred directly to the estuarine case.

1.4.6 Recent fisheries research

Two areas of recent fisheries research have direct impact on the determination of freshwater flow needs into estuaries. The first involves the effect of water temperature on fish. Temperature may be an important factor to determine the timing of migration. Low flows may result in increased river temperatures. This is not only from effluent and power station returns, but from the heating effect of the sun on inter-tidal mudflats. Heating is generally countered by the slug of cold water entering the estuary from the river each night. However, with reduced rainfall and increased abstractions, the slug of cold water may be too small to prevent a build up of temperature at the head of the estuary. The impact on fish of such high temperatures may be difficult to quantify, but there is evidence that they:

- delay or prevent migratory fish entering the estuary; and
- affect the viability of eggs with chronic exposure.

Research is also being carried out by the Institute of Freshwater Ecology (IFE) for the Agency. The project is reviewing the available data on flow needs for fish, and will give guidance for the selection of minimum residual flows.

1.4.7 Risk assessment research

This report proposes an approach to the determination of freshwater flow needs that uses elements of risk assessment techniques. An ongoing Agency R&D project titled "Strategic risk assessment: Further development and trials" has the objective:

> 'To further develop and trial the strategic risk methodology to enable the Agency to incorporate risk into its decision making over priorities in both the long-term and annual corporate planning'.

The aim is to base decision making on analysis of the risks facing the environment, both at an operational and strategic level.

The project takes risk expressions and probabilistic methods used in the nuclear industry and for flood defence design. It applies these or equivalent expressions to a wide range of environmental risks, and trials resulting modelling techniques to a range of these risks.

Part B - BACKGROUND INFORMATION

2. ESTUARINE CHARACTERISTICS AND PROCESSES

2.1 Physical characteristics

2.1.1 Characteristics

An estuary can be defined as a dynamic semi-enclosed body of water, which forms a transition between the river catchment and the open sea where fresh and saline water mix. The dynamic nature is predominantly influenced by the variation in energy transfer across the two open boundaries which are controlled respectively by tidal forces and freshwater discharges at the seaward and landward ends.

Estuaries are further characterised as the part of the river influenced by tidal effects. Whilst the landward limit is easily defined, as the point above which tidal effects are never found, the seawards boundary in many cases is less well defined. It may be defined in geographical, topographical, chemical (salinity), biological or hydrographical terms. Recent legal judgements on the Severn and Humber have focused on the topographic definition.

Estuaries vary widely in size and shape. They may be long, thin and fiord like, resulting from the drowning of previous valleys, or they may be broad and shallow, such as Poole Harbour or The Wash. Many estuaries have bars at the mouth, either sand bars formed by littoral drift, moraine bars that are relics from the ice age, or rock bars, resulting from the geological conditions. The shape of the estuary has a profound influence on the propagation of the tide along the estuary.

In a classical trumpet shaped estuary where the width and depth reduce exponentially in an inland direction, the tide may be funnelled and amplified as it progresses inland. However, even in such an estuary the frictional effects ultimately dominate and the tide peters out.

In a deep fiord like estuary the tide is affected less as it propagates along the estuary and the tide at the head of the estuary may be similar to that at the mouth.

The presence of a major bar at the mouth of an estuary will severely constrict the propagation of the tide into the estuary. The consequence is that low waters are maintained well above the open sea low water, whilst high waters may be significantly lower than the open sea high water.

A major impact of the frictional resistance in an estuary is that it induces an asymmetry in the tidal shape. In the open sea the tide is near sinusoidal. However, as the tide progresses up an estuary it becomes progressively more distorted in the same way as a wave approaching a beach steepens. As the tide progresses up the estuary the rising limb, the flood tide, becomes shorter and steeper, whilst the falling limb, ebb tide, becomes longer and flatter. As the volume of water moved in the flood and ebb is similar, a consequence of this asymmetry of tidal shape is that during flood tides the landward currents are often much stronger than the subsequent seaward ebb currents.

Estuaries may have more than one channel. It is often the case that the flood tide advances reasonably uniformly across the estuary as the tide is compressed into a narrowing overall section. However, during the ebb tide the particular geometry of the estuary coupled with the physics of expanding flows often results in the main ebb currents being focused in one or more channels and avoiding other channels. Hence the nett residual current may vary across the estuary. Some channels in the estuary may be ebb dominant whilst others are flood dominant.

2.1.2 Categories

Estuaries have generally been classified into three main categories which relate the magnitudes of tidal discharge to the freshwater flow (Pritchard, 1955 and Simmons, 1955):

- Highly stratified (salt wedge) estuaries, where the tidal forces are small with respect to the river freshwater flows;
- Partially mixed estuaries, where both the tidal forces and freshwater flows are large;
- Well mixed (homogeneous) estuaries, where the tidal forces are large compared with freshwater flows.

Throughout the world, most estuaries would be classified as partially mixed, however there is a continuum between types 1, 2 and 3. Since both freshwater flows and tidal forces are variable in time, the position of any estuary within the classification will also vary. Due to the geometrical characteristics of an estuary it is also possible for neighbouring reaches of an estuary to exhibit different characteristics.

2.2 Morphology (long term sediment process)

2.2.1 General

The interaction between the tidal forces and freshwater flow inputs together with the morphology, geology and sediment availability within the estuary, have a major influence on the estuary form by determining areas of erosion, stability and shoaling.

The following section describes the instantaneous processes occurring within the estuary. However, these processes are occurring second by second, minute by minute, tide by tide, throughout the seasons and over the years. The long term consequence of these processes is the establishment of a sediment regime that is specific to the individual estuary and its tidal and hydrological conditions.

There are several features that determine long term sediment patterns. These are discussed briefly below.

2.2.2 Sediment sources

Sediment sources in an estuary are either from the sea or are land based, i.e. from rivers. Sea based sediments come from coastal erosion or adjacent rivers. The coastal sediments travel along the coast driven by tide and wave action forming littoral drift. At openings such as estuary mouths sand bars tend to form. Whether or not a bar forms, its long term stability is determined by the rate of supply of coastal sediment and the outflow from the estuary, which in turn is determined by the combination of the river flow and the tidal outflow. In areas with large tidal prisms the outflow is often sufficient to inhibit the bar closing the estuary, but with low river flows and small tidal prisms seasonal closure is possible.

Generally, the tidal asymmetry of more rapid flood tide and less rapid ebb tide within the estuary draws material into the estuary, but is less effective in flushing it all out. Hence coastal sediments are drawn into the estuary. In stratified and partially stratified estuaries this effect is accentuated by the landward drift in the lower layers of the water column. There are, however, ebb dominated estuaries such as Southampton Water.

2.2.3 Estuarine channels

In the upper reaches of the estuary the tidal asymmetry still has a major impact, sediments tending to be pushed landwards on the flood. During the ebb as water levels drop, the scour capacity of the receding water, in addition to the fresh water flows, is often sufficient to scour incised channels through the accumulating sediments leaving silts and clays on the banks but eroding the bed down to harder sand or gravel deposits.

These channels are typical of natural channels in soft erodible material. They are likely to be sinuous with the meanders progressively moving seawards. In confined channels this takes the form of sand bars from alternate banks moving seawards. The rate of progress of these, and their scale, can be significantly affected by the fresh water flow regime.

2.2.4 Shoaling zone

In the middle reaches of the estuary the sediment pattern is the result of a complex interaction of the coastal based sediments and the land based sediments. Well into the estuary the land based sediments tend to build up. The shoaling zone has already been mentioned as an area of preferential siltation and the location of this varies with tide and freshwater flow. Besides the shoaling zone the impact of salinity on residual flows in channels across the estuary can have a profound effect upon sedimentation patterns.

In estuaries where a large density difference occurs between the bed and surface water (a high degree of stratification), the distribution of shoals can be related to the limits of salinity intrusion. In a well mixed estuary this association is less clear and areas of shoaling are influenced more by the physical features of the estuary, eg. islands, divided channels, non uniform flow and cross sectional area.

It follows therefore that the pattern of shoaling in estuaries varies with the type of mixing, it is also true that estuarine sedimentation is affected by the magnitude, frequency and duration of the

7.6 Preliminary assessment of technical approach

If programme and funding permit, it may be beneficial to make an initial assessment of the estuary. This could be through an impact matrix as described in Chapters 6 and 8. In some circumstances there may be an opportunity to develop a preliminary model in order to gain an understanding of the estuarine dynamics, or to examine reports from a previous modelling study.

From this assessment, one will determine the significant impacts, processes and uses within the estuary.

7.7 Selection of preferred approach

The final selection of a technical approach for the determination of freshwater flow needs of an estuary will not be based on technical factors alone. Chapter 8 describes a methodology to decide a preferred technical approach. The use of decision matrices will help design this approach and enable a coherent case to be made to study managers for the preferred computational modelling. However, it should be recognised that estuary management and flow determination is a wide-ranging and politically sensitive process. Computational modelling should form a vital part of this process, providing results on which decisions can be made. However, it will not and must not be the driving force behind the decision making process.

The preferred modelling approach must therefore be:

- Credible to the estuary manager, in its scope and budget. However complex and critical the impacts to be analysed, there will be a budget. The approach should provide a realistic scope for modelling within the budget. It may compromise on accuracy. This should be made clear to the estuary manager, who may be able to extend the budget if justification is clearly given;
- Based on real needs within the estuary. The approach must focus on those areas where modelling is needed for estuary management. Modelling frequently develops its own priorities, such as developing or testing new software, investigating an interesting computational feature, or indulging in pure research;
- Capable of correctly identifying differences between the strategies. The model, however simple or complex, must be designed so as to be able to assess a range of strategies and schemes. The form of the model must be such that it is able to compare differences of impact of such schemes;
- Credible to outside bodies. The modelling may be reviewed by a range of estuary users. The scope of work proposed must be credible to both technical and non-technical bodies.

Finally, selection should remember that:

- the newest modelling software with the most features is not necessarily the best for a specific project - a proven existing program in house may do the job just as well with no investment in software;
- the biggest, most detailed computational model is not necessarily the best. Despite the trend towards large, multi-use models, careful project definition and model design may

2.2.6 Impact of man

Man's development of an estuary can have a major impact on the long term sediment patterns.

- confining the estuary will focus more energy further inland, resulting in loss of saltings and sand banks together with increased erosion at structures
- loss of tidal prism, through either confinement or from introduction of tidal barrages can seriously affect the asymmetry between flood and ebb tides and consequently change the net residual movement of sediment. There are many examples where such activity has resulted in rapid accretion of the lower estuary. In its extreme form this can result in stabilization of the bar at the estuary mouth resulting in bar closure during periods of low freshwater flow.
- deepening of an estuary can also have extreme consequences not just from changing the hydraulics by allowing the tide to advance further inland, but also by allowing saline water to advance inland and to both pollute ground water and move the shoaling zone landwards.

Attempts have been made to characterise the sediment regime in an estuary to its general features of tidal range, sediment supplies, general geological features and river characteristics. However, in general for all but the simplest of estuaries these characterisations have very limited use when predicting changes likely by altering a single feature, such as freshwater flow. As a result estuaries have to be studied on an individual basis.

2.3 Sediment movement (short term)

2.3.1 Categories of mobile sediment

Mobile sediment can be considered in two categories :

- particulate material including all sands, gravels and in some circumstances course silts
- fine sediments i.e. silts and clays, being floccular in nature and potentially cohesive

2.3.2 Particulate materials

The movement of the particulates is relatively straight forward. They respond to instantaneous velocities. If these forces are sufficient to carry the sediment they are eroded, if not they are deposited. For any given grain size or grain size mix there is a unique sediment transport capacity for a given bed shear force and water depth.

2.3.3 Fine sediment

The movement of fine silts and clays can be considered in three main phases: erosion, transport and deposition.

- Erosion takes place when the shear force on a deposit exceeds the critical shear. Erosion takes place at a mass rate related to the excess shear force above the critical shear. Erosion can also be initiated by wave activity and changes in salinity affecting the ionic bonding of the material.

- Transport - once the fine sediments have been eroded and are in suspension the transport capacity very rarely limits the capacity of the flow to move the sediment. The result is that the mode of transport becomes important. The mode, be it fully suspended wash load or at the other extreme fluid mud, is dependant upon the background energy. The turbulence generated by the tidal flows is often sufficient to keep much of the light particles well in suspension. However, in some circumstances, particularly in deeper or heavily silted estuaries, floc concentrations can become so great near the bed that they form a light "fluffy" mass which moves with the tide and is termed fluid mud.

- In earlier sections the occurrence of shoaling zones was discussed. In these areas there is an increased tendency for the formation of fluid mud and also for high suspended sediment concentrations often referred to as "Turbidity Maxima". Other contributions to such hyper-concentrations are wave activity which creates persistent erosion of shore line sediments in specific localities.

- Deposition occurs when shear stresses fall below critical levels, sediment concentrations at the estuary bed increase and eventually the sediment becomes immobile. For particulate sediment, deposition occurs to reduce the sediment movement to the actual transport capacity. However, fine sediment tends to fall out at a mass rate dependant upon the shear stress deficit below the critical stress level for deposition. It should be noted that this shear stress for deposition is often well below the critical value for erosion, due to the fact that erosion has to break down the structure of the deposit. For particulate sediments the critical shear for erosion and deposition are nearly identical as there is no cohesive structure to the sediment.

- For fine sediments deposition is aided by the flocculation of the fine silts and clays. In this process a number of particles coalesce to form a larger but low density structure. These larger structures can settle faster than the individual particles and hence increase deposition rates. Flocculation occurs because of the ionic attraction between particles. It is influenced by amongst other things:

  - the mineralogy of the sediment.
  - the ionic composition of the water, which depends on salinity.
  - level of turbulence - too much inhibits floc formation but a little is helpful.

  Of specific interest here is the dependance of floc formation on salinity. If freshwater flows change, salinity changes and hence siltation patterns change.

2.4 Water quality

2.4.1 Flow and quality

Tidal flows in estuaries act to dilute and disperse many discharges into these waters. However, the long term persistence of those discharges can create a serious build up of pollutants. Furthermore due to the rapid siltation occurring within the estuary, many of the pollutants, particularly the more noxious, become bound into the sediment in the estuary bed. These can be resuspended: during times of high tidal ranges; during extreme river flows; or during intervention by man in dredging or introduction of engineering works.

Further, flow and quality are closely correlated. Any change to the residual flows is likely to have an immediate impact on water quality in the estuary. Following from this there may be a direct impact on the ecology of the estuary, especially on fish health and migration. This impact is considered below and in Section 3.7.

2.4.2 Key parameters

There are a great many water quality parameters but if we consider four of the main parameters they will give an indication of the way water quality can be affected:

- Dissolved oxygen is a principle measure of the health of an estuary. In its pristine condition the oxygen content in the water of an estuary will be close to the saturation concentration. Aeration of the water column takes place in the river, at sea and in the estuary itself. Aeration is augmented by wave action, by currents and by flow over weirs. There are naturally occurring causes for a reduction in dissolved oxygen below saturation, but these are generally not significant.

- Discharge to rivers, estuaries and coastal waters generally contain pollutants that temporarily or permanently take up dissolved oxygen from the water. Such pollutants include discharges from sewage treatment works, industrial effluents, farm wastes and natural organic wastes from the catchment. Once in the water column these wastes absorb oxygen and some become adsorbed to the sediments to be reactivated when the sediments are remobilised. Fortunately the natural process of aeration is constantly acting to re-aerate the waters so that even if conditions close to a discharge result in poor dissolved oxygen the conditions some distance away may be quite acceptable. However, if the quality does not recover, there may be a resulting impact on ecology and especially fish, as described in Section 3.7.

- Water temperature is an often forgotten, but important, parameter. In estuaries where there are extensive low tide flats, heating of lowflow channels and tide-banks at low tide by the summer sun can cause water temperatures to exceed 30°C, well over the lethal limit for salmonids. There needs to be sufficient flow of freshwater, and a slug of cold riverwater flowing into the estuary at night, to prevent, avoid, or dilute high temperatures in the low water drainage channels. The resulting impact of temperature on ecology is described in Section 3.7.

- Nutrients emanate from many sources including domestic and industrial wastes as well as extensively from farm drainage and effluent. The nature of nutrients is that they act as fertilizers promoting plant growth. They are used as such on farms and when they enter the aquatic environment they continue to act in that way. The most obvious impact of additional nutrients entering an estuary is the enhanced growth of sea grasses, sea weed and algae. In its most extreme form nutrient enrichment results in wide spread algae blooms, with its attendant problems of toxicity, dissolved oxygen reduction, fish kills and putrid water, i.e. total eutrophication. Such conditions can only occur with a combination of nutrients, water temperature and sunlight, they are therefore transient and seasonal.

- Heavy metals enter an estuary from both domestic and industrial discharges, as well as from air borne sources. They tend to settle in the water column and adsorb on to sediments. They can be remobilised by re-suspension or changes in salinity. Once dissolved and in the water column they can be accumulated in filter feeders such as mussels and prawns, resulting in toxic elements in the food chain.

As can be gathered from the above, water quality is normally a problem of the middle and upper estuary and is hence impacted upon by the complex interaction of tidal, saline and sediment processes occurring in that region. Modification to these parameters can have major effects upon water quality.

2.4.3 Interaction of quality and sediment

Water quality in the estuary is not just a function of the lowest flows entering the system. Indeed, the estuary tends to act as a reservoir accumulating contaminated sediments and pollutants throughout the year, but releasing their effects from time to time.

The interaction between water quality and sediment regime is strong. The ability of an estuary to maintain a clear channel is dependant as much on the middle and high range flows as on the low flows. The main impact on water quality is therefore not necessarily just at low flows. Hence it is important from all aspects to maintain an overall flow regime with high and middle range flows besides keeping the low flows above a minimum value.

2.5 Salinity

2.5.1 Salinity profiles

A feature of any estuary is that at its head is freshwater from a river, whilst at its mouth there is full open sea conditions including sea salinity. The estuary is therefore the area where fresh water gradually mixes with salt water. Hence there is a changing and increasing salinity along the estuary from head to mouth.

Saline water is heavier than fresh water, hence there is a tendency for the heavier salt water to stay near the bed of the estuary whilst the fresh water tends to stay near the surface.

The degree of mixing along the estuary and over the vertical is determined by the tidal conditions and the relative magnitude of fresh water flow. For instance, where tidal range and hence tidal energy is high, mixing will be enhanced. However, where fresh water flow is high and hence density differences are high, mixing will be reduced. Consequently, in estuaries with low tidal range but high fresh water flows there will be a tendency for the fresh and salt water to separate and for a saline wedge to develop, i.e. the estuary is "stratified". Conversely where tidal range is high and fresh water flow is low, then mixing of fresh and sea water will be rapid and the estuary will be "well mixed".

Most estuaries in the UK lie somewhere between these extremes being termed "partially mixed". The mixing characteristics of a given estuary can change seasonally with fresh water flow and tidal range. For instance an estuary that is stratified during neap tides in periods of high fresh water flow may well be partially or even well mixed during spring tides and low fresh water flows during the summer.

2.5.2 Salinity and flow

The longitudinal variation of salinity varies with fresh water flow and tide. During periods of high river flow the salt water and salinity profile moves seawards whereas during low flows saline water ingresses towards the tidal limit of the estuary. In all but most extreme low flow conditions the head of the estuary, whilst being tidal, will be entirely fresh water.

Furthermore, some estuaries may have a small volume compared to the fresh water flow whilst others may be comparatively large. In small estuaries the salinity within the estuary responds very rapidly to fresh water flow. By comparison some estuaries such as the Humber or the Severn have a large volume compared to the river flow. In them the salinity regime changes much more slowly. The salinity regime itself becomes seasonal and may be better correlated to the accumulated river flows over the previous month, quarter or even year rather than over the previous day as in small estuaries.

The salinity regime can have a profound effect upon the flow regime in an estuary. In a well stratified estuary the surface flows are strongly ebb dominant. However, in order to compensate, the near bed flows will be strongly flood dominant as far inland as the tip of the saline wedge. Landward of this point the near bed flows are dominated by the fresh water flow and are hence ebb dominant. The consequence of this is that any mobile material in the near bed zone of a stratified estuary will be moved towards the tip of the saline wedge. This zone accumulates material and sediment, hence it is often referred to as the shoaling zone in an estuary. However, it must be remembered that the location of the tip of the wedge will move with the tide and with variations in fresh water flow. Hence, the shoaling zone normally covers a reach of estuary.

In partially mixed estuaries the impact of salinity on flow regime is less marked. However, there is still a strong tendency for near bed flows in the upper reaches of the estuary to be ebb dominant whilst those in the lower estuary are influenced by the vertical variation of salinity and tend to average over the tidal cycle to be flood dominant. Again this results in a shoaling zone.

In well mixed estuaries the flows are generally tidally dominated with salinity having little impact on the flow regime.

The longitudinal and lateral variations in salinity can also have a marked effect upon the flow. The more saline water is heavier than fresh water, it therefore has more momentum. Lateral density gradients can drive flows, or more often residual flows, which determine the overall circulation in an estuary and hence determine sediment patterns.

2.5.3 Toxic effects of chlorinity

During droughts, seawater may intrude into freshwater zones that are used for irrigation and for watering livestock in the landward reaches of estuaries. The crop yields of sensitive crops, such as are grown in market gardens starts to be affected as the chloride content rises above about 300ppm (Rintema 1981). This is close to the value in residual flows into some estuaries, for example the Thames, during droughts. Livestock become affected by chloride values in excess of about 600ppm (Ayers and Westcot 1994).

A salinity of 0.5ppt (Cl ≈ 250ppm) is often used as defining the limit of saline intrusion into estuaries. This value, which can be described as the toxic limit, is about the lowest salinity that can be determined to direct reading salinometer and is only 1.4% of the normal salinity of seawater. The plants inhabiting the banks of UK estuaries vary in their sensitivity to the chlorinity. However, there is few which tolerate the large differences in salinity that occur in the vicinity of the saline front. (0.5-25ppt).

2.6 Ecology

2.6.1 Background

The flora and fauna throughout an estuary are dependant upon the well being of the estuary including:

- water quality and temperature;
- sediment quality including the geology of the area;
- salinity; and
- stability of habitat.

We should consider the biota to be defined by three types of ecosystem:

- benthal, both infauna and epifauna, including bottom living fish and crustacea;
- pelagic fish, including migratory freshwater species; and
- intertidal species, including plants and higher life forms.

2.6.2 Aquatic species

Benthal species, the infauna living within the sediments, include worms, and all forms of burrowing species of molluscs and crustacea. In addition to these forms are the epifauna, animals living on, or attached to, the seabed or rocks thereon, and free swimming species of crustacea and fish that are closely associated with the seabed.

The infauna are most heavily affected by changes in sediment quality. For instance, in areas subjected to polluted sediment, such as areas receiving combined storm overflows (CSO) from summer floods, the sediment profile often has a thin aerobic layer followed by a deeper anaerobic layer which has formed from the accumulated organics and polluted sediments. Whilst some species can tolerate these conditions most cannot. Hence the area is often devoid of these basic building blocks in the food chain. Such areas tend to be in the vicinity of significant discharges. However, they can also be in the areas of significant sedimentation and as discussed earlier this can move with salinity and hence fresh water flow regime.

Fish are primarily affected by water quality, though benthal species feeding, or in some cases living, in burrows are also affected by sediment quality. Each species has a specific tolerance range in terms of dissolved oxygen, temperature and other parameters. Keeping the water quality within these ranges is the first part of the requirement for maintaining healthy fish populations in the estuary. However, there are other issues. Maintaining an unpolluted food chain is also necessary. As discussed above, this is dependant upon having relatively unpolluted sediment. Furthermore fish in estuaries often rely on the upper reaches of tidal marshes to provide nursery areas for young fish and these can be strongly affected by changes in sediment regime and salinity and the impact of man on the estuary.

2.6.3 Non-aquatic species

Estuaries provide habitat to a wide range of non-aquatic species, both in the tidal zone and the associated terrestrial habitats. The coastal margins also provide habitat to a wide range of specialised salt tolerant plants and other animals. Most significantly they provide food to a wide range of birds, both indigenous and migratory. In addition the estuaries provide a resource for human activities and recreation, some of which are directly linked to the biota.

The flora of estuaries varies from seaweeds and seagrasses that tolerate full seawater salinity to those seaweeds and specialised terrestrial plants that are tolerant to relatively low salinities. Often only a single species is tolerant to a small salinity range. Hence major changes in the distribution of salinities will almost certainly put these plants under severe stress. Although in some cases other plants will re-establish in such areas, a major increase in salinity at specific locations in the estuary may significantly reduce the diversity of species that could persist there.

The bird population of an estuary is also acutely dependant upon the food source, largely the benthal biota and smaller fish. As mentioned above, these organisms depend on the water quality of the estuary, the sediment quality and the salinity regime. Subtle changes in any of these can have considerable effect upon the balance of the food chain that supports the bird populations.

Man is probably the most adaptable of estuarine users. Negative impacts on water quality, visual quality, water sports, fishing or wildlife observation have been common in many estuaries close to urban areas, particularly as industrialisation has occurred. In recent years ecological damage due to over exploitation has been recognised and additional impacts, when proposed by developers, have often been vigorously opposed. All of these issues are of key importance in maintaining a healthy and biodiverse environment within the estuary.

2.6.4 Example - the impact of fresh water abstraction

In a study of the impact of changes in the pattern of fresh water abstraction on invertebrate fauna in the Thames Estuary, Warwick and Williams (1984) argued that the distance of penetration of marine species into estuaries, and of freshwater species into brackish water is usually correlated with salinity tolerances. They considered salinity to be the "master factor' governing estuarine distributions provided that water quality conditions such as oxygen concentration, remain favourable. A salinity of about 5ppt is constitutes a significant ecophysiological boundary, referred to as the 'horohalinicum', at which the numbers of both marine and freshwater species reach a minimum. However, marked fluctuations in the fauna occur at the region of the horohalinicum, both seasonally and between years.

Epibenthic species and zooplankton, particularly crustaceans such as copepods, amphipods, mysids, isopods, shrimps and prawns, migrate up and down an estuary with changing salinity and are largely unaffected by it. However, benthic infauna, for example molluscs, leeches and annelid worms, are frequently eliminated locally under conditions of increased salinity during droughts. Flow regulation often reduces the variations in salinity.

3. ESTUARY USES AFFECTED BY FRESHWATER FLOWS

3.1 Introduction

All human effects with respect to modifying the freshwater flows to estuaries occur in the catchment area and therefore affect the up river boundary condition to the estuary, and boundaries where rivers enter the estuary along its length. Most effects tend to reduce or regulate the natural inflow, for example:

- water abstraction for human, agriculture and industrial purposes.
- water storage to regulate supplies, eg. reservoirs.
- water transfer schemes.

The change of usage of a catchment can also have serious implications in changing the flow inputs to estuaries. Increased urbanisation causes large areas of impermeable surfaces which increase the runoff and concentration of water into drains and this could increase the propensity for flood flows. Change of usage, for example, from forest to agriculture can increase runoff but also increase the sediment input to the estuary thus increasing the supply of material for siltation. Therefore unless careful management of the catchment is undertaken all human developments will influence the sediment patterns within an estuary.

In the UK during the 1990s, due to lower than average rainfall in a number of areas, there has been increasing demand for water abstraction, either directly or by creating storage in reservoirs for use in periods of drought.

In the case of the Humber Estuary and the Great Ouse, barrages and flood defence works control and or abstract water from the catchments and therefore the effects have already, or probably, are still working through the intra estuary mechanisms to change the form and function of the estuary. If our estuaries are to continue to service all the existing uses and be sustainable into the future then the effects of modifying the freshwater flow inputs to the estuary need to be studied for both short and long term effects before approving projects.

3.2 Abstraction/Transfer

The abstraction and transfer of freshwater flows for water supply and irrigation represents man's largest impact on the natural estuarine system.

Transfer removes water from one catchment and increases flow in another. A major example of this in the UK is the abstraction from the Severn for public water supply in Birmingham. This boosts flow in the Trent system, which receives the effluent. Other examples are Lune-Wyre, Trent-Witham-Ancolme, Ely Ouse-Essex and Tyne-Tees-Yorkshire.

Abstraction for domestic and industrial use in a catchment changes the flow hydrograph of estuary flows by reducing the frequency of occurrence of mid-range flows and increasing low flows. An example of this kind of abstraction is the Thames catchment, which dramatically enhances the low freshwater flows in the Thames, downstream of the sewage discharges.

Abstraction for agriculture, especially spray irrigation, is unlike any other abstraction in that very little of the abstracted water is returned to the river system. This form of abstraction reduces river flow volume at the time of abstraction (summer if directly sprayed). Major examples are the recent increase in spray irrigation in the Anglian region and the current development of winter storage reservoirs for irrigation. A minor, but significant, abstraction is for farmers to maintain ditch levels, perhaps to qualify for environmentally sensitive area (ESA) payments.

Salt and silt intrusion due to low freshwater flows can cause water quality problems at downstream water intakes where these are not protected by a weir. Examples of such intakes are those on the Trent for power stations and transfer to the Witham, intakes on the Great Ouse for irrigation, navigation and conservation, and intakes on the Kent Stour for irrigation.

3.3 Dilution

Some freshwater is required for the dilution of effluents, unless the effluent quality exceeds the river quality objective. In a river with excess dry weather flow, these flows allow a reduced standard of effluent treatment. If dry weather flows are fully utilised, the reservation of flow to provide significant dilution may be expensive.

3.4 Navigation

Central to navigation use is the maintenance of water levels and navigation channels. There is significant pressure to maximise the size of ships that can use ports. It is therefore increasingly important to maintain and if possible increase water depths. Larger ships also mean longer ships, hence the position of shoals in the estuary become important, especially at bends or dock entrances where a ship is swinging or where two ships have to pass. Issues arising from this trend include:

- Maintenance of channel regime. Ideally the freshwater flow should be managed to ensure that scour of the estuary bed maintains navigation depth;
- Small changes in freshwater flow can change siltation patterns and increase the need for maintenance dredging. Flood/ebb channels may change in location and dominance. Shoals may become larger. A good example of these changing siltation patterns are those observed at King's Lynn.
- Historic "steps" in dredged depths can have long term impacts on estuary morphology. This is seen in the Humber.
- Salt/silt intrusion can adversely affect lock operations.

3.5 Recreation & amenity

Recreational use of an estuary is often seasonal, with peak use in the summer months when flows are low. Related issues to recreation may include:

- navigation and access to marinas and minor ports. The issues discussed in Section 3.4, above, apply to both commercial and recreational navigation;
- fishing, especially where saline intrusion into estuarine waters and upstream rivers may reduce the potential for angling, and perhaps result in fish kills;
- water contact sports, such as swimming, sailing and water skiing may demand high water quality for reasons of health; and
- nature conservation, which is also a major recreational occupation.

3.6 Nature conservation

The relationships and interactions between the biota of an estuary and freshwater flow are complex and at present poorly understood. Estuary managers and nature conservation groups alike, should accept that quantitative answers cannot be provided as to the impact of changes in the estuary on all aspects of the ecology of an area.

Some of the issues to be considered are that:

- River flows affect salinity of estuaries. Salinity is an important factor in the natural system. It should be noted that occasional changes in the estuary (such as saline intrusion) may be significantly more damaging to the ecology than regular (daily) fluctuations which will result in salt tolerant creatures becoming established;
- River waters are commonly their main source of nutrient to estuaries. The role of river borne nutrients is important in the ecology of the estuary, because such nutrients 'drive' the growth of algae, the basis of the estuary food chain. The JoNuS study has studied this issue;
- Rivers are conversely a source of toxic and other pollutants;
- Habitat squeeze due to sea level rise will affect the brackish as well as the saline environment; and
- Pollutants can accumulate in the sediment/fauna of estuary because salinity causes changes in water chemistry resulting in the deposition of pollutants.

In addition to the Agency's general conservation duties, specific new duties to consider nature conservation apply for all activities which may affect a European Site. These are described in Section 3.8, below.

3.7 Fish movement & health

3.7.1 Fish populations

Estuaries hold large numbers of fish which change in composition through the year. There are species which live all their lives in the estuary. These may either:

- live in the low-water channels (gobies, many flatfishes); or
- survive in pools (blennies, sticklebacks, gobies) during low tide if they are species of the upper shore or fish associated more with deeper shore water (wrasse).

Some fish, notably the gobies, are able to tolerate a wide range of salinity (euryhaline) and spend all their time in the fluctuating salinity in estuaries.

Other species spend only part of their life history or part of the year inshore. For example, many species, such as cod and whiting, enter estuaries in spring as young, or their adults enter to reproduce in the lower salinity water and only leave the following autumn, finding both shelter from predation and an abundance of small food organisms in the shallow estuarine waters. Other species such as whitefish (Coregonidae) enter from fresh waters to brackish estuaries.

Perhaps the best known species are those which migrate through estuaries, including:

- the eel, which reproduce offshore and return as young in the case of the eel; and
- the salmon and sea-trout which return from the sea to rivers to spawn in the upper rivers.

Such migratory fish, in particular the salmonids, have been the driving force in fishery conservation terms for successful preservation of fish stocks, without which many rivers in the British Isles would not have retained their present fish populations.

3.7.2 Migratory fish

The ideal estuary flow regime enables migratory fish to pass through the estuary at will at the appropriate time of year. Most rivers are able to provide adequate flows throughout the year. The reduction in river flows in estuaries as a result of man's intervention has caused great problems for migratory fish. The affect of low flows has been accentuated in many instances by the use of weirs on rivers used to ensure the reliability of fresh water abstraction points.

The salmonid fisheries are amongst the most studied and best recorded. There are minor variations in migratory behaviour between species or sub-species that occur world-wide but for the British Isles the requirements of the Atlantic salmon *Salmo salar* L. can be taken as indicative. These can be summarised as:

- The eggs are laid by the returning adults in course sand/gravels in shallow, fast running, low temperature, upland waters.

- The fish larvae hatch to fingerlings (parr) which live for one to several years in the upland river reaches feeding upon insect larvae and other benthic invertebrates.

- The young salmon parr respond to cold water runoff events in the rivers in late spring of their second or later years to begin their descent to the sea, by which time a hormonal and colour change has marked their change to the smolt stage. The fast swimming smolt require good flow paths through or over weirs and passage through any areas of poor water quality. This is the first time that estuarine environmental conditions are important.
- After two or more years in the Atlantic Ocean the sexually maturing adult fish begin to return to the stream or river of their birth. This is the stage, in early summer to mid autumn, when estuarine conditions are most critical for the survival of the fishery, as if fish cannot reach the upland areas for mating and spawning, there will be no eggs laid.

The flow and water quality requirements within estuaries for the two sensitive periods described above are discussed in more detail in the following section.

3.7.3 Need for suitable flow regime to stimulate migration

The trigger to start down river migration of young salmon (smolts) is cold freshet flows. The actual stimulation of the smolt run is not therefore a part of estuarine conditions. There are two features that have been shown to be important in the success of a smolt run. The first of these has already been mentioned. The smolts' drive for seaward passage should not be frustrated by man-made blockages of the river. Some weirs form the shoreward edge of estuaries, for example the Dee at Chester, which need to be set to preserve flows for the smolt run.

The second is the need in the estuary for residual freshwater flows to be such to maintain low flow channels to allow the seaward migrating fish to run the gamut of estuarine conditions that could cause excessive mortality. For example, areas of poor water quality caused by effluents may, at low tide, receive very much lower dilution compared to that at mean or high tide.

The landward phase of migration is the phase that is most affected by estuarine flow conditions. This is largely due to the seasonality of the migration of adult fish returning from the sea to spawn. Fish from the Atlantic appear to arrive in UK continental shelf waters from late spring onwards and swim along the coast until the odour of the discharges from the rivers of origin are detected in the coastal waters or estuarine discharges, (DH Mills, 1989). These extremely low levels of natural odorous substance are thought to trigger the very strong drive to swim upstream. There is a need for sufficient freshwater release from estuaries for returning salmon to first detect regional flows such as the west coast/south coast and then their home river.

In general salmon movements upstream are known to be affected by water temperature, light intensity and the height of the river. Buller & Falkus (1994) quote a minimum water temperature of 4° C before fish will move upstream and an upper temperature of 20° C in summer at which salmon remain in deep pools. Alabaster and Gough (1986) showed that for English estuaries such as the Thames, salmon migration was effectively prevented by temperatures in excess of 21.5 °C. This temperature is the same as that recommended by EIFAC for the EC Fisheries Directive as the upper limit for the maintenance of salmonid fisheries (Alabaster, 1980).

In estuaries where there are extensive low tide flats, heating of lowflow channels and tide-banks at low tide by the summer sun can cause water temperatures to exceed 30°C, well over the lethal limit for salmonids. In these circumstances salmonids need to be able to take shelter in deep pools, as a return to the sea means there is an inevitable risk of increased predation. In order to avoid unsatisfactorily long delays in the estuary there needs to be sufficient flow of freshwater to prevent, avoid, or dilute high temperatures in the low water drainage channels.

Recent work by Potter (1988) shows that in the Fowey, the fish may leave the estuary and return to the sea during low estuary flows. Fewings (1997) makes the observation that there appear to be two groups of fish returning to the Itchen at different times in the summer. It is now thought that there is only one group, some being held up in the estuary by environmental conditions.

In many estuaries which carry domestic and industrial wastewaters there is a need for freshwater flows for dilution. Effluent control has greatly improved in the UK over the past forty years, but lowland rivers still cause some difficulties. In particular this is true of combined sewerage overflows (CSO's) which often occur as a result of sudden summer rainfall events. Alabaster and Gough (1991) showed that in the Thames estuary salmon migration was reduced or ceased with reduced dissolved oxygen. In the Ribble estuary Priede et al. showed that pronounced oxygen sags caused fish to leave the estuary for the sea. In addition to low dissolved oxygen, there can be problems with other substances. The English Dee has had problems with elevated concentrations of ammoniacal nitrogen in the upper estuary as a result of low summer flows.

It is too simple to conclude that adequate conditions would be achieved by maintaining the summer time flows into estuaries at some elevated level to achieve cool opaque waters, since

- the resources to achieve this are not sustainable now, and indeed never were; and
- examination of a range of rivers shows a variation in which period is most critical.

For instance, salmon in the Clyde respond to high flows in April and early in summer whilst Thames salmon require higher flows in July/August. In the Clyde the early summer critical period may be due to the need for seaward movement of smolt whilst in the Thames the problem is the later low flow pattern to the river and the effect of urban heating and pollution.

3.7.4 Summary

The above discussion indicates that when estuary management is considered, and in particular when modelling studies are undertaken:

- freshwater flow, quality and temperature are critical to fisheries; but
- the data needed for a sound ecological evaluation may differ between estuaries.

3.8 Relevant legislation

The activities of the Agency in estuaries are prescribed by a large number of Acts. Important among these are the Water Resources Act, 1991, the Land Drainage Act, 1991, and their predecessors. In addition, there are many local Acts which govern the activities of the Agency and other authorities in particular estuaries.

The recent Conservation (Natural Habitats etc) Regulations (SI 1994 No. 2716) impose significant new duties on all competent Authorities, including the Agency, who authorise activities which could affect a European Site. At present all existing Special Protection Areas (SPA), including a number of estuary sites are classified as European Sites under the EU Wild Birds Directive 79/409IEEC.

English Nature have submitted a list of candidate Special Areas of Conservation (cSAC), including several estuary sites. These are currently being considered by the European Commission prior to their adoption by the Council of Ministers. At that time all SACs agreed by the Council of Ministers will be considered as European Sites for the purposes of the UK regulations.

The Conservation (Natural Habitats etc) Regulations, in Section 48, requires a body such as the Agency to:

- make an appropriate assessment of the conservation implications for any European Site that may be affected by an application before giving consent;
- consult English Nature or the Countryside Council for Wales as appropriate;
- consult the general public if the Agency consider it appropriate; and
- taking account of conditions which may be imposed, only agree to the consent once it is established that it will not adversely affect the integrity of a European Site, subject to considerations of overriding public interest.

In addition to the duties laid on the Agency in their consideration of new applications, the Agency also has a duty to review existing decisions and consents (Clause 50M) in the light of these Regulations, broadly following the requirements laid down for new applications. These reviews, which should cover all licences and consents which could affect a European Site are already being planned by the Agency.

The statements in the above section are the opinions of the authors, who are not lawyers. They do no provide an authoritative guide to the law. Legal advice should be sought on all matters of interpretation of these Regulations.

4. COMPUTATIONAL MODELLING TECHNIQUES

4.1 Techniques currently available

4.1.1 General

Numerical models of hydrodynamics, water quality and the like for estuaries are now so widely used that a diverse range of model types and applications have come into being. These may be divided into four main groups of models:

- Statistical models;
- Empirical or 'black box' models;
- Simplified hydrodynamic models, such as water quality 'box' and plume models;
- Full hydrodynamic models, with an accurate representation of the hydrodynamic equations, often with additional modules to simulate water quality and the like.

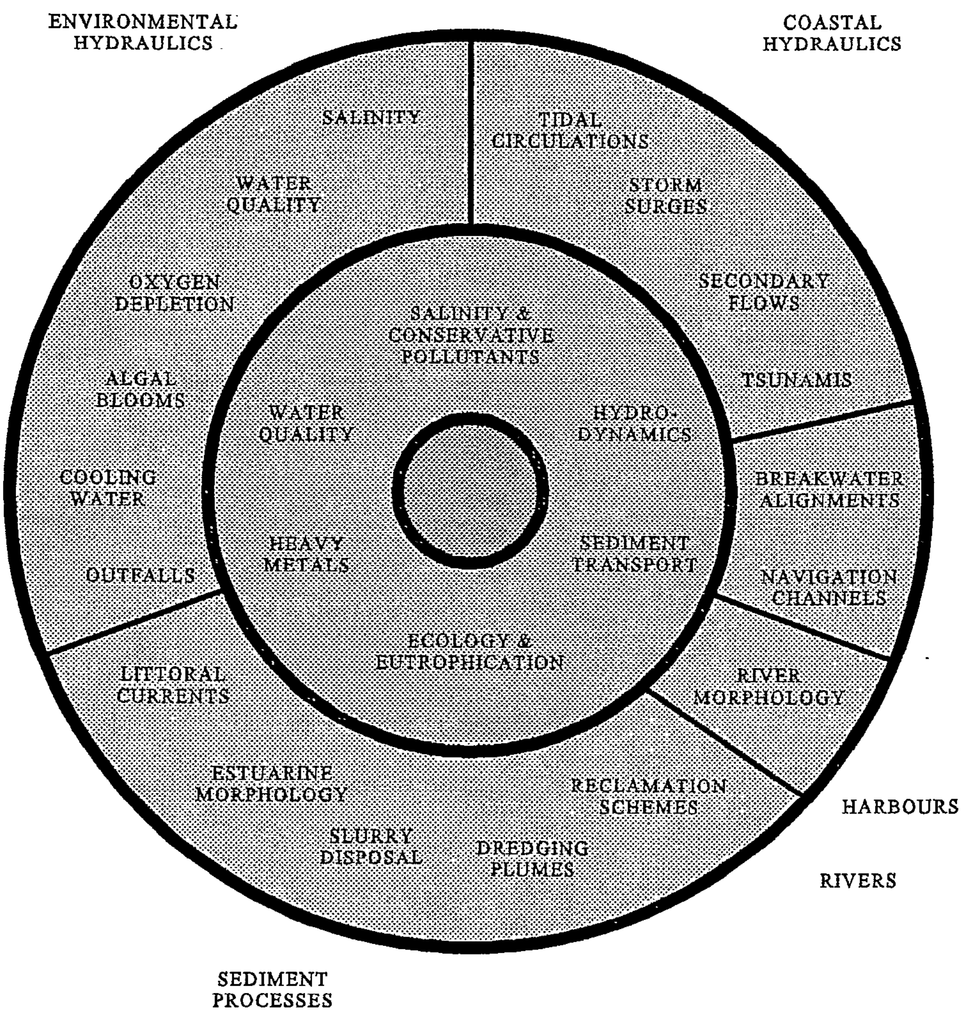


Figure 4.1 : RANGE OF APPLICATIONS OF ESTUARINE MODELLING

4.1.2 Full hydrodynamic models

Figure 4.1 (based on Abbot, 1997) shows the wide range of full hydrodynamic model types available and the applications to which they are typically applied. Despite the trend towards single program suites with a wide range of modules, it remains difficult to build a model that can be used for a wide range of purposes, such as flood defence, water quality, morphology and wave modelling. There are significant differences in:

- Scale and detail of the models; and
- Time steps and scales of the processes modelled.

However, it may be possible to use base topographical data, flow and level data, and other general models between applications. Hydrodynamic models may further be defined as listed below (based on Cooper and Dearnaley, 1996). Flow, quality, sediment and ecological modelling may require:

- fully 3D flow models;
- hydrostatic pressure 3D flow models (3DH);
- Boussinesq 2DH models;
- hydrostatic pressure 2DH models;
- 2D 2 layer models (2D2L);
- hydrostatic 2DV models (horizontal 1D models with vertical variation modelled); and
- 1D models.

Quality and sediment modelling may also use plume models.

Sediment modelling may further require point models and particle (Lagrangian) models.

All model types have inherent limitations, and should not be applied outside the applications for which they were designed. The strengths and limitations of the model types available are set out in Figure 4.2.

The different model types and their selection for a particular project are also discussed in Chapter 8 of this report, and the associated quality control manual.

4.1.3 Statistical and simple models

Statistical approaches and tide averaged or box models, although simple by present computional modelling standards, remain a useful tools for an initial assessment of an estuary, or for analysis to a budget.

For example, detailed statistical and correlation analysis could be carried out on flow sequences and dredging records, together with anecdotal evidence on siltation and navigation difficulties. These may give a clear understanding of the flow regimes and sediment patterns.

Model type	Strengths	Limitations
Full 3D	1) Full and accurate modelling of transverse and vertical variations of parameters in estuary.	1) Limited application to date to estuary and coastal applications. 2) Free surface treatment complex. 3) Extensive data collection required for calibration. 4) Expensive to run.
Hydrostatic 3D	1) Good modelling of transverse and vertical variations of parameters in estuary. 2) Wider use to date than full 3D approach.	1) With some grid layouts, less accurate in modelling of density effects than full 3D models. 2) Extensive data collection required for calibration. 3) Expensive to run.
Hydrostatic 2D	1) Established modelling approach. 2) Model can be built from similar data set to 1D model. 3) Calibration data requirements not excessive. 4) Will give reasonable representation of most modelled uses and processes.	1) Vertical profiles due to stratification not represented. 2) Care needed at model limits to establish realistic boundary conditions.
2D 2 layer	1) Allows simulation of stratified flow without using full 3D model.	1) Care needed to establish realistic layers and flows between layers.
Hydrostatic 2DV	1) Allows simulation of stratified estuary without complexity of full 3D model. 2) Uses similar data set to 1D model.	1) Transverse variations across estuary not represented.
1D	1) Simple and cheap to set up. 2) Robust in operation 3) Existing model may exist.	1) Transverse variations across estuary not represented. 2) Vertical profiles due to stratification not represented.
Plume, point & particle	1) Gives accurate representation of surface and 3D plumes not truly represented by 2D models. 2) Simple to use.	1) May require float tracking or 2D modelling to establish flow paths.

Figure 4.2 - COMPUTATIONAL MODELS - STRENGTHS AND LIMITATIONS

4.2 Data requirements and collection

4.2.1 Appraisal of data

Early consideration of the current availability of data for modelling is essential. Data availability may influence the model specification (for example, readily available data may allow construction of a more detailed model at no additional cost) and certain data sets, such as flow, level and topography will be required for almost all model configurations. The data required for different model types are discussed in more detail in Chapter 8 of this report, and the associated quality control manual.

4.2.2 Availability

The Agency will hold much of the available baseline data for a study. However, significant data are often held by other bodies. Baseline data may include:

- Agency data
  - Tide levels
  - Freshwater flows
  - Water quality
  - Some ecology
- Port authorities
  - Bathymetry
  - Some tides
  - Currents
  - Sediment movement and dredging
  - Ship sizes and constraints
  - Ship movements and pilotage
- Fisheries data
  - From MAFF, SFCC and fishermen
  - Fish species and stocks
  - Shellfish
- Local authorities
  - Particularly for uses
- Nature interests
  - From English Nature, RSPB, wildlife trusts
  - Other ecology
- Industry
  - Abstractions and returns.
- Research
  - Universities.
  - Research programmes (eg LOIS, SABRINA).

It is important to collect information about proposed developments and uses as well as the existing and historic conditions. Liaison will be needed with the planning authorities.

4.2.3 Collection methods

General

The accuracy of an estuarine model will depend largely on the quality of the data set used to build and calibrate the model. It may have a greater effect on the model results than the software used or the design of the model itself. The design of surveys is therefore a critical aspect of the modelling process. Data must be collected in sufficient detail in critical areas such as:

- Model boundaries;
- Areas at the focus of a project, such as outfalls and navigation channels; and
- Areas that control the behaviour of the estuary, such as ebb and flood channels, sandbars and mudflats.

Management issues

Whilst planning data collection and survey, management of this data should also be considered. Issues to be decided are:

- Format of data. This should preferably be digital, with paper records minimised;
- The potential cost of purchasing data, and of digitising paper records should not be forgotten;
- The project programme should allow for time to:
    - identify data sources;
    - extract data from the source; and
    - process it to the required format.
- Managing data, including storage, availability to others and compatibility with existing systems. The use of a GIS for data management and storage should be considered for all large projects; and
- Maintenance, including updating and avoidance of data corruption.

Topographic data

The most basic items of data for an estuarine model are the basic topography (bathymetry) of the study area and the shape of the estuary's coastline. Modelling of the outer estuary may be possible from Admiralty charts alone. However, it should be remembered that:

- These charts err on the side of caution as to the point of view of navigators; water depths are therefore underestimated;
- Data is more comprehensive in navigable areas. Main navigation areas have more detailed coverage than, say mudflats that may be critical to the dynamics of the estuary; and
- Coverage is often inadequate for modelling in the inner estuary.

Additional data sources may be from port and harbour authorities, but it is likely that topographic data collection will be required in the inner estuary.

Freshwater flows

An extensive network of stream gauging stations provide more-or-less continuous measurements of river flows near the tidal limit of most major rivers in Great Britain. However, this does not mean that the freshwater inflow to estuaries is well known. Due to the difficulty in measuring tidal flows, rivers are measured upstream of the hydraulic tidal limit although with ultrasonic gauges it is technically possible to measure tidal flows. There are often side tributaries or areas of direct runoff that drain to the estuary downstream of the tidal limit on the main river. These tributaries may or may not be gauged.

Naturalised freshwater flows can form the basis of a statistical approach to setting flow requirements for the smaller, less sensitive estuaries. They can allow comparison with present flow duration curves, and proposed future curves after additional resource development.

Tidal flows and levels

Tidal flow and level data will be required for:

- Boundary conditions for both calibration and simulation; and
- Internal model measurements for calibration.

Water quality

Data will be needed for calibration and for water quality boundary conditions in the model.

Morphological field work

The collection of sediment data to assess short term changes is a routine process, although a large scale data collection exercise will be an expensive exercise. Long term morphological changes are less easy to quantify.

Ecological assessments

Detailed biological surveys may be needed to provide full ecological data for a model.

4.2.4 Collection programme

Assessment of the available data sets should continue through the impact identification described below. Data surveys should be designed for the computational models required for the technical approach. These surveys should then be costed. The model design process may be iterative, where data collection costs must be kept within a fixed budget.

4.3 Modelling low flows in UK estuaries

4.3.1 Saline balance

The pattern and limit of saline intrusion in tidal deltaic channels is determined by the balance between the rate of longitudinal mixing causing the landward movement of dissolved salt and the net seaward movement induced by a fresh water discharge. The rate of longitudinal mixing is governed by the strength of the tidal velocities, shape of the channel cross-section and by gravitational circulations induced by longitudinal density (salinity) gradients. The 1D cross-sectionally averaged rate of longitudinal mixing may be quantified in terms of an effective coefficient of longitudinal dispersions, D_x (m^2/s). As yet, this coefficient can only be quantified using relatively crude empirical relationships which have to be calibrated for each estuary. This means that for a 1D model to be accurate at low flows they must be included in the calibration tests.

4.3.2 Gravitational circulation

One of the most important aspects of the hydraulics of the deeper seaward reaches of many UK estuaries is the longitudinal gravitational circulation that is driven by the longitudinal density gradients within the estuary. The magnitude of the net longitudinal pressure gradient, dp/dx, at a depth, z, which causes the gravitational circulation is a function of the slope of the mean tide level, $d\eta_o/dx$, and the vertical variation in the tide-averaged longitudinal density gradient, $d\rho/dx$, as follows:

$$\frac{d\rho}{dx}\Big|_z = g\bar{\rho}_g\frac{d\eta_0}{dx} + g\int_z^{\eta}\frac{\delta\bar{\rho}}{\delta x}dz$$

Where ρ_s is the density of surface water (kg/m^3)
g is the acceleration of gravity (9.81 m/s^2)

The strength of the gravitational circulation varies directly with the magnitude of the product of the depth and the longitudinal density gradient. It is reduced by vertical mixing, which is usually heavily damped in stratified flows, and by energy dissipation at the bed, which is increased by the occurrence of high tidal velocities in the lower layers. The presence of a longitudinal density gradient within an estuary causes the mean tide levels to rise in a landward direction. The net landward pressure gradient and the net landward residual flow disappear at a 'null point' in the estuary where the two terms on the right hand side of the above equation cancel each other out.

4.3.3 Stratification and 2-DV models

The pattern of the gravitational circulation will vary according to the degree of stratification, but it is not dependent on the existence of vertical density stratification. Many relative deep estuaries with weak or negligible vertical stratification have strong gravitational circulations. The longitudinal density gradients tend to distort the shape of the velocity profile on the flood and ebb phases of the tide and thereby induce a net landward longitudinal movement of water in the bed layers seaward of the 'null point' where a turbidity maximum usually occurs. There is a corresponding net seaward flow of water in the surface layers of the estuary giving rise to a two-layer circulation, which controls the water quality in many UK estuaries. The effect is strongest in deep sluggish estuaries and weakest in shallow estuaries with strong tidal currents. It can only be modelled by using a layered 2D in-the-vertical model.

The predictive capability of layered width-averaged models of deeper estuaries (ie the Tyne or Itchen) depends largely on the method of simulating the effect of stratification on vertical turbulent exchange. Ideally, this should be a well formulated universal function with well defined coefficients that do not have to be adjusted for each estuary. A less important longitudinal dispersion coefficient incorporates the effects of lateral variations in identity and flow velocity.

4.3.4 3-D models

Full three dimensional models have so far, only been used usually to simulate the seaward reaches of the larger UK estuaries. To date, it has not been economic to use 3D models to simulate the fine details of all the bends etc in a small estuary. The fine grid required to do this gives rise to impartially long run times. There is usually little benefit in using 3-5 relatively coarse cells to simulate variations across an estuary, because they would not be able to resolve the detail the secondary flows in the cross-section. However, 3D models do not necessarily need more calibration data than simpler models.

4.4 Level of accuracy and limits to existing knowledge

4.4.1 Level of accuracy

There are three areas that currently limit the level of accuracy that can be obtained from computational models:

- Computing power;
- Limits to existing knowledge; and
- Data accuracy.

There will always be a need to balance model detail with the time period covered by the model simulations. The wrong balance will result in excessive simulation times.

It is usually computing power that restricts our ability to simulate time scale and length scales that nature uses. For example, sediment entrainment is governed by small scale turbulence of the order of millimetres acting in an unsteady fashion over a period of seconds. To represent anything other than the entrainment of a single sediment particle requires computing power beyond that of the most advanced mainframe. The same is true of boundary friction, diffusion and dispersion of pollutants and freshwater mixing.

The pragmatic way around this problem is to integrate processes over much greater time and distance scales. Small scale turbulence will be averaged over model elements of 100m or more in space and over minutes, hours, tidal cycles or even longer in time. The way in which such integration or averaging is carried out determines the type of model developed. For example a steady state model of an estuary may well produce very acceptable results in terms of the seasonal variation of water quality or salinity, but it would not be very good for determining the magnitude of processes within the tidal cycle. Whenever an average is taken or an integration is carried out, there is a potential loss of accuracy.

Further, there remain areas of estuarine science that are not fully understood at present. These include both large scale processes, such as sediment transport and morphology and smaller scale such as the adsorption of metals on particles, or the resistance of moveable bed forms in a tidal flow. The laws that are derived for use by engineers and other practitioners represent the integration of processes occurring at much smaller scales. There are hence a range of approximations intrinsically built into a model that will again potentially reduce accuracy.

Finally, it should be remembered that although there have been advances in computing power and physical understanding of the processes occurring in estuaries, these advances have not always been matched by the accuracy of the field data that is collected. Measurements of quality, sediment flux and even flow can still have significant errors attached.

Hence there are still real practical problems with using a model, particularly if it is required to simulate a long period of time, such as a year or more to investigate seasonal trends. Model choice is important. It will be dependant upon:

- the final use envisaged for the model, and the accuracy required from the model results;
- the scale of the model and the accuracy with which those processes are represented in the model; and
- the accuracy of the field data used to build, calibrate and test the model.

4.4.2 Model accuracy requirements

Model accuracy considerations

In specifying the accuracy required from a computational model four criteria must be considered. These are:

- the problem being assessed;
- the quality of the data set;
- intrinsic limitations of the model; and
- credibility to other interested practitioners.

Problem assessment

The accuracy required from a mathematical model or any other means of assessment must be primarily related to the problem being addressed. This will often require high accuracy in a few critical areas for key parameters. Lower accuracy is usually acceptable for other parameters and in less critical areas. However, since many aspects of modelling are interdependent, achieving the required accuracy may depend on achieving high accuracy in another aspect of the model. For example, accurate water quality modelling usually requires an accurate hydrodynamic model, or at least a good understanding of the critical flow processes and estuary dimensions. Another example is sediment transport models which are often very sensitive to small changes in velocity predictions.

Data set assessment

A second aspect to accuracy that needs careful consideration is the accuracy of the available data. All data are subject to error. This error will include:

- gross errors;
- minor errors; and
- natural variability.

Data errors

Occasional inaccurate measurements or errors in the processing of raw data are present in many data sets. Gross errors can often be detected by screening and the suspect point may then be treated with caution. It is bad practice to completely ignore a suspect point as it is rarely possible to prove that an unusual value is the result of an error and not a correct measurement of a rarely occurring event. These points should be retained in the data set, but treated as outliers, so that the effects of either including or excluding them can be considered. In addition to gross errors many data sets will contain smaller data errors that cannot be detected by screening, but may be subject to significant error. These errors will show themselves as occasional scatter in model calibration and verification.

Natural variability

Another source of scatter in model calibration or verification is 'natural variability', when apparently similar conditions lead to different values that have been correctly measured. Natural variability is an intrinsic feature of natural systems that are only partially monitored. For example, in river flow measurements, similar water flows may be associated with different water levels because of unmeasured changes in river cross-section. As another example, water quality may vary in an apparently random manner because of unmeasured changes in run off or effluent flow and quality.

Natural variability causes data scatter whose range can only be defined by repeated measurement, or reduced by more extensive and intensive surveys. The amount of natural variability needs to be carefully considered in the design of data collection for model calibration and verification as all too easily a single data set can be used for model calibration with no knowledge of how the measured value relates to its natural variability.

Intrinsic model limitations

An important cause of scatter in model results is intrinsic limitations in the model. All models simplify the natural processes they seek to represent. This simplification is carried out most importantly in the assumptions used to set up the model. For example the use of a 1-D or 2-D model automatically limits the processes included in a model. However, even in a 3-D model simplifying assumptions are made in the scale of processes that can be represented. A physical model avoids some of these simplifications, but introduces other assumptions which may be even more significant especially in water quality and sediment modelling. Assumptions about model dimensions are simple to understand, other assumptions about the way processes are represented may appear subtle and esoteric, but can sometimes have a major effect on the results obtained.

Combining the intrinsic limitations of the model with the natural variability of the data and any data errors present gives an overall uncertainty about the accuracy of the results. One practical consequence of this uncertainty is that there is a minimum scatter associated with a particular combination of estuary, data and model that cannot be reduced without a major improvement to either the data or the model. Efforts to force an improved calibration without such improvements will at best be ineffective and at worst could give misleading results. As the financial and time costs of major improvements to the model or the data are large, initial choices about the model and the scale of data collection are critical in the final outcome of the study.

Specification of objective accuracy requirements for a model is superficially attractive, but is fraught with practical difficulties. At the beginning of a study it is usually impossible to say how accurately a model will be able to reproduce a given data set. In practice this may not matter provided the model is actually predicting the correct direction of any change that is proposed and approximately its correct magnitude.

Model credibility

A third criteria for model accuracy is that promoters and critics of the proposal should as far as possible be satisfied that the model provides an adequate assessment of the anticipated impacts. An independent peer review is a useful method for establishing the reliability of a model. Such a review can assess accuracy in relation to the probable quality and reliability of the available data and the capabilities of the model itself.

4.5 Costs, input and programme implications

4.5.1 Costs, inputs and programme

This section gives an overview of the implications to costs, input and programme from using computational models. Detailed costs, inputs and programmes are presented in Chapter 9 of this report.

In any study there are two parts to the cost of a modelling project:

- Survey and data collection costs; and
- Model building and running costs.

Modelling studies have significant cost. This cost may be small when included within, say, design of flood defences, but as a stand-alone study to check a licence application, may be a unacceptably high proportion of the auditing Agency area's budget. Possible management approaches to budgetary problems are described in Chapter 8. However, it must also be stressed that modelling studies will almost invariably provide an improved quality of result over manual methods of analysis.

It is interesting to note that although computing power and model complexity have increased together, the costs of modelling projects have not risen in step with these factors.

Survey costs are dependent on the level of spatial and calibration detail required in the model. As such, they are relatively fixed, for a typical model to be run over a series of spring, neap and average tides. A more complex model may need little more topographical survey detail, but additional level and quality survey points for calibration. Costs rise steeply for long term data collection, where instruments are left in place for months rather than days.

Modelling costs are linked closely to time input by the modellers. These inputs do not increase linearly with model complexity since:

- most if not all computing can be carried out on standard PC based machines with acceptably short run times, resulting in fixed computing overheads; and
- use of data processing tools such as GIS allows quick processing of complex data sets.

Use of computational modelling does impose programme implications onto any study. Of the data collection and modelling components to the work, it is the data collection that may provide the greatest constraint. Survey contracts may need to be tendered, and appropriate periods in the year chosen to collect data for calibration.

4.5.2 Balancing modelling costs with accuracy benefits

The most practical time to consider the balance between modelling costs and the reliability or accuracy of the final model is at an early stage while there is still time to influence the data collection programme and the model assumptions. Time may be usefully spent reviewing the issues of importance for an estuary study, and if appropriate developing a simple preliminary model to gain a better feel for the key features of the estuary.

If problems with the assumptions of the model or the extent of data collection are not thought through at an early stage, they may not become evident until model development is well advanced and the costs of the required changes are large. In such circumstances the costs and benefits of additional modelling need to be carefully considered, especially as additional funding will often need to be obtained and justified.

Where the expense of the required modelling approach is not justified by the scale of the proposed development, two approaches may be considered. The scope of the modelling may be reduced to what is affordable with experienced engineering judgement applied to cover issues which cannot be covered adequately by the model. Alternatively, if modelling at the required detail is essential, additional funding can be sought for the modelling. This is only likely to be forthcoming where the scope of the model can be extended to allow its use on a wider range of proposals in the estuary. This issue is reviewed in Chapter 7.

4.6 Future trends

The future trends of computational modelling will be closely linked to the computing power available. It is certain that the power available on the average modeller's desk at low cost will continue to escalate. It will become possible to create models that are:

- more realistic;
- more detailed in space and longer in time; and
- more integrated.

More realistic models will involve added dimensions to modelling. Fully dynamic 1-D hydrodynamic models are now routinely used where a backwater model would be used a few years ago. 2-D and layered models are often used in place of a 1-D model. There will be a trend towards use of 2-D and 3-D models as a matter of routine, although it is hoped that this will not result in unnecessary complexity in models. Often a simple model will still provide all information and results needed for a study.

Faster computers will also allow more detailed models. Grid sizes will be reduced, and models could be run at shorter time steps and for longer periods of simulated time. This will reduce the

degree of integration of processes and may increase accuracy. It will also allow simulation of local topography and hence local flow effects and processes.
Finally, the above changes will allow increased integration of models. At present, model construction may be biased to a particular modelling discipline, be it floods, water resources, quality or sediment. The model scale and type may be dictated by the discipline involved. However, increased detail within models will allow a base data set to be used for a wider range of studies, although again it is hoped that this integration will not replace use of simple single purpose models where appropriate. This integration of models requires close co-operation between the various modelling disciplines.

Major developments are expected in two areas of modelling, discussed in detail in Chapter 6. These are:

- geomorphological modelling; and
- ecological modelling.

It is certain that considerable advances will be made in computational modelling over the next few years. What is less certain is whether the specialist modelling software required will be reduced in price to match the hardware. There is considerable investment involved in writing and marketing complex simulation software. It is possible that the advances possible in modelling will be limited by the cost of the software and the budgets available for its use.

It is further hoped that these future trends in computation modelling will be matched by similar developments in the field of data collection. A number of new technologies have been applied to data collection in recent years. However, data collection remains a costly exercise. It is therefore possible that the application of these advances in modelling will again be limited by the cost of data collection. Additional data will be required to build and calibrate a more detailed model. It should also be noted that much existing data, that will still be used, particularly, for model calibration will be of low definition, and may not make best use of the increased model accuracy.

If the costs of building and running a complex model do not reduce in line with the associated hardware costs, the definition of a computational modelling project will become critical. It will become more important to consider methods of identification for key impacts and uses in the estuary, and consider the use of a simple, preliminary model to assess the need for and, if necessary, design the complex model. The use of impact assessment and simple models are discussed in Chapter 6, following.

Part C - METHODOLOGY FOR ESTABLISHING FRESHWATER FLOW REQUIREMENTS

5. APPROACHES CURRENTLY IN USE

5.1 Existing practice by Environment Agency

5.1.1 Introduction

Discussion with Agency staff, involved in projects, modelling and operations has allowed a picture of the UK estuaries and existing practice to be developed. Most staff contacted showed a good appreciation of estuarine processes and the potential of computational modelling. However, this may have been due to the consultees being knowledgable; some comments were also made about general lack of appreciation through the Agency.

It was, however, also apparent that:

- few regions had recent experience of establishing freshwater flow requirements; and
- study had concentrated on a few major estuaries.

The following sections summarise the responses received from Agency staff. A list of staff consulted is included in Chapter 10. Background information on each region's estuaries has been taken from the NRA studies on residual flows (Wade, 1992). The responses have been set out as follows:

- Region specific comments; and
- General comments on data collection, models and cross-functional liaison.

5.1.2 National Headquarters

Agency policy on water resources will impact computational modelling in the following areas:

- The methodology for assessing licences;
- The holistic approach to river basins;
- The internal organisation of the Agency; and
- The availability of funding.

In the most general terms, the Agency wishes to use the most appropriate methodology for each analysis carried out. This may require the Agency to:

- audit licence applicant's models and calculations;
- co-operate with other bodies in the study of an estuary; or
- carry out their own modelling study.

There is a trend towards the audit of other's work due to pressures of time and funding. However, this can never be a full solution. Audit of models cannot be successfully directed by the Agency without internal expertise and modelling capability. Further, with the increased pressure on water resources, rivers and estuaries, it has become essential to look at river basins holistically. It may be necessary for the Agency to hold a full basin model to examine the wider impact of local changes in estuary or river use.

Internal reorganisations within the Agency and an integration of policy should increase the cross-functional liaison between modelling groups. Although there is currently an emphasis on management from the Agency areas, centres of excellence at area level will still serve regional, and if necessary national, needs.

The above comments assume that there is no increase in funding available for computational modelling within the Agency. It should be noted, however, that more funds could be made available for modelling, if an increased share of the total Agency budget can be justified as a priority at a corporate level.

5.1.3 Anglian Region

Anglian Region has many estuaries. Its rivers may be divided into three groups:

(1) The Wash and the North - Ouse, Nene, Welland, Witham and Ancholme. These rivers have high tidal ranges, flat areas and short estuaries giving problems of saline intrusion, slow flows, poor river flushing and water quality.

(2) The Norfolk Broads - Waveney, Bure and Yare. These rivers have a much lower tidal range and share an estuary; saline intrusion is less significant. Water quality problems include algae and dilution. The area has high environmental significance.

(3) Suffolk - Blackwater & Chelmer, Colne, Stour and Gipping. These are small rivers in oversized estuaries and medium tidal ranges. The large estuaries originated when the freshwater flow was greater as the course of the Thames was different. This small freshwater flow has little influence on the estuary.

There are other small rivers in the region, for example along the north Norfolk coast. Despite their small size, some drain into important areas for nature conservation.

However, only the first group of rivers, especially the Great Ouse and the Wash, has been considered in detail, the studies being linked with the Ely Ouse-Essex transfer scheme. Here, most available modelling techniques have been applied to examine flow, quality, navigation and ecology. Quality modelling has been carried out for the second group as part of flood studies for Broadland. Away from these important estuaries, most rivers and creeks on the Norfolk and Suffolk coastline have been given SAC/SPA status. In the longer term, all these small estuaries will need to be studied, particularly as to their environmental indicators.

5.1.4 Midlands Region

Midlands Region contains two major rivers and estuaries, the Severn and the Trent/Humber. There are no minor estuaries within the region.

A residual flow to the Severn estuary is required to:

- maintain the passage of migratory fish;
- maintain the quality of abstracted water at Gloucester; and
- provide dilution for discharges to the tidal river.

Abstractions and reservoir releases are co-ordinated to provide this residual flow. It is thought that a varying residual flow related to tidal height may be beneficial for the environment.

Until recently, heavy industrial usage of the Trent made it unsuitable for public water supply abstraction, and there have been no flow related controls on river abstractions. However, improving river quality, water supply abstraction and concern over long term damage to the Humber estuary has resulted in a series of studies on licencing policy and control rules for the Trent.

Extensive modelling has been carried out on both the Severn and the Trent. Studies have included flood control, water quality and, for the Severn, tidal power. A few recent studies have taken a broad, multi-disciplinary approach. The studies on the Humber, shared between Anglian, Midlands and North East Regions have shown the significant gaps in our knowledge as to long term morphological changes caused by flood banks, dredging and the like.

5.1.5 North East Region

Most Yorkshire rivers drain to the Humber estuary. Due to the extensive water supply grid in South Yorkshire, abstractions and return of effluent make these rivers un-naturalised. There are internal transfers between rivers, but these all drain to the Humber if not used for supply. Prescribed flows for rivers are fluvially controlled, without concern for the Humber estuary. However, as noted above, recent concerns about the condition of the Humber estuary have increased study of this basin.

In Northumbria, the main estuaries are the Tees, Tyne and Wear. Work has concentrated on the clean-up of these rivers with the decline of heavy industry in the region. All three rivers have residual flows set, and may be supported by releases from Kielder Water. Little work has, however, been carried out concerning the environmental requirements of the rivers and estuary. To date, the improvements to river quality can only be beneficial to the environment.

Modelling has been carried out in the major rivers and their estuaries. The most recent models use a vertically stratified 1-D model (2DV) to examine the effect of residual flows on saline intrusion.

5.1.6 North West Region

North West Region contains relatively small rivers, but includes significant estuaries such as the Mersey, Ribble and the Wyre. Some residual flows have been set to protect abstractions, dilution, fisheries and navigation. The main problems appear to be in the setting of minimum acceptable flows to rivers, rather than to their estuaries.

The southern rivers in the region suffer water quality problems due to urbanization and industry. There has been considerable work carried out to clean up the Mersey estuary. However, interestingly, there is no residual flow set into the estuary. The demand for water is falling, and there is no problem of supply. The Mersey Management Group includes representatives from both the Agency and North West Water. Their focus is mainly on water quality.

Those residual flows that have been set have been calculated by ad-hoc methods. SWALP methodology has been tested on the rivers, but the region staff are not convinced on its suitability for the region.

Modelling has concentrated on the Mersey, Ribble and Wyre estuaries.

5.1.7 South West Region

Most rivers and estuaries in the region are small, for example the Axe, but the region also bounds the Severn estuary in the north and the Poole harbour in the east. There are no residual flows set for the estuaries, but prescribed flows are set to protect against over abstraction. There are potential problems with increased abstraction and effluent due to tourism, and the need to maintain beach quality.

Modelling has been used on a range of estuaries. Poole Harbour has been extensively studied, using 2-D models. 2-D modelling has been used in a number of other locations, but most small estuaries have been analysed using mass balance and simple box models.

South West Region has developed a regional database for the estuaries, but it needs constant work to keep it up to date. The region is developing a strategic modelling plan to determine the type of model, if any, needed for each estuary, and the likely time scale for its development.

5.1.8 Southern Region

Interest in the Southern Region has centred on the Solent and the Medway and Stour estuaries, due to the demand for increased abstractions in these areas. Some work has also been carried out on the Itchen.

Southern is another region taking a multi-disciplinary approach. The studies for the Kentish Stour, associated with Broadoak Reservoir, have carried out process and use impact assessments, to determine all issues critical to the freshwater flow needs of the estuary.

5.1.9 Thames Region

Thames Region is unusual in having a single estuary. Many existing MRFs are relatively long standing arrangements, the River Thames being a good example. Here the flow needs of the estuary were agreed in a 1986 public enquiry, resulting in the Lower Thames Operating Agreement. The key issue is the residual flow at Teddington Weir, downstream of the major reservoir extractions.

During the enquiry, the factors considered were water resources and downstream water quality, plus navigation to a lesser degree. Water quality modelling was carried out, especially downstream of the main storm sewage outfall at Beckton, and to determine the potential saline intrusion. Ecological factors were not considered. The freshwater flow needs of the estuary were not considered; rather, an MRF was established that would not significantly damage the estuary.

Fisheries were not considered in any detail. Thames Region may now have to re-appraise the situation if they wish to further improve fisheries, perhaps to maintain a larger salmon population in the Thames.

The residual flow is maintained by integrated management techniques, considering river flow, storage and groundwater. Dissolved oxygen levels are maintained above 30% saturation by increasing effluent quality at London's main sewage treatment works, use of a mobile bubbler to inject oxygen into the river, or by suspending or reducing abstractions for water supply.

5.1.10 Welsh Region

Welsh Region contains many small rivers, but does include large estuaries on the Dee, Tywi and Tawe. Rivers in the north and west are largely rural and un-regulated. The conservation of trout, salmon and wildfowl is of particular interest. Those in the south drain through coastal urban areas, with their attendant abstraction and dilution requirements.

Particular attention has been given to the Dee with where there is considerable conflict for water use. The uses include fisheries, navigation, recreation, dilution and abstraction. Modelling has been used too in a number of studies. However, Wade (1992) comments that 'Overall the Dee is a highly, and well, managed catchment, although the one question that remains unanswered is "How was the residual flow chosen?".'

5.1.11 Data collection policy

The extent of data collection varies between regions. Some regions, such as Midland, collect data on a routine basis only, sufficient being collected to meet most expected modelling needs. Data is therefore rarely collected for a specific project. Most regions, though, collect a range of baseline data, but supplement this as required on a project-by-project basis. They consider that baseline data alone cannot be adequate for most modelling studies.

Management of data is largely carried out independently by the regions. There is a general feeling that the data management is difficult and needs significant resources that are rarely available. Data held in central repositories is usually out of date.

The WAMS project was designed to unify this data management, but cannot be considered a success. A number of other initiatives, such as the ZAP teams, LOIS and JoNuS have contributed to the standardisation of data collection. A common comment was that even though data was available, there was rarely the time or budget to use it fully. Most Agency staff did, however, consider that data was freely available between disciplines.

In summary, there is no consistent approach to data collection and management , and whilst the data is freely available, it is rarely used to best advantage.

5.1.12 Computational models used

Across the regions a range of computational models are used from a range of software suppliers. Models are required to be fit for purpose. It could be said that there are no standard models, but there is a standard approach to the modelling tasks.

One modelling system of interest is the ECOS small estuary model developed by the Plymouth Marine laboratory. This system provides a modelling framework, that should allow a initial basic estuary model to be simply set up, and then developed in complexity as required by particular studies in the estuary. Models start at simple box models and tidal average models, and can be worked up to full 2-D models. Despite its apparent power, the model appears only to have been used by its proponents in South West Region. Others preferred to carry out simple models on a spreadsheet, then use a commercial modelling package for 1-D and 2-D modelling.

Comments on the quality assurance and control of computational modelling work ranged from an off-the-record none, to fairly formal in-house systems. Hydraulics Research Ltd have produced guidance documents for river modelling. An Agency working group has produced a similar document for water quality modelling. Individual modellers also have their own procedures for quality control.

5.1.13 Cross-functional liaison

The interaction between the various disciplines and different regions within the Agency was perceived differently by different individuals. This perception appeared to be more a function of the individual, rather than the Agency region. In theory, this cross-functional liaison should be facilitated by specialist "functional chimneys" and working groups within the Agency. Most people considered such liaison to be effective, but that it often relied on personal contacts built up over a period of time. Project teams were, by definition, usually cross-functional, but there was less interaction with Agency operations staff. It was felt that formal liaison channels would not always be helpful. Again it was felt that the disciplines talked and exchanged data, but that the spinoffs from this liaison did not always develop due to lack of time and budget.

5.1.14 Added value from Agency consultation

The notes above have briefly set out some of the regional variations in estuarine studies within the Agency. Other information collected during consultation has been used to develop the management and technical approaches presented in Chapters 8 and 9 of this document. Consultation has been particularly useful to obtain:

- a clear overview of Agency practice, both at a management and a modelling level;
- information on research work being carried out; and
- direction in the preparation of the management and technical approaches.

5.2 Shortcomings of existing arrangements

A number of shortcomings in existing practice have been identified though consultation with Agency staff:

- There appear to have been few examples where a holistic approach to determining freshwater flow needs of estuaries have been applied;
- Water resources modelling and water resources impacts appear to be considered separately from functions such as flooding, water quality and the like, although this situation may be improved by recent changes in Agency organisation;
- There appears to be some variation between individual and local against regional approaches and policies to modelling and data collection;
- Liaison between disciplines and regions could, on occasion, be improved;
- Estuarine experience could be disseminated better through the Agency;
- Although data appears to be freely available between disciplines and regions, there is inconsistency between data collection and handling arrangements and data protocols;
- Modelling quality procedures are not consistently applied throughout the Agency.

5.3 Identification of issues

The issues identified from consultation with the Agency are:

- Agency staff have a good understanding of estuarine processes and methods of analysis. However, are the Agency in a position to apply this knowledge in a cross-functional study to find the freshwater flow needs of an estuary and set a revised MRF?;
- To what extent should liaison be formalised between regions and disciplines?;
- To what extent should modelling approaches and procedures be standardised between regions?; and
- Should data collection, management and archiving be standardised between regions?

5.4 Practice by others

5.4.1 Europe

Discussion with Danish Hydraulic Institute and Delft Hydraulics have shown that the European approach to estuaries is similar to that currently used in the UK. They have developed or are developing software within their software suites for morphological and ecological modelling. Both organisations see this as an important growth area of work in the future.

5.4.2 North America

Contacts with a number of organisations in the USA indicate a similar level of understanding and application of computer technology to estuarine processes as the UK.

Delaware River

The Delaware River supplies water to the New York conurbation, perhaps 10% of the US population, and also to major industry. The Delaware River Basin Commission itself has been in existence for some 30 years and was innovative at the time of its inception, transferring power to manage water resources from about 10 state organisations to a single non-political basin manager. Discussions with Gerald M Hansler, the Executive Director of the Commission, show that releases from upstream reservoirs are controlled by:

- An estuary salinity model (including ground water);
- A daily river flow model; and
- A river and estuary quality model, that uses BOD as its major indicator.

These models have been in use for many years and in some ways are old technology. However, they are retained as they are trusted and have been validated by many flow sequences in the basin. Pollution in the river and estuary has been progressively reduced over the past 20 years, to give a present situation where fish and other biological indicators can be used as a measure of quality - there are presently 38 recorded species of fish in the river, as opposed to 3 species 20 years ago.

Overall, the Delaware River Basin Commission uses its models in a similar manner to those used in the UK. The difference is perhaps that the Delaware is a longer river than most in the UK. The time of travel in the river allows use of operational hydrological models to control reservoir operation both to maintain residual flows and control flood flows. There is no move towards morphological or ecological modelling at present.

San Francisco

Discussions with Beth Quinlan of Black & Veatch indicate a similar level of technology used within San Francisco Bay.

Texas

Modelling of the Gulf Coast appears to be more advanced. Neal Armstrong of the University of Texas indicates that apart from the range of models described above, ecological modelling is being used to manage freshwater inflow. Ecological functions have been represented as a function of flow and salinity, or as a set of biotic viability limits for parameters such as bay salinity, freshwater inflows, fishery harvest targets and the like (Matsumoto et al. 1994).

5.4.3 South-East Asia

The management of estuaries in South-East Asia is currently dictated by development and economic, and in particular water supply needs. The situation is typified by the environmental outcry in Japan in 1996 at the news that a estuary barrage was to be constructed across the country's last natural river. However, it was also significant that most of the outcry came from Japanese environmentalists. There is growing environmental awareness in the region, and this will in due course become an integral part of the engineering profession, as has happened in the West. Brief comments on a practice in number of countries are set out below.

Malaysia

In Malaysia there are numerous estuarine systems, some of which are large and complex. 1-D and 2-D modelling has been applied to many of these estuaries. It has been carried out in most cases to determine the limit of salinity and the regulated flows needed to maintain intakes for water supply and irrigation. Morphological modelling has been carried out in a few locations as part of flood defence schemes. The models built have been project specific, and it is understood that they are not used as part of an estuarine management system.

The DoE in Malaysia carried out a fairly comprehensive water quality monitoring scheme, including estuaries.

Indonesia, Philippines & Japan

The situation is similar to Malaysia. In Japan, few natural estuaries remain, evidenced by recent environmental protests against the construction of a barrage across the last remaining major natural estuary.

Thailand

Modelling studies have been carried out, concern again being centred on saline intrusion and water supply. Of particular concern is the Chao Phraya river system, that flows from the north and west of the country southwards to Bangkok and the Gulf of Thailand. Modelling is being used basin wide to balance urban and irrigation demands with the need to maintain a significant flow in the Chao Phraya estuary.

Mekong Estuary

There are continuing studies on the Mekong, where there is concern that saline intrusion could affect the estuary, Vietnam's rice bowl.

Hong Kong

Computational modelling has been used extensively in Hong Kong, which forms part of the Pearl River delta. 1-D and 2-D modelling has been used to examine water quality issues and the short term sedimentation caused by dredging and reclamation.

5.4.4 Summary

It is perhaps not unexpected that the Western world has a more holistic view of estuary management than the growing economies of the Pacific rim. In the UK, there is a strong awareness of the issues concerning the freshwater needs of estuaries, and a significant awareness of the tools available for analysis. However, in many locations, existing MRFs have been established by traditional methods, and until these MRFs are challenged by the water companies, additional analysis is unlikely to be carried out.

5.5 Standards currently adopted

5.5.1 General water quality

The water quality classification of estuaries used in the UK is based on a scheme devised by the DOE and the National Water Council 20 years ago. This classifies estuaries into four groups:

Class A	Good quality	Score	24-30	points
Class B	Fair quality	Score	16-23	points
Class C	Poor quality	Score	9-15	points
Class D	Bad quality	Score	0-8	points

The scoring system allocates 10 points to biological quality, 10 to aesthetics and 10 to chemical quality (dissolved oxygen). The scoring system is subjective, but provides some measure of comparison between estuaries. The scoring system is set out in Table 5.1.

The value of a classification based on scoring is that it tries to take account of the main factors which affect the perceived quality of an estuary. For fresh waters, the river ecosystem classification divides inland surface waters into five classes based on Dissolved Oxygen, BOD, Total Ammonia, Unionised Ammonia, pH, Hardness, Dissolved Copper and Total Zinc, with the first three parameters being the main determinants for the better quality classes. This approach has not been extended to estuaries and has the disadvantage of not including biological and aesthetic indicators.

Table 5.1
Scheme for Classifying Estuaries

DESCRIPTION	Points awarded if the estuary meets this description
Biological Quality (scores under a, b, c & d to be summed)	
a) Allows the passage to and from freshwater of all relevant species of migratory fish, when this is not prevented by physical barriers.	2
b) Supports a residential fish population which is broadly consistent with the physical and hydrographical conditions.	2
c) Supports a benthic community which is broadly consistent with the physical and hydrographical conditions.	2
d) Absence of substantially elevated levels in the biota of persistent toxic or tainting substances from whatever source.	4
Maximum points	10
Aesthetics (Choose one case only)	
a) Estuaries or zones of estuaries that either do not receive a significant polluting input or which receive inputs that do not cause significant aesthetic pollution.	10
b) Estuaries or zones of estuaries which receive inputs which cause a certain amount of pollution but do not seriously interfere with estuary usage.	6
c) Estuaries or zones of estuaries which receive inputs which result in aesthetic pollution sufficiently serious to affect estuary usage.	3
d) Estuaries or zones of estuaries which receive inputs which cause widespread public nuisance.	0
Water quality (Score according to quality)	
Dissolved oxygen exceeds the following saturation values:	
60%	10
40%	6
30%	5
20%	4
10%	3
below 10%	0

The points awarded under each of the headings of biological, aesthetic and water quality are summed. Waters are classified on the following scale:

Class A	Good quality	Score	24-30	points
Class B	Fair quality	Score	16-23	points
Class C	Poor quality	Score	9-15	points
Class D	Bad quality	Score	0-8	points

From NRA WQ Series No.4 (Dec 1991)

Table 5.2 - Standards and Water Quality Objectives for the Thames Estuary

Reach	Quality Objective	Chemical Standard	Biological Standard
Teddington to Battersea	Passable to migratory fish. Maintenance of a coarse fishery within the physical constraints of the estuary. Aesthetically pleasing appearance.	In any quarterly period the dissolved oxygen value to be greater than 40% sat for 80% of the time. DO greater than 10% for 95% of the time. Minimum DO 5% sat. Maximum temperature 25°C. Compliance with EC Dangerous Substances Directive, Daughter Directives & Red List Standards.	Self supporting dace fishery as indicated by fish of the year. BMWP score greater than 25.
Battersea to Mucking	Passable to migratory fish. Maintenance of a euryhaline fish population consistent with the physical characteristics of the estuary. Maintenance of a commercial eel fishery. Aesthetically pleasing. appearance.	In any quarterly period the dissolved oxygen value to be greater than 30% sat for 80% of the time. DO greater than 10% for 95% of the time. Minimum DO 5% sat. Maximum temperature 25°C. Compliance with EC Dangerous Substances Directive, Daughter Directives & Red List Standards.	Minimum of 9 species of fish to be identified during power station intake surveys. Data from commercial eel returns to be examined as a potential future standard.
Mucking to Seaward Limit	Passable to migratory fish. Maintenance of a marine fishery consistent with the physical characteristics of the estuary. EC Designated Bathing Beaches to be satisfactory. Aesthetically pleasing appearance.	In any quarterly period the dissolved oxygen value to be greater than 60% sat for 80% of the time. DO greater than 10% for 95% of the time. Minimum DO 5% sat. Maximum temperature 25°C. Compliance with EC Dangerous Substances Directive, Daughter Directives, Bathing Beach and Bathing Water directives & Red List Standards.	Suitable standards to include measure of commercial fish catches and protection of marine nursery grounds to be evolved over next 2 years.

In the Thames Estuary, more sophisticated water quality standards are applied for operational management (EA, 1997). These standards and objectives are shown on Table 5.2.

The standards shown are related to quality objectives and concentrate on maintaining adequate dissolved oxygen to sustain the fishery. To assist in their management of the estuary, the Agency have an operating agreement with the water and sewage undertakers to maintain the quality of the estuary. This agreement and the associated abstraction licences include the following aspects:

- Sewage works increase treatment to produce effluent that is of much higher standard than the consent during the summer months.
- The Thames mobile bubbler may be called out to aerate the estuary if storm sewage overflows or pollution incidents occur.
- Abstractions may be reduced to increase freshwater flow if there is a threat to estuary dissolved oxygen, subject to the water resource position of the water company.
- The residual freshwater flow may be progressively reduced if the volume of water in storage falls below threshold limits.

This operating agreement illustrates the importance of effluent quality for maintaining estuary quality during the low flow, high temperature, summer months. In these conditions there is a significant risk of serious water quality problems including fish kills following summer storms. The operating agreement also provides opportunities to balance the risks and consequences of poor water quality in the estuary with the risks and consequences of water shortage if abstraction is reduced for a period.

5.5.2 EU Directives

EU Directives, translated into UK law, set limits on acceptable water quality in estuaries. Principal directives include:

• Dangerous Substance Directive	(76/464/EEC)	and daughter directives.
• Bathing Waters Directive	(76/160/EEC)	SI 1991 No. 1597.
• Shellfish Directive	(79/923/EEC)	SI 1997 No. 1331.
• Nitrates Directive	(91/676/EEC)	SI 1996 No. 888.

The UK legislation typically refers to mandatory limits set down in the Directives, but recent legal opinion indicates that the Agency should have regard to Guideline limits where these are given. In the case of the Nitrate Directive, the UK regulations require the Agency to review the eutrophic state of estuarial waters in 1997 and at 4 yearly intervals thereafter.

The implications of the Habitats Directive for estuaries are discussed in Section 3.8.

5.6 Review of standards

5.6.1 Changes in standards

There are currently relatively few standards controlling estuary water quality compared with freshwater quality. The thrust of new standards for estuaries is likely to be towards the ecological health of estuaries as indicated by the Habitats Directive and Nitrate Directive which both seek to conserve the ecosystem.

This trend to consider estuary ecosystems will increase the emphasis placed on estuaries of high ecological value, where water quality problems are often less apparent. In these estuaries, more comprehensive water quality and biological monitoring is likely to be required. This may in turn increase demands for ecological modelling, though at present capability to carry out this type of modelling is limited to Research Organisations and the results require very careful interpretation.

The need to manage the water quality of estuaries affected by urbanisation or industrialisation will remain. In these estuaries, tighter discharge consents are improving median water quality, but in many cases intermittent discharges continue to be a problem. This is most evident by the presence of fish kills. In past decades there would often have been no fish to kill. Improvements to water quality have allowed fish to recolonise some estuaries, so the impact of intermittent discharges is dramatic. To avoid this problem, further improvements are required, particularly to combined sewer overflows. These are being addressed as part of the AMP2 settlement between the water industry, OFWAT water regulators, the Agency and the Government. The improvements to CSOs are also designed to improve compliance with bathing water standards at designated beaches, some of which are in or adjacent to estuaries.

The management of water quality in the Thames Estuary is likely to become a model for other estuaries, with discharge consent standards and abstraction rates varying seasonally to deliver the water quality required to achieve environmental goals at an acceptable cost to river users. These studies are likely to require continuing estuary water quality modelling to determine the sensitivity of estuary quality to freshwater flow and effluent quality.

5.6.2 Standards for fish

At present, existing water standards do not explicitly include standards to maintain fish populations and migration. As described in Section 3.7, the parameters that may need additional legislation are temperature and dissolved oxygen.

Alabaster and Gough (1986) showed that for English estuaries, such as the Thames, salmon migration was effectively prevented by temperatures in excessive of 21.5 °C based on historic records of fish movements and estuary temperatures. This temperature is the same as that recommended by EIFAC to the compilers of the EC Fisheries Directive as the upper limit suitable for the maintenance of salmonid fisheries, and could be usefully included as a required water quality standard.

The EIFAC recommendation for dissolved oxygen in estuaries was 5 mg/l as a 50 percentile and 2 g/l as a 95 percentile although for full freshwater the EEC salmonid requirement is set at 9 mg/l with a lowest permitted level of 7 mg/l. Research has also shown that in the Thames estuary salmon migration was reduced at 2.7 mg/l dissolved oxygen to 10 % of the fish moving previously and weekly runs ceased at 2.4 mg/l. In the Ribble estuary pronounced oxygen sags caused fish to leave the estuary for the sea. In the estuary, with DO below 55 % avoidance of the effluent occurred and fish movement was inhibited by 40%. The above values could again be usefully be included as a required water quality standard, although the values chosen may vary from estuary to estuary.

5.7 Identification of mitigation options

Until recent years, impact mitigation works in estuaries followed the classical engineering approach, that capital works can always mitigate the impact. For example, flooding can be solved by bank raising, salinity intrusion into a water supply intake by a barrage, pollution by a longer outfall and sedimentation by dredging.

This approach remains effective where man's impact on the estuary is small. However, worldwide, the demand for water is such, and man's use of estuaries so great, that these low impact cases have become the exception. Consideration of mitigation options in isolation, ignoring knock-on effects on other estuary uses and processes is no longer an acceptable approach. Estuaries must therefore be assessed holistically, taking full consideration of the interaction and long term effects of uses and processes.

Such a holistic approach is concerned less with the development of the estuary, than its management. The demands and relative benefits of the various users must be balanced. For example, is the demand for water abstraction such that its incremental value will pay for additional dredging in the downstream shipping channels. Further, the Habitat Directive demands no impact on parts of an estuary. Here, habitat development may be necessary to balance development elsewhere.

There will also be new challenges. For example:

- Capital works may be needed for the conservation of intertidal areas, following their compression due to sea level rise; or
- Minimum flows may be seasonally managed to minimise dredging or morphological change.

In summary, management of most estuaries has become more complex due to their increasing level of use. This complexity demands a holistic approach, and more complex analyses of estuary processes and uses. Computational modelling provides a tool that, when used wisely, can provide quantitative answers to these analyses.

6. APPROACHES FOR THE FUTURE

6.1 Introduction

Future estuarine studies will require a more holistic view. Future studies for determining or revising MRFs will need to take all significant processes and uses into account. In particular, ecological and morphological factors will be studied. The result of this holistic approach will be a need for more complex and multi-use models. It may become rare for a single process study - for example water quality - to be carried out. Each study will also need to examine the impact on other processes, and these impacts will be quantified by computational modelling. New developments in modelling may allow quantitative assessment of morphological and ecological impacts.

The cost of computational models has probably decreased, due to inexpensive, powerful computers and to more advanced software. However, the cost of a holistic study will be higher, as it requires a number of models. There is therefore a need for more rigorous scoping of major estuarine models, to achieve acceptable study results at acceptable cost. This section examines the tools that may be used in the future for such holistic studies. It examines the rigorous use of existing techniques, namely:

- Impact and risk assessment;
- Preliminary models; and
- Sensitivity analysis.

It also describes the recent advances in computational modelling, in the areas of:

- Morphology; and
- Ecology.

Finally, it describes possible approaches to data collection in the future.

6.2 Impact and risk assessment

6.2.1 Preliminary assessments

One approach to meet more rigorous scoping requirements is to carry out a formalised preliminary assessment of the estuary. Such an assessment is, in reality, carried out in any modelling study. This is usually informal in nature, relying on the project team's knowledge of estuary to eliminate many impacts and uses, leaving those critical for study. However, a holistic view of the estuary requires consideration of all impacts and uses. It is possible that previous studies have missed significant impacts, such as ecological or morphological changes. Such an approach does not invalidate the practitioners intimate knowledge of an estuary. It does, however, require all assumptions to be questioned before acceptance.

Perhaps the simplest approach to a preliminary assessment is the use of an assessment matrix similar to those commonly used for environmental impact or risk assessments. Such a matrix can be used to rank known impacts and uses in terms of risk and thus direct investigations. This process is largely qualitative. A more detailed approach is the construction of preliminary coarse computational models to add quantitative information to the matrix.

These approaches are discussed in the following sections.

6.2.2 Matrix analysis

The use of a series of decision making matrices is a powerful, if qualitative, approach to the assessment of an estuary. A possible layout for a simple example of an assessment matrix is shown in Figure 6.1, below. This matrix is used to record the existing and available data and computational models. The approach allows an assessment of data collection needs, and perhaps the potential for a preliminary computational model.

Impact on/by change in freshwater flow	SALT WATER ZONE			BRACKISH ZONE			FRESH WATER ZONE			Comments
	R1	R2	R3	R4	R5	R6	R7	R8	R9	
DATA										
Topographic	F	F	F	F	F	F	F	F	L	
Quality/Salinity										
Flow/Level	F		L	L	L				F	Tide & flow gauges
Sediment			L	L			L	L		Limited data for projects
Ecology		L	L	L			L	L	F	Various studies
MODELS										
Flood				1D	1D	1D	1D	1D	1D	Flood defence design
Quality/Salinity	2D	2D	2D	2D						For outfall design
Resources/operation										
Morphology/sediment										
Ecological/Fish							S	S	S	Flow correlation
CHARACTERISTICS	Stratified, deep channels			Wide, shallow, mudflats			Meandering lowland river			

Key: Data: No data; L Limited data; F Full data

Models: 1D, 2D, 3D Dimension of model; S Statistical

Notes: Hypothetical example only shown.
R1 to R9 represent estuary reaches.

Figure 6.1 : Data availability matrix

The above matrix is self explanatory. The format of matrix shown here is not fixed, and can be adapted for a particular estuary or study. In particular, the use of a larger A3 format would allow for detailed notes to be made on the matrix itself. The matrix should, however, always include a full range of uses and processes, as a check list to ensure that no impacts are not reviewed during the study. The concept of a data availability matrix is used in the technical approach described in Chapter 8.

6.2.3 Application of risk assessment

The use of decision matrices together with elements of risk assessment methodology offers a more powerful analytical tool than the simple matrix presented above. In risk assessment terminology:

A Hazard - Is a situation with the potential to cause harm.
A Risk - Is an expression of the potential of a hazard to cause harm. This can be expressed as:

RISK = LIKELIHOOD x IMPACT

where:

Likelihood - The probability of the estuarine design standards being derogated, assessed by considering the estuary processes and uses and how close they are to the relevant standard.
Impact - The consequence of a hazard occurring.

Abstractions and their associated MRF conditions can then be identified as a *hazard* to the estuarine processes and uses. These techniques can equally be applied to other hazards such as river quality or effluent load. The concept of risk assessment applied to estuary management is shown in Figure 6.2.

There are two scenarios illustrated in this figure it:

- A low impact scenario, resulting in small variations of a parameter in the estuary. However, when combined with a high estuary management standard for this parameter, a high likelihood of failure results.
- A high impact scenario, resulting in large variations of the same parameter in the estuary. When combined with a low estuary management standard, a low likelihood of failure results.

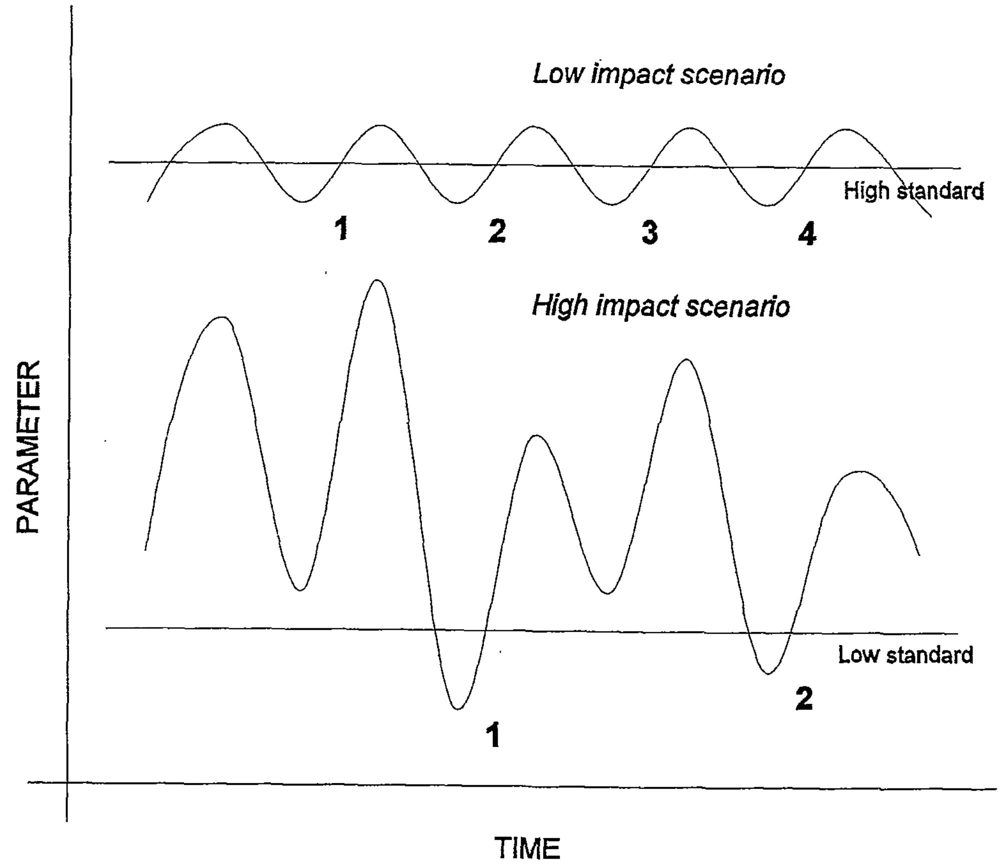


Figure 6.2 - RISK ASSESSMENT SCENARIOS

6.2.4 Risk assessment of key impacts

Two matrices can be used to carry out a step further, assessing the likelihood and impact of a range of uses and processes and calculate an average risk for each issue and reach. These matrices are:

- an impact matrix; and
- a risk matrix.

In order to quantify risk, it is necessary to first put a scale to the likelihood of the hazard causing an estuarine event and the consequent severity of the event. Scales can be as large or as small as required, depending on the complexity of the analysis considered to be necessary. However, this report suggests a scale of 1 to 5 as being appropriate. A larger scale may allow closer definition of risk, but the implied accuracy of the scale may be false. The scales are described below:

LIKELIHOOD		
CATEGORY	DESCRIPTION	SCALE
Frequent	Likely to occur on many occasions.	5
Probable	Likely to occur regularly.	4
Occasional	Likely to occur occasionally.	3
Remote	Unlikely, but possible.	2
Improbable	Very unlikely, may never occur.	1

IMPACT		
CATEGORY	DESCRIPTION	SCALE
Catastrophic	Permanent, long term impact on estuary system.	5
Critical	Small permanent or major short-term impact to estuary system.	4
Serious	Significant short-term impact to estuary system.	3
Marginal	Minor impact to estuary system.	2
Negligible	Negligible impact to estuary system.	1

In these matrices, impacts and uses are more closely defined than the data availability matrix described above. All potential uses and processes should be included, but those of known interest should be sub-divided to reveal particular issues that require consideration. For example, the general "fish" category is replaced by three, fish communities, salmonid migration and angling.

Typical matrices are shown in Figures 6.3 and 6.4, below. The risk is calculated by multiplying the two scales, reach impact and likelihood from Figures 6.3 and 6.4.

Use/aspect	FRESH WATER ZONE		BRACKISH ZONE		SALT WATER ZONE		Comments
	R1	R2	R3	R4	R5	R6	
ABSTRACTION/TRANSFER							
Water use	5	5	3	3	2	1	Water supply for urban area
River flow regime	4	4	3	2	2	1	
Salinity	5	5	4	4	2	1	Saline wedge may be critical
Morphological change	4	4	4	4	3	2	Long term effects unknown
DILUTION/FLUSHING							
River water quality	4	4	4	3	3	3	Effluent from STW
NAVIGATION							
Commercial	3	3	3	3	3	3	Dredged channel
Leisure	2	2	2	2	1	1	Summer only
RECREATION & AMENITY							
Recreation	2	2	2	1	1	1	Some sailing and canoeing
Amenity	2	2	4	4	1	1	Visual benefit in urban area
NATURE CONSERVATION							
River plant communities	4	3	3	2	2	1	
Invertebrate communities	4	4	3	2	1	1	
NNR/SSSI	1	1	5	5	1	1	Nature reserves
FISH							
Angling & fisheries	1	1	1	1	2	2	
Salmonid migration	4	4	3	3	2	2	Temperature may be critical
Fish communities	3	3	3	3	3	3	

Key:

No impact	1
Low impact	2
Medium impact	3
High impact	4
Extreme impact	5

Notes: Hypothetical example only shown.
R1 to R6 represent estuary reaches.

Figure 6.3 : Impact assessment matrix

Likeli-hood	Use/aspect	RISK by REACH						Average Risk	Comments
		FRESH WATER ZONE		BRACKISH ZONE		SALT WATER ZONE			
		R1	R2	R3	R4	R5	R6		
	ABSTRACTION/TRANSFER								
4	Water use	20	20	12	12	8	4	13	Water supply
2	River flow regime	8	8	6	4	4	2	5	
3	Salinity	15	15	12	12	6	3	11	
4	Morphological change	16	16	16	16	12	8	14	-
	DILUTION/FLUSHING								
4	River water quality	16	16	16	12	12	12	14	Effluent
	NAVIGATION								
3	Commercial	9	9	9	9	9	9	9	Dredged channel
1	Leisure	2	2	2	2	1	1	2	
	RECREATION & AMENITY								
2	Recreation	4	4	4	2	2	2	3	
2	Amenity	4	4	8	8	2	2	3	Visual benefit in urban area
	NATURE CONSERVATION								
3	River plant communities	12	9	9	6	6	3	8	
3	Invertebrate communities	12	12	9	6	3	3	8	
4	NNR/SSSI	4	4	20	20	4	4	9	Nature reserves
	FISH								
2	Angling & fisheries	2	2	2	2	4	4	3	
3	Salmonid migration	12	12	9	9	6	6	9	
4	Fish communities	12	12	12	12	12	12	12	
AVERAGE RISK per REACH		10	10	10	8	6	5		

Notes: Hypothetical example only shown.
R1 to R6 represent estuary reaches.
Risk by reach given by LIKELIHOOD x REACH IMPACT from Figure 6.3.

Figure 6.4 : Risk assessment matrix

Once the magnitude of each risk has been assessed, the risks can be prioritised and used to guide the level of computational modelling required. A suggested table of risk and level of modelling is given below.

RISK	CLASSIFICATION	LEVEL OF MODEL
1-2	Negligible	None
3-7	Acceptable	Simple
8-12	Undesirable	Intermediate
13-25	Unacceptable	Complex

On completion of this matrix risk assessment, there is clear direction as to the aspects of the estuary that require investigation by computational modelling and the complexity of the model.

6.2.5 Seasonal variations

It is likely that there will be seasonal variations in the critical uses. These could be expressed as:

- summer/winter (as shown in the example in Chapter 13). This may reflect low summer flows or seasonal recreation and amenity;
- 4 seasons; or
- 12 months, where migratory fish are an important aspect.

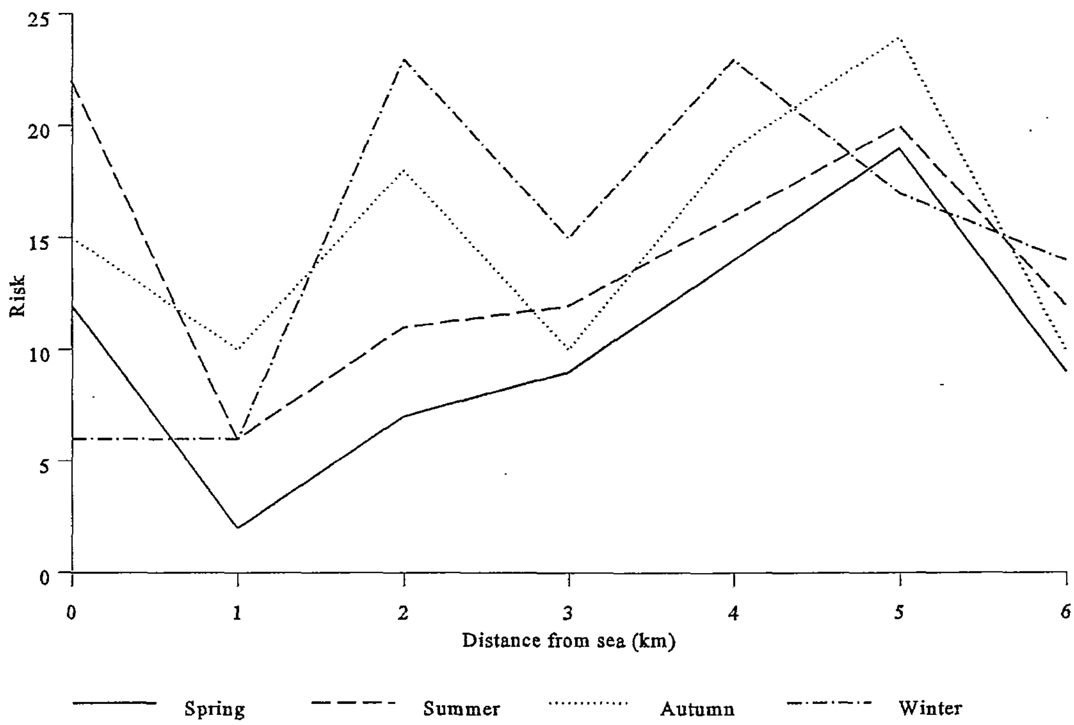


Figure 6.5 - ANNUAL VARIATIONS OF RISK

All seasons could be put onto a single matrix. For case any other than the summer/winter split, the resulting matrix would become very large and difficult to read. A better option will be individual matrices for seasons or months - if the matrix is prepared on a spreadsheet, the tabbed page facility could be used to advantage. The resulting weighted sensitivity ratings can then be plotted on a graph, as shown on Figure 6.5, to give a visual indication of variations in rating both seasonal and along the estuary.

6.3 Preliminary models

6.3.1 The concept of a preliminary model

A simple model can be used to determine:

- critical processes and uses in an estuary;
- the likely magnitude of problems, and whether detailed study is required; and
- the likely areas of particular interest, for example the main areas of sedimentation or the limits of significant salinity;

The results from the model can then be used to guide the design of the detailed model. It may aid definition of the model limits and the grid size or section spacing in particular areas or interest. It may also guide the extent of data collection, additional data being taken from the areas of particular interest.

It is also possible that the simple model may show that there is no problem with a particular use or process, and no further modelling will be necessary.

6.3.2 Sources of preliminary models

For a preliminary model to be an effective tool, it is important that it can be quickly built and run, so that it can be economically used for the planning of a full model study. A simple, preliminary model may be:

- an existing model, perhaps built for another discipline. For example, the hydrodynamic part of a water quality model could be used for an initial assessment of flood flows;
- built from coarse data, such as Admiralty charts and existing surveys;
- a coarse model perhaps using a 1-D rather than 2-D or a non-stratified rather than a stratified model, or a level-pool storage routing rather than a full 1-D model; or
- an uncalibrated and unverified model.

In all cases it should be remembered that the accuracy of the preliminary model may be low. Interpretation of results must take this into account.

6.3.3 Examples of preliminary models

The concept of preliminary models is used, in part, by all engineers. There are many studies where conceptual design on a spreadsheet later requires a detailed computational model. The use of a preliminary computational model takes this natural design process a step further and formalises the previously largely intuitive process. Three examples of such a process are given below.

In the Willingdon Levels (Eastbourne) studies for East Sussex County Council, an initial level-pool flood routing model was used to prove the concept of compensatory flood storage and a tidal outfall after development of the levels. Subsequent detailed design required used of a full 1-D hydrodynamic model. The initial model helped design the full model giving information on levels and the required extent of the detailed model.

A tidal power barrage study was carried out for the Conwy estuary. A simple tidal power model was used to prove the concept of a barrage and find the impact on the tidal prism. A full 1-D model was then used to refine these results and investigate salinity and water quality. The same topographic data used for all studies, but level of detail increased in areas of particular interest.

In many coastal studies, for example Port Rush, Northern Ireland, a coarse gridded 2-D model is used for initial assessment of a long sea outfall. Having used this model to establish the flow currents in the region, and the basin viability of the scheme, a fine grid model of the inner area was developed for the design of the outfall. In this case, 3-D modelling was not needed, but it could have been based on the 2-D models. In this case, the base topographic and calibration data was the same for both models.

6.3.4 Practicality of preliminary models

Mar (1974) in his review of multi-disciplinary modelling studies stated that:

> "The strategy to construct models without data and then employ sensitivity analysis to identify critical components where research and new data would enhance model performance is not commonly practised".

Unfortunately such an approach is impracticable for most estuarine computational model studies. A great deal of base data, in particular topographical data, is needed to achieve even a simple model that bears some resemblance to reality. If this data has to be collected, the issues of programme and cost become significant:

- It is usual to collect all data in a single programme, with, say, quality data being collected in parallel with topographic data. If these tasks are separated to allow construction of a preliminary model, the overall programme of a study will lengthen; and
- Collecting two sets of topographic data, and lengthening the study programme will result in a more costly study.

Further, the complexity of the preliminary model must be carefully judged since:

- The model must not become too complex; in that case one might as well go straight to a full study;
- The model must not be too simple. Modelling experience shows the behaviour of rivers and estuaries to be controlled by relatively detailed topographic features, be it a narrowed section of a river, a promontory that redirects currents, or sand bars that control the ebb and flood channels. Omitting such details may also lose the essential character of the estuary; and
- The model must provide more information than would have been given by the experience and co-operation of modellers and the practitioners working within the estuary.

6.3.5 Conclusions

The use of preliminary models to target critical areas of a study has considerable potential. However, use of such models will usually result in longer and more costly studies. Preliminary models should therefore be considered in two instances:

- where existing models or data allow a preliminary model to be built and run very quickly, without additional data collection; or
- for extremely large projects, where the penalties to cost and programme are not significant.

6.4 Uncertainty and use of sensitivity analysis

6.4.1 Uncertainty

Within computational modelling of estuaries, there are three areas of uncertainty and potential error:

- Uncertainty in physical processes. Do the model algorithms represent reality?;
- Uncertainty in data collection. What are the errors in measurement of parameters?; and
- Uncertainty in model build. Even if the algorithms and data are correct, has the model been configured to represent reality?

Physical processes

The algorithms used for some processes remain partially empirical. For example:

- Sediment transport remains partly empirical and different assumptions can result in widely different answers;
- Ecological responses to changes in flow or quality are an active area of research; and
- Fundamental parameters as Manning's 'n' rely on a degree of judgment by the modeller.

The modelling process must consider these areas of ignorance and uncertainty.

Data collection

All data collected in the field has some intrinsic error in the collection process itself. This error must be remembered during model building and use.

Model build

There will also be uncertainties in the model build. In places, model grids or section spacing may not ideally represent the physical situation. In others data handling errors by the builder may result in errors in, say, bed levels.

Controlling uncertainty

There will always be a degree of uncertainty in the modelling process. This can be minimised by:

- Rigorous quality assurance in the model build;
- Rigorous calibration and verification/validation;
- Thorough sensitivity analysis; and
- Careful and informed interpretation of all model results.

6.4.2 Quantification of uncertainty

The objective of most estuary modelling is to quantify the previously identified key impacts of a proposed development such as water level or quality changes. These changes may also be used as primary information by other specialists to help them quantify other impacts such as ecological or economic changes which cannot be predicted directly by the model.

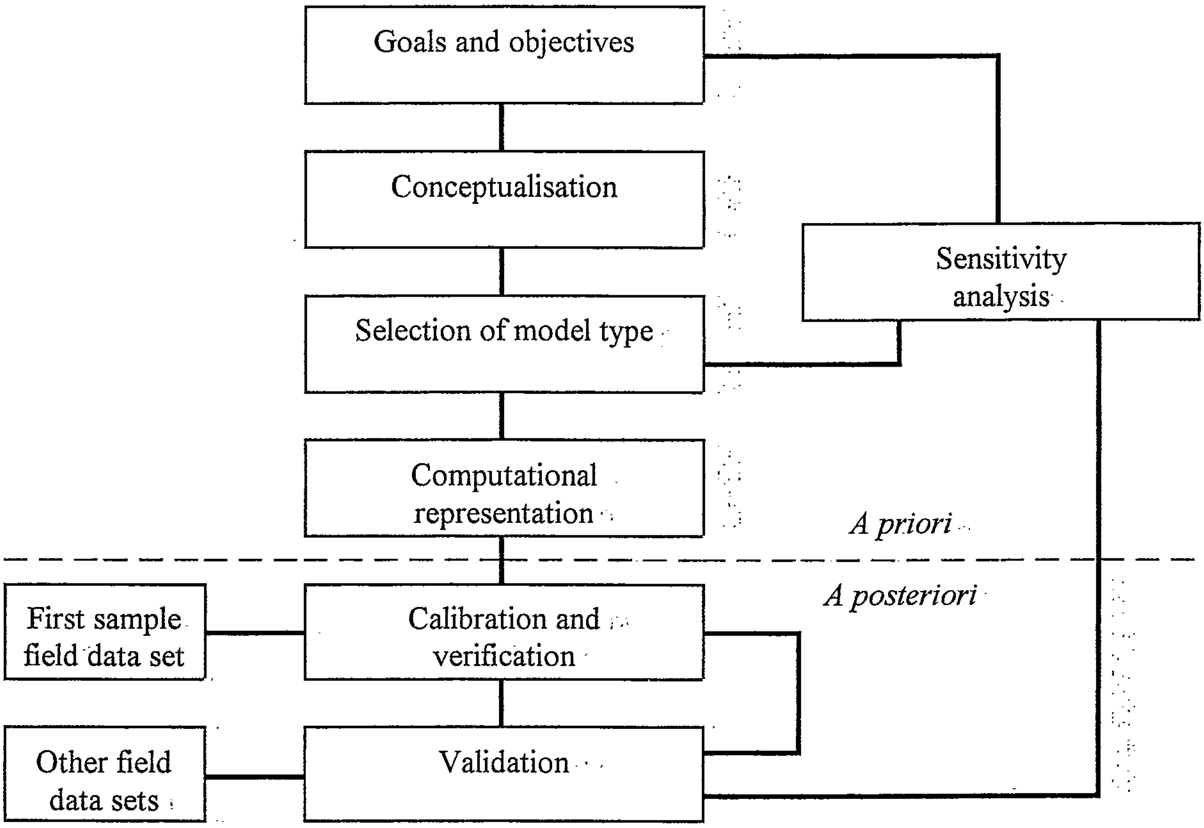
Model results often form a key component of environmental assessments providing one of the few methods available to quantify the changes which may occur. As such, one of the key roles of a model is to provide an indication of the scale of the changes that are likely to occur to those not directly involved in the assessment. This places a major emphasis on the quality of the presentation of model results which has led to the development of commercial packages which meet these needs. In some cases, GIS may be used to aid results presentation, particularly where the results affect a land area as in the case of flood plain mapping.

Model results are often projected as providing reliable predictions of the results of a particular course of action. This is an objective which is achieved in many cases. However, on occasions the reliability of model predictions is less certain than their developers would like to admit. An important part of the model assessment report should be a consideration of the sensitivity of the model conclusions to uncertainties in data or assumptions made in the development of the model.

All models are sensitive to the underlying assumptions they are based on. In many cases the results are sensitive to the assumed values of coefficients which are site specific and cannot be directly measured. In such cases sensitivity tests are invaluable as a guide to how sensitive predictions are to these values and whether the calibration tests are equally sensitive to these assumed values. In general the reporting of model results should include sensitivity testing for all variables whose value cannot be checked during model calibration. This testing will indicate how robust the proposed predictions are to uncertainties in model coefficients, and possibly highlight the need for further investigation or development of a more robust solution.

6.4.3 Use of sensitivity analysis

The use of sensitivity analysis in the modelling procedure is illustrated by Figure 6.4.



From: Pollard (1991)

Figure 6.4: Sensitivity Analysis in the Modelling Process

The figure shows the two basic forms of sensitivity analysis. *A priori* analysis establishes the relative magnitudes of changes in the simulated model output to changes in the model parameter values. *A posteriori* analysis examines the distribution of model responses that are possible, given the distribution of estimated parameter values. It is important since calibration of a model does not imply that all parameter values will be known exactly once the model has been calibrated. There remain errors of estimation associated with the calibrated parameter values. *A posteriori* analysis can be used to guide future data collection and, if appropriate, research.

Computational modelling sensitivity analysis is generally *A posteriori*, since the initial stages of a study are generally to collect sufficient data to build and calibrate the model. *A priori* analysis is therefore not possible, as it requires point estimates of all parameters to be available.

6.4.4 Application of sensitivity analysis

Sensitivity analysis should always be carried out in computational modelling studies. Competent computational modellers have always carried out some sensitivity analysis in a study, but the analysis has not always been rigorous or comprehensive. With the increasing complexity of modelling studies, a better defined programme of sensitivity analysis is needed.

The calibration and validation procedure will test the sensitivity of a range of calibration parameters. Final sensitivity analyses will also be required as part of model scenario testing and as part of any design carried out by the model. The validity of any design must be checked against a range of parameter uncertainty.

6.4.5 Automatic calibration of models

One approach to calibration, that includes a degree of sensitivity analysis, is the automatic calibration of models. Within this approach, objective functions within the model program are used to give best fits to the calibration data.

Automatic calibration has been an object of research for many years. Some of the earliest pipe network programs included a function for the automatic calibration of roughness. The MIKE 11 1-D river model includes a module for the automatic calibration of Manning's 'n'. A recent report (Lavedrine, 1995) describes work to:

- develop a means to measure the quality of fit between computed and observed data;
- develop objective functions in order to reduce the subjectivity of the calibration procedure; and
- test these functions for a simple model.

The report concludes that:

- objective functions can reduce the subjectivity in calibration; and
- the automatic calibration procedure is promising and requires further development.

Despite these promising results, the use of automatic calibration must be treated with some caution. During calibration, the optimisation of parameters for quality and sedimentation against recorded data can be a complex procedure. Functions that work well for a simple trapezoidal channel may be stretched by the more usual complex model. In particular:

- in subjective calibration, differences between model and recorded data at one or two points may be accepted as:

  - a result of data error; or
  - not important to the model performance.

  It may be difficult to build such judgements into automatic calibration;
- care must be taken where recorded data indicates model parameters outside the usual text book range; and
- care must be taken that the calibration does not force model parameters outside the acceptable range.

Although automatic calibration is likely to be further refined, it must always be interpreted by experience. A mean value from the text book is almost invariably more reliable than an extreme, and possibly rogue, value from the field.

6.4.6 Generalised sensitivity analysis

As modelling studies become more complex, with more impacts and parameters to be considered, the need for a more systematic approach to sensitivity analysis may be required. A particular form of *A posteriori* analysis is generalised sensitivity analysis (Pollard, 1991).

Generalised sensitivity analysis overcomes some of the subjectivity in calibration by identifying the combinations in parameters that will satisfy the field observations. There may be many such combinations, and the approach is therefore computationally intensive.

A large number of model simulations are run using a wide range of model input parameters. All parameters are, however, kept within their naturally occurring ranges. Monte Carlo simulations are carried out by randomly selecting a set of parameter values from these ranges and running the simulation model. The results of each model can then be classified as acceptable, predicting results within the confidence limits of field observations, or unacceptable. This procedure is repeated many times to accumulate a set of parameter values giving acceptable results, and another giving unacceptable ones.

The key idea is then to identify the subset of physically realistic parameters that account for acceptability of the result. The distribution of the parameter values associated with acceptable results is compared with that for unacceptable results. If the two distributions are statistically similar, the parameter is unimportant for this calibration.

This approach has considerable potential for identifying the critical parameters in a calibration. It is, however, probably only applicable to large, complex, modelling studies, since:

- only a large project will be able to absorb the additional cost of large numbers of model simulations and their analysis; and
- for many studies with few parameters, critical parameters, such as roughness, will be known from experience.

6.4.7 Conclusions

Most modellers are aware of the importance of sensitivity analysis and use it within computational modelling studies. However, as models become more complex a more rigorous approach to such analysis becomes essential. This must take the form of a specified programme of sensitivity tests to the model. It may be supplemented by techniques such as automatic calibration and generalised sensitivity analysis, but such approaches must not be allowed to displace the judgement of the experienced practitioner.

6.5 Geomorphological modelling

6.5.1 Morphological simulations

Estuaries are transitory features. Even without man's influence, major changes occur to the form of an estuary within a few generations. With man's help, such changes may occur within a single generation. On occasion, more rapid changes, with a time scale of weeks rather than years, may occur. However, the future changes may not be apparent during the design, construction and initial operation of a flood defence scheme, port or other engineering works. Such changes have been identified within the Humber.

At present, the modelling of sediment transport and morphological changes can be simulated through use of a moving bed computational model. However, the results from such models are of low accuracy. This is due in part to the chaotic (chaos theory) processes that form a central part of sediment processes. Different sediment transport equations may give answers which are different by a factor of 10, showing that we do not, as yet, fully understand the natural mechanisms involved. Collection of sediment flux data for calibration is expensive, and again of variable accuracy. It is particularly difficult to estimate tidal silt loads. It is therefore possible to simulate sediment movement, in order to design an intake for minimal deposition, or to predict the short term effects of a dredging plume. However, the prediction of morphological changes over a long period, say 50 years, cannot be made with confidence.

It must be accepted that we cannot predict the long term future and we should therefore be very cautious of any changes made to an estuary. There is a need for further research into morphology and its simulation, with emphasis on the science of coastal processes.

6.5.2 Current research

MAFF have recently started major research initiatives in this area. A scoping study has been commissioned by MAFF/EA/EN/EPSRC/NERC on research into long term estuary morphology and processes. The aim is to understand the long term processes and effects of changes on estuaries. HR Wallingford are heavily involved in this scoping study (HR Wallingford, 1997).

MAFF have widened the scope of research to include geographers and geologists. It will be funded through MAFF money with NERC and EPSRC. It will be a thematic project (like LOIS but hopefully more effective). MAFF's role will be to link basic science with applied R&D.

This research programme will provide new data for the simulation of morphological processes. These advances will need to be incorporated into management strategies for estuaries and the computational models used in their analysis.

6.5.3 Scoping study conclusions

The study has clearly shown that:

- there are currently no long term estuary management tools. One can only interpret and extrapolate short term processes;
- with the current accuracy of sediment transport predictions, these extrapolations can be very wrong; and
- no predictors of long term morphology have been identified.

In particular, there is great uncertainty in the prediction of:

- long-term impacts associated with both natural variation and construction works;
- the feedback between ecological and chemical processes and estuary form; and
- the feedback between evolving estuary form and water quality.

An additional problem in looking at long term processes is identifying the "kicks" that occur to change coastal processes, such as "episodic" extreme events, sea level rise and reclamation. Another major example is navigation depth changes. For thirty years "Panama" sized vessels have been used. Bigger container vessels are now being built, requiring a depth increase of navigation channels of many metres. It is currently impossible to predict the changes in the estuary due to such dredging.

6.5.4 Modelling methods for long term prediction

The scoping report proposes objectives for a long term model or predictive tool that:

- predicts the future evolution of an estuary form given the existing processes;
- predict the impact of changes in process or shape on water quality and ecology; and
- will enable the manager to design with confidence a self-sustaining estuary morphology.

Three modelling approaches are discussed:

- 'Top-down' or regime approach;
- Probabilistic approach; and
- Hybrid approach.

These approaches are briefly described below.

6.5.5 'Top-down' approach

A 'top-down', or regime, approach assumes an energy balance in the estuary, where inputs in sediment and water are exactly balanced over some time period. The balance is obtained by the evolution of morphological forms, such as creek systems and estuarine meanders.

This approach is quick to compute, allowing full sensitivity analyses to be carried out. There are limitations in the need to assume the estuary to start in equilibrium, and difficulties in predicting the speed of change. The approach is also not suited to localised changes in the estuary; many engineering changes are local in nature.

6.5.6 Probabilistic approach

In the probabilistic approach, process models are used in a probabilistic manner to identify long-term change. The models are based on physical principles, so can include additional changes and processes in the estuary, and are well suited to localised changes. However, they are computationally expensive and rely on a good understanding of sediment processes.

6.5.7 Hybrid approach

The hybrid approach uses a combination of 'top-down' and process modelling. Appropriate models are used to define the hydraulic conditions within an estuary. These models are then used in combination with a well-founded empirical relationship to evolve the estuary morphology in response to an imposed change.

This approach is new and has rarely been applied to estuary management. It relies on the quality of the empirical relationship. However, the approach has considerable potential in combining both detailed and localised process modelling and the speed of a regime approach.

6.5.8 Conclusions

There remain significant gaps in our knowledge and computational modelling techniques that management of estuaries to obtain a self-sustaining morphology. In the short term, the manager must try to minimise the impacts of estuary change, aware that he cannot accurately predict the long-term effects of the change. In the next few years, research should give methods that can increase confidence in the long term management of the estuary.

6.6 Ecological modelling

6.6.1 Introduction

Ecological parameter modelling

Most ecological modelling carried out to date has not simulated the full ecosystem and its interaction with water quality and other parameters. Modelling of, say, dissolved oxygen has been carried out and the DO controlled to limits acceptable to flora and fauna. Whilst this approach is adequate for many studies, it fails to consider the interaction of parameters on the ecosystem. For example, fish populations may be affected by DO and temperature. A small change in one of these may give additional stress on the fish and a resulting large population change. Full ecological modelling can give an indication of such effects.

Full ecological modelling

The concept of whole ecosystem modelling for estuaries has been developed at a number of research organisations such as IMER (now known as PML) and ITE, the latter dealing with the more terrestrial aspects of estuary ecosystems such as saltmarsh bioenergetics, the development and evolution of saltmarsh vegetation, and bird and mammal inter-actions in estuarine edge communities. There are also a number of commercial estuarine models to which selected ecosystem components can be added such as 3DSL and ISIS from HR Wallingford, and from Danish Hydraulics Institute (DHI).

The use of such modelling has largely as yet remained an area of academic work, mainly because to produce a plausible simulation there is a need for an enormous amount of data for the environmental variables and the vital data and rate coefficients. Only in a very few estuaries are there adequate data for water quality modelling, and usually even key species, such as cormorants or fish at the top of the food chain, or major diatoms and heterotrophic bacteria at the base of the food pyramid, are only occasionally recorded with sufficient frequency for models to be verified. Finding sufficient independent data sets to allow scientifically acceptable calibration and verification runs is excessively rare.

6.6.2 Examples

Gembase

One of the pioneering models of estuary ecosystems was GEMBASE, developed at PML in the 1970's as part of the SABRINA multi-disciplinary studies in the Severn estuary and Bristol Channel (Radford, 1979). GEMBASE was itself only possible after a physical model of the area had been developed by IMER (Uncles 1980) and did not initially include water quality or secondary production beyond zooplanktonic grazers. Later developments from PML were reported by Radford (1988 and 1994). GEMBASE was later combined with the more flexible Emms - Dollard model under EC JEEP auspices and has been developed as ERSIM used in the North Sea, Baltic and Mediterrean Sea; it could be used in estuarine conditions if needed.

ECOS

Less complex ecological models have subsequently been packaged by PML and EA using ECOS, a model that originated as a one dimensional model of the Tamar estuary that could be used for metal speciation simulations. Two and three dimensional versions are now available and as a result of work with EA on simple, readily available, modelling facilities. These can now be supplied with simple templates that make them usable with a variety of hydrodynamic inputs to suit available data and for a number of purposes, for example sedimentary simulations, water quality with conservative or non-conservative substances, and with primary and secondary production. Modified versions have also been used in fully freshwater systems (Radford, 1998).

Empirical models

In addition to full deterministic ecological models there are number of empirical models that have been developed for use in rivers or the sea. Some of these have been applied in estuaries with some success. One of the earliest of these was the Habitat Evaluation Procedure (HEP) developed by the US Fish and Wildlife Service in which the habitat requirements of an area are evaluated by simulation before and after a development, and a score for its suitability for one or many species of (originally) fish predicted. This HEP approach has recently been built into a suite of models available from Delft Laboratory, ECLAS, DELGEM, MORRES, EKOS and when used with a GIS system can provide useful evaluation of the future status of plant and animal communities in rivers, estuaries and shallow marine waters (Duel, 1995). It is possible that the riverbank conservation programme SERCON could in the future be adapted for use in estuaries, as experience with it, and the necessary data bases, are built up.

BENOSS

A further specialist model BENOSS (Biological Effects aNd Organic Solids Sedimentation) has recently been developed by the Dunstaffnage Marine Laboratory (DML) and EA/SEPA to allow evaluation of the expected changes in marine macro-invertebrate community structure as a result of domestic waste water discharges. This has some application in estuaries and a related model DEPOMOD allows evaluation of organic loadings and the effects on benthic life under fish culture rafts in lochs and shallow waters. (Chromey, 1998).

Fish populations

A range of models have also been used for the study of fish populations. Some of these have been described in Section 3.7. The modelling of temperature as a parameter is well established. It has often been simulated as part of cooling water studies, but has been rarely applied to full ecological processes. In view of the impact of temperature on fish and fish migration shown in recent research, it is likely that the simulation of heat pollution will be required in future studies for the ecological management of estuaries.

Another approach is population modelling (Milner, 1998). If fish life cycles can be described by simulation models, the impact on fish stocks of changing parameters can be studied. This approach becomes possible if the parameters are linked to fish survival, thus allowing the ecological model to simulate population changes, including cyclic non-linear features, such as explosion and feedback.

6.6.3 Conclusions

Ecological modelling has been successfully applied, but usually in an academic setting, due to its complexity and the amount of data needed for a complete study. However, commercial software is becoming available for the estuary practitioner, to allow wider use of such models. There is no doubt that at present, such models should be used:

- with care; and
- with expert direction.

Finally it should also be remembered that in a natural system:

- empirical relations, such as flow and population, are fraught with danger and should be treated with caution; and
- uncertainty and sensitivity analysis are very important in ecological modelling. All simulations should therefore be fully tested.

6.7 Data collection policy

6.7.1 Introduction

User requirements and comments

Consultation with the Agency (see Chapter 5) shows that:

- data management is difficult and needs significant resources that are rarely available;
- data is available but difficult to locate; and
- most Agency staff consider that data was freely available between disciplines.

Problems that have been experienced by consultants include:

- the disparate nature of data. It is difficult to collect data for a project, as it is lodged in so many different locations. The collection process invariably takes longer than expected; and
- that data is not held in digital format - or indeed even that there is a digital record of the location or contents of paper data.

The above findings suggest that there is potential for improving the Agency's data handling functions.

Long and short term data collection

It is apparent that routine sampling and project specific data collection allows the simulation of short term estuary process and use, such as water level and quality. However, data for long term analysis of morphological changes in the estuary are more difficult to acquire. Long term data sets are only available for a few major ports in the UK (HR Wallingford, 1997). At present routine data collection is again only carried out for ports. This data collection concentrates on deeper navigation area, often missing potential changes in the salt flats and intertidal areas.

With the advent of geomorphological modelling, there is a need for long term data collection of changes in estuary form, to allow verification of such models, and to allow the prediction of future changes with some confidence. Long term data collection is considered below.

A further area where data collection may be inadequate is for ecological modelling. It is uncertain whether detailed and regular ecological surveys can be economically justified. It is probable that the existing counts of birds and monitoring of fish populations will serve as an early warning of changes in ecology of an estuary. If such a change is identified and considered significant, a full data collection program can then be implemented.

6.7.2 Data requirements

Existing data

The range of data requirements for modelling projects is described in Chapter 4, and in the Computation Modelling Quality Manual. Existing data will normally be available from a range of sources, and will include:

- baseline data, such as topographic survey and mapping;
- routine data collection and sampling; and
- project specific data.

Project data

Although some Agency regions aim to collect data by routine sampling that will be adequate for future modelling needs, most studies will need to apply data in the following way:

- baseline data can be used for basic model construction;
- additional survey will be needed for localised topographic detail and calibration for the area of interest; and
- sampling data and earlier studies can be used for secondary calibration and validation.

Long term data collection

As noted above, there is a significant lack of data recording the long term changes in estuaries form. It is important to set up regular measurements of estuary topography to allow future calibration of geomorphological models.

The exact data needs of the next generation of computational models will become apparent as the current MAFF sponsored research into morphological processes and their simulation progresses. The Agency should keep this research in view and implement long term monitoring in important estuaries as soon as is practicable. The data must, however, consist of topographic/bathymetric survey to show changes in estuary form across the whole estuary. This survey must have at least enough local detailed information to allow calibration of a model. Traditional bathymetric surveys are labour intensive and expensive in the intertidal zone. It is therefore likely that this data collection will use tools such as:

- remote data sensing. Satellite and airborne data sensing is a rapidly developing field, the development of new data processing algorithms opening up new area for estuary studies;
- acoustic doppler current profilers (ADSPs), especially with new instruments that work in shallow water;
- advanced specification bed frames, useful for recording data during major fluvial or tidal events; and
- remote bathymetric surveying. Use of echo sounders or helicopter bourne radar may reduce the traditional costs.

If all relevant data is to be used, there is a need for all the above data to be readily accessible. This is discussed in the following section.

6.7.3 Data databases

Maximum use of available data will only be made if it is held in an accessible form. In order to make data accessible it must be:

- stored at a location known by all users; and
- easily recalled, reviewed and downloaded for a study.

To achieve these aims, data should ideally should be held centrally, and in a digital form such as a geographical information system (GIS). A GIS overcomes many of the usual data storage problems, since it gives the user a visual entry to the data held in its associated databases. This visual approach is especially helpful when dealing with geographical or spacial data, as is used predominantly in modelling and other estuary studies. Any such data system should be co-ordinated through the Agency's GIS core service. However, this approach does have operational problems in that:

- investment is needed to set the system up;
- resources are needed to maintain it and keep it up to date;
- individual project teams must have the budget and will to send data through to this central repository; and
- there is real potential for the system to become large as to become unworkable.

An alternative approach is for each Agency regions to maintain a database for each estuary. In some cases, the database or GIS may exist as a result of studies; the Humber is a case in point. Further, the form of this database is not critical. A database could be used rather than a GIS to hold the estuary records. This database does not even need to hold the actual data, provided it contains an accurate description of the location of the paper records within the Agency offices. A simple database system will still need updating, but the resources needed to keep it current will be far less than a full GIS. Investment in maintaining such database should result in reduced data collection costs in future projects.

One essential component of any database must be a metadata structure. The data for any estuary will vary in age and will be obtained from different sources using different techniques. It is therefore important for the user to know what confidence can be placed in each item. The attributes or metadata for each item should include:

- data title;
- contact name;
- data source;
- scale of capture;
- who captured it;
- how and when captured;
- period the data covers;
- a reliability assessment factor, and;
- any comments.

It is pertinent that this metadata in itself forms a viable reference to non-digital data sources.

6.7.4 Conclusions

Maximum use of available data will only be made if it is held in an accessible form. There is a need for the Agency regions to maintain a database for each estuary. The database should ideally centre around one or more GIS applications for ease and clarity of use. The form of this database is not critical, but it must be kept up-to-date. Investment in maintaining this database will result in reduced data collection costs in future projects.

7.0 ESTUARY MANAGEMENT APPROACH

7.1 Introduction

The value of estuaries for commercial, industrial and recreational use is widely acknowledged. The importance of the freshwater inflow to an estuary is not widely recognised and when it is, managers are not aware of the possible implications. Most decisions regarding the use of freshwater as a resource are undertaken by planners in relation to water supply for human and industrial use, and managers of the catchments in determining abstraction, storage and transfer schemes. In the past little consideration has been given to the effect of the schemes on estuaries and coastal zone management.

In recent years, with the requirement for environment impact assessment of major schemes the effects are beginning to be addressed but are still only considered of secondary importance compared to other issues. Any environmental statement should include an evaluation of the scheme with respect to freshwater input to the estuary and cumulative impact of previous schemes. The effects of the previous scheme on all aspects of the estuarine environment should also be taken into account. Where such impacts are likely to affect the estuary dynamics and the users of the estuary, then mitigation measures should be introduced. In many UK estuaries, freshwater flows may have already been modified and in some cases the effects may have only been small or not been noticed. Further controls or abstractions however may cause flows to reduce below a threshold which could change the sediment, quality or ecological dynamics of the whole estuary. In order to assess the likely implications, appropriate studies should be undertaken into the likely impacts.

One problem however, is that there are few methods of actually assessing the effects of altering the freshwater flow into estuaries. As indicated earlier the effects can be 'masked' by other processes at work in the estuary and some effects may only manifest themselves in the long term. One method is to make long term historical associations of gauging station data against records of bathymetric change, hydraulic and biological trends to identify how the estuary has responded to natural variations in the past. These changes can then be related to the change which is likely to occur from the development under consideration.

Numerical models can be used to give an indication of the likely effects. However, to incorporate these effects, the models should include density currents, stratification and morphological change, thus requiring the more expensive 3D modelling techniques which are still being developed. Such models are still only likely to be able to predict effects in the short term, say up to 5 years, and will not account for the many effects which may take longer to have an impact on the estuary and its users. A technical approach using modelling is given in Chapter 8.

The problem facing the estuary manager is shown in Figure 7.1. Data is available. However, it must be synthesised into decision making information for the manager.

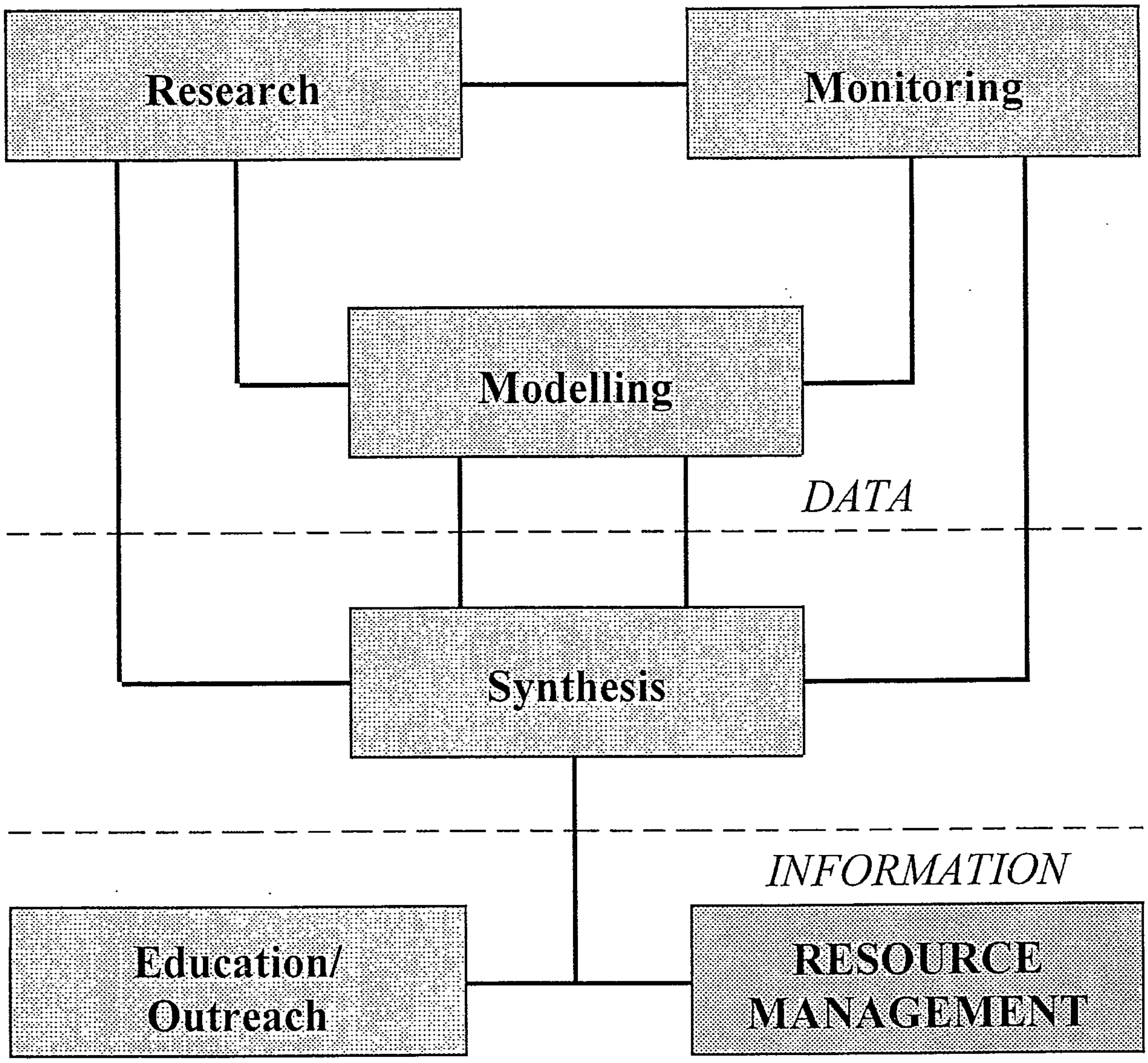


Figure 7.1 - CONCEPTUAL MODEL OF DATA AND INFORMATION FLOW

7.2 Overall approach

Estuary management should be interactive. It must be based on a combination of technical studies with interest groups. This approach applies equally to establishing the freshwater flow needs of estuaries and to other estuarine issues. Management strategies must be developed that are both:

- technically viable; and
- understood by all those affected, as to the issues and impacts of the possible strategies.

Ideally both the Agency and interest groups should be involved to ensure the early identification and resolution of conflicts, and a measure of consensus in the final plan. Unfortunately, this involvement and agreement cannot be guaranteed. If possibly, formal consultation forums should be established, such as an Estuary Management Committee or an Estuary Users Group.

Technical studies should:

- assess the issues;
- identify options and strategies;
- determine impacts; and
- select the preferred option.

Consultation should:

- provide background and baseline information;
- identify issues;
- provide feedback on options and impacts; and
- give support to the selected option and strategy.

The sequence of approach should be:

Consultation	**Technical**
Identify key users	
Consider consultation arrangements	
Preliminary contacts & baseline data	Review baseline data
Create forums	
Identify issues	Review issues
	Identify options
Feedback on options	Identify impacts
Feedback on impacts	Recommend final option
Feedback on selected option	

At all times in this approach, the likely level of public interest should be considered, and the need to inform a wider audience of the:

- strategy development process;
- issues;
- options;
- impacts; and
- outcome.

7.3 Key interest groups

The key interest groups will include:

- Users
  - Port owners and shipping companies
  - Commercial fishermen
  - MoD
  - Local ferry operators
  - Wildfowlers (BASC)
  - Nature reserve owners
  - Bird watchers (RSPB)
  - Industry using power for cooling
  - Water supply and sewage undertakers
  - Sailing clubs
- Regulators
  - Environment Agency
  - English Nature (especially in SAC/SPA estuaries) and the Countryside Commission for Wales
  - Local navigation authority
  - Sea fisheries joint committee
  - MAFF
- Others
  - Local councils
  - Wildlife trusts
  - Holiday industry
  - Farmers and fish farmers
  - Other pressure groups, such as Friends of the Earth

The first contact with these key interest groups probably needs to be made with individual organisations. Subsequent contacts should be considered with combined groups.

The consultation mechanism must be considered, as to whether one group is sufficient or whether it is better to have several. This may depend very strongly on local attitudes, personalities, conflicts and agreements. The aim is to have relatively small groups which can work together productively. Large groups may result in people not making their contribution, or opposing interests taking fixed stands.

7.4 Identification of issues and strategies

7.4.1 Identification of issues

The identification of issues will be an interactive process between the technical groups and the consultee groups.

The technical groups will carry out a preliminary identification of issues from:

- a review of the baseline data;
- past experience of the estuary;
- experience elsewhere;
- an assessment matrix; and
- perhaps some simple modelling.

The consultee groups will:

- consider the technical groups preliminary list of issues; and
- check it against their local knowledge and requirements.

7.4.2 Identification of strategies

The management group should draw up a "wish-list", a list of objectives, including the statutory quality standards, navigation or fisheries in local Acts, related to each of the issues identified for the area. The assessment matrix should be used to identify the priority and flexibility of each objective. Where possible absolute targets (those set by legislation) and desirable targets (those which should be achieve where possible, but can be relaxed) should be set.

Conflicts between these objectives should be identified and a range of strategies produced which address the conflicts in different ways. The implications of achieving these strategies now, and in the future, should be reviewed. This may include impacts and costs.

7.4.3 Selection of preferred strategy

A preferred strategy should be selected by:

- reviewing the implications of each strategy with the consultees.
- modifying the strategies if necessary in the light of comments; and
- selecting a preferred strategy.

7.4.4 Implementation programme

When the strategy is implemented, there must be some on-going monitoring and review procedure to ensure that:

- the programme is being implemented as planned;
- the results are as predicted;
- impacts are controlled; and
- development in the estuary is as planned and does not threaten the gains achieved.

Such monitoring may be based on the consultation groups.

7.5 Agreement on standards

7.5.1 Legal Requirements

The minimum requirement of an estuary management strategy is that it should satisfy the legal requirements applicable to the estuary. These legal requirements arise from:

- National law (including EU Directives); and
- Local Acts.

National law, which is mainly concerned with water quality standards, has been discussed in Sections 5.5 and 5.6. General principles on the infrastructure standards required to satisfy these legal requirements were agreed between the Government, the water industry and its Regulators as part of the AMP2 settlement on water industry prices for the years 1995-2000. These agreed standards have been incorporated into the Agency's current guidelines on setting discharge consents.

In many estuaries there are local Acts or conditions in abstraction licences which lay down standards affecting aspects of estuary management. Most often these Acts or conditions protect navigation or fisheries interests. They must be included in estuary management strategies where they still apply. In some cases, however, the Acts or conditions may not be appropriate or relevant to present circumstances. In such cases, part of the strategy may include negotiations with the present beneficiaries for their modification or repeal.

7.5.2 Consultation on standards

The different organisations with a statutory, commercial or environmental interest in an estuary should be consulted fully as part of the development of an estuary management strategy. These consultations will reveal the issues and standards of key importance to each organisation and highlight areas of consensus and identify conflicts of interest. A critical outcome of the consultation process will be identification of who would bear the costs and who would receive the benefits of any desired improvements to the estuary. The ability and willingness of the identified organisations to pay for or contribute towards the improved estuary standards needs to be established and their contributions agreed.

7.5.3 Appropriate standards

The appropriate non-statutory standards agreed as part of an estuary management strategy will vary from estuary to estuary. These standards must be compatible with existing legal requirements and be accepted as fair and reasonable by those organisations directly involved. Where agreement cannot be reached by consensus, a public, local inquiry may be necessary to resolve conflicting interests.

7.6 Preliminary assessment of technical approach

If programme and funding permit, it may be beneficial to make an initial assessment of the estuary. This could be through an impact matrix as described in Chapters 6 and 8. In some circumstances there may be an opportunity to develop a preliminary model in order to gain an understanding of the estuarine dynamics, or to examine reports from a previous modelling study.

From this assessment, one will determine the significant impacts, processes and uses within the estuary.

7.7 Selection of preferred approach

The final selection of a technical approach for the determination of freshwater flow needs of an estuary will not be based on technical factors alone. Chapter 8 describes a methodology to decide a preferred technical approach. The use of decision matrices will help design this approach and enable a coherent case to be made to study managers for the preferred computational modelling. However, it should be recognised that estuary management and flow determination is a wide-ranging and politically sensitive process. Computational modelling should form a vital part of this process, providing results on which decisions can be made. However, it will not and must not be the driving force behind the decision making process.

The preferred modelling approach must therefore be:

- Credible to the estuary manager, in its scope and budget. However complex and critical the impacts to be analysed, there will be a budget. The approach should provide a realistic scope for modelling within the budget. It may compromise on accuracy. This should be made clear to the estuary manager, who may be able to extend the budget if justification is clearly given;
- Based on real needs within the estuary. The approach must focus on those areas where modelling is needed for estuary management. Modelling frequently develops its own priorities, such as developing or testing new software, investigating an interesting computational feature, or indulging in pure research;
- Capable of correctly identifying differences between the strategies. The model, however simple or complex, must be designed so as to be able to assess a range of strategies and schemes. The form of the model must be such that it is able to compare differences of impact of such schemes;
- Credible to outside bodies. The modelling may be reviewed by a range of estuary users. The scope of work proposed must be credible to both technical and non-technical bodies.

Finally, selection should remember that:

- the newest modelling software with the most features is not necessarily the best for a specific project - a proven existing program in house may do the job just as well with no investment in software;
- the biggest, most detailed computational model is not necessarily the best. Despite the trend towards large, multi-use models, careful project definition and model design may

enable a simple model to provide all the required results, with the attendant cost savings; and

- the optimum approach will be appropriate in:
  - accuracy;
  - cost; and
  - technology.

7.8 Weighing up risks and uncertainties

7.8.1 Risk and uncertainty

Strategy implications are assessed in a wide variety of ways including assessment of the impacts, costs and benefits of the strategy or an individual proposal within a strategy. A mathematical model primarily helps to quantify the impacts of a strategy. This is of particular value for the environmental assessment and also provides key baseline data to help quantify the benefits of the strategy. It must, however, be remembered that each computational model program has limits both in its intrinsic formulation and in the assumptions made in the building of a specific model. This results in:

- uncertainties in the results; and
- a degree (usually small) of risk that strategies directed by the model will fail.

This section briefly considers the management issues of risk and uncertainty. Technical approaches to assess these issues are discussed in Chapter 6.

7.8.2 Uncertainty in modelling

Once the modelling is complete and a draft modelling report is available, the assumptions made in the development of the model should be critically reviewed in the light of the conclusions from the modelling. This overview should consider:

- the robustness of the conclusions, considering any areas of weakness identified; and
- model conclusions, perhaps identified by sensitivity testing, where the model conclusions are particularly dependent on assumed coefficient values.

If necessary, further testing should be carried out to check the robustness of the conclusions.

7.8.3 Risk and strategy

A strategy that is sensitive to small changes in the performance of the mathematical model used to test it is likely to be a risky strategy. This is because the uncertainties in modelling mean that the outcome of the strategy in reality cannot be predicted with confidence from the modelling. In these circumstances, there are four different approaches that could be pursued:

- pursue an alternative strategy whose outcome can be predicted with greater certainty;
- accept that the range of possible outcomes from the strategy would be acceptable;

- develop a more sophisticated model that can predict the outcome of the strategy with acceptable certainty (this may require extensive data gathering and may pose technical challenges); or
- develop an acceptable alternative method of predicting the outcome of the strategy with satisfactory certainty.

7.8.4 Consultation and risk

Wherever possible, model reports should be available for public scrutiny and opportunities taken to explain to other parties with an interest in the project how the model has been developed and why it leads to the conclusions that have been drawn. These explanations should demonstrate the performance of the model with a realistic assessment of its strengths and weaknesses, particularly concentrating on factors critical to the conclusions drawn from the modelling. It should be remembered that an honest assessment of uncertainties and risk in the project will often be well received by the public.

7.9 Sources of funding

7.9.1 Introduction

The Agency is not the only organisation that has an interest in the development of models and estuaries. Other organisations include Port Authorities, the water companies, major users of estuary water (for example, power companies), English Nature and the Countryside Commission for Wales and local councils. Most of these organisations have, on occasion, already developed estuary models for their own use which cover the estuaries and issues that they are concerned about.

7.9.2 Opportunities for joint funding

In the current political climate, where funding is limited, the joint funding of estuarine studies must be considered. However, the extent to which it is desirable or practical for the Agency to either sub-contract modelling work or to jointly fund development of an estuary model with other interested parties is not straightforward. For example, funding for the development of a water quality model by a water or power company will usually be to support a future development proposal by the company. The Agency will eventually be asked to issue a discharge consent or abstraction licence. By participating in model development the Agency will:

- Gain a greater understanding of the assumptions, strengths and weaknesses of the model; and
- Allow agreement of a range technical of issues and model results with the Developer; but
- Its participation in model development may be perceived by objectors as compromising the Agency's independent role as a Regulator.

7.9.3 Estuary management groups

However, where suitable opportunities exist, the Agency should co-operate in funding model development with other regulatory agencies. Such agencies include English Nature and the Countryside Commission for Wales, navigation authorities (where different from port authorities), sea fisheries committees and MAFF. The problem is that most regulatory agencies only have access to limited funds for model development. However, a joint approach by a group of regulators to the major local utility companies (water, sewerage, power and ports) with an interest in an estuary may be positively received, especially if joint funding can be demonstrated in everyone's interest.

If such co-operation can be developed as an Estuary Management Group, the Agency is less likely to be seen as compromising its independent role. Here, the inclusion of most interested parties in the group may allow a degree of management by consensus (Suszkowski J. and Schubel J.R. 1994).

7.9.4 Agency in-house modelling and review

If the Agency feels that it is unable politically to participate in the joint funding of models, it then has the options either to:

- Develop its own in-house model to test development proposals; or
- Rely on technical audits of the developer's modelling to carry out its regulatory duties.

If the Agency were to employ its own model, or perhaps a simpler analysis method, it runs the risk that its approach may not be as sophisticated as the Developer's model. This may make it difficult for the Agency to substantiate its position in opposition to the Developer and its analysis may not be credible at a public inquiry.

If the Agency relies on auditing or reviewing the Developer's model, there is a:

- Small but real risk that a rapid review may not spot a critical deficiency in the modelling. This risk can be minimised by careful selection of reviewers and allowing adequate time for a thorough review appropriate to the importance of the development proposal. This review may include commissioning of additional model runs to allow the reviewer to test additional scenarios;
- Risk that the developers model will be so focussed on their own development needs that it omits potential impacts. These omissions may be *geographical,* if the extent of the modelling is limited, or *parametric*, perhaps omitting significant uses or processes from the modelling. It will then require a strong reviewer to demand major extension to the Developer's model.

In major estuaries, if co-operation through an Estuary Management Group proves impossible, the Agency's involvement may be unavoidable. The range of developments planned and the range of competing organisations with interests in the estuary may make it essential for the Agency to invest in a powerful state-of-the-art model to ensure that it can investigate conflicting interests independently. In these situations, outside organisations may still be willing to invest in the model development, providing that they have some influence over the scope of the model and perhaps the opportunity to use the model in the future for their own studies.

In smaller and less developed estuaries, there are unlikely to be funds available for the development of a complex Agency model. In these cases, any development proposals would need to be supported by the Developer's own modelling, noting that in the case of flood defence, the developer will often be the Agency. The Agency, in its regulatory role, would then have to rely on auditing and review of the Developer's modelling. This process could be carried out internally or by independent consultants.

Despite the economy of the review process, it does not seem prudent to give up all modelling work to the Developer. There may still be benefit from the Agency developing its own, albeit simpler model. This model would provide understanding of the estuary and the impact of the developers proposals. Whilst not being complex enough to be used in opposition to the Developer's model, it would allow the Agency to consider scenarios not analysed by the Developer and highlight deficiencies in their model. The combination of a simple model and review of the Developer's analyses will provide a powerful auditing tool.

7.9.5 Research funding

Another potential source of funding is applied research funding through the various research councils. Such funding would usually be directed through a university. Development of a model using this type of funding would normally require a specific research topic to be addressed. National or international research programmes coordinated by NERC and other similar organisations may on occasion be able to fund collection of field data or model development in a particular estuary of interest.

Overall, it is rare for aspirations in applied research to meet the often short-term needs of estuary management. Any opportunities should be used to advantage when they arise.

7.9.6 Management policy issues

The above discussion of joint funding of modelling studies raises a number of questions of Agency policy. These are:

- Does the Agency wish to maintain its capability in computational modelling? If credible estuary models are to be built increased budgets will be required. These increased budgets will only result from a political decision at high level to remain within the modelling field.
- If modelling is no longer carried out by the Agency, is a credible regulatory role possible through review and audit of others work alone?
- To what extent does co-operating with other interested parties in developing estuary models compromise the independence of the Agency as a regulator?

7.10 Dissemination of modelling results

The presentation of modelling results to technical audiences, project managers, outside organisations and the general public is an essential component of any modelling study. The prime building block is the Technical Report (W113) for the project. This Technical Report discusses the approach, assumptions and processes used to develop the model and the operational conditions that were tested. The recommended scope and contents of this report are described in the companion volume R&D Technical Report W168 'Quality control in computational estuarine modelling', Section 5.6, 'Reporting'.

This R&D Technical Report (W113) is the essential basis for all other dissemination of results. However, in itself, the TechnicalRreport is primarily of interest to and comprehensible by, fellow specialists. This report will provide vital information in any subsequent review, audit or Public Enquiry into the modelling. A common fault of such technical reports is that insufficient details and data are included in the report to allow effective dissemination of the results. Such omissions by outside consultants may be driven by a desire to protect commercial advantage, or simply by a lack of budget. Project managers must therefore ensure that reports contain adequate information.

Despite its importance, the report needs to be summarised for managers and decision makers. The results must be presented in such a way as to be readily understood by specialists in other disciplines within the Agency and by outside organisations. Particular care is needed in preparation of material for public consultation or exhibition. The model results need to be readily understood by local councillors, members of the public with local knowledge and special interest in some aspect of the project and other interested parties.

All presentations require the following components:

- Non-technical explanation of the modelling approach;
- Highlighting of key assumptions or constraints in non-technical terms;
- Visual demonstration of the adequacy of the model calibration;
- Where possible, a good dynamic simulation of well known local events to provide non-technical verification;
- Visual demonstration of changes arising from the project; and
- Interpretation of results in a non-technical manner that is relevant for use by other specialists or decision makers as source data.

Particular care must be taken to present model results in a balanced way. It must be remembered that:

- The non-technical observer of the model will often give a credence to visual model results or dynamic simulations that is not merited. Presentations must include a clear statement of the likely accuracy of the model;
- However, care must also be taken to ensure that the presentation does not accidentally highlight small, non-critical anomalies in the modelling. The non-technical observer may fix on such anomalies, missing the wider technical picture.

8.0 ESTUARY TECHNICAL APPROACH

8.1 Introduction

8.1.1 General

The previous chapters of this report have reviewed the current status of research into estuarine processes and estuary freshwater flow needs; possible future trends in determining these needs, and the place of computational modelling in such studies. Chapter 7 has set out a management approach for studies of freshwater flow needs. This chapter sets out a technical approach to determine such freshwater flow need studies.

The stages of this approach are shown below:

STAGE 1	Review existing reports and check data availability.	(8.2)
STAGE 2	Classify estuary type and select estuary reaches.	(8.3)
STAGE 3	Determine external review, complete data and impact matrices.	(8.4)
STAGE 4	For low impact uses and processes, use simple analysis methods.	(8.5)
STAGE 5	If appropriate, carry out preliminary analysis.	(8.6)
STAGE 6	Review design standards and set out study standards.	(8.7)
STAGE 7	Complete risk matrix, seasonal variations and risk assessment.	(8.8)
STAGE 8	For each use and reach, select appropriate analysis method.	(8.9)
STAGE 9	Rationalise and optimise model design.	(8.10)
STAGE 10	Cost modelling studies.	(8.11)
STAGE 11	Consider joint funding of modelling, or simpler models.	(8.12)
STAGE 12	Set up modelling contracts.	(8.13)
STAGE 13	Carry out or manage modelling studies.	(8.14)
STAGE 14	Analyse model results and set MRF.	(8.15)
STAGE 15	Post-project appraisal.	(8.16)

8.1.2 Complexity of approach

The approach is designed to make best use of existing and emerging technology. Use of risk assessment guides the estuary manager towards the required complexity of analysis method. The approach also allows the manager to use simple methods where appropriate, in a similar way as that used in the SWALP procedure. However, the use of such simple methods should be seen as less than ideal since:

- estuary processes and uses and their interaction are more complex that the usual issues within a non-tidal river. The SWALP style approach cannot deal with this complexity;
- use of a simple approach may add little to ones knowledge of the management or needs of an estuary than the methods used to fix the last round of MRFs a generation ago;
- consultation suggests that MRFs cannot be reliably set on the basis of estuary type and known issues alone. Each UK estuary is unique, and results from one location cannot be transposed to another with any confidence.

Use of computation models has therefore become essential to analyse the complex pressures on estuaries today. It is to be expected that computational modelling of some kind - even statistics or a steady state balance on a spreadsheet - will be used for all but the simplest estuary study.

8.1.3 Technical approach

The recommended technical approach is shown as a flow chart in Figures 8.1 and 8.2. These flow charts show the main steps in determining the freshwater flow needs of an estuary and hence setting an MRF or similar flow regime. Figure 8.1 shows the main actions within a study. Figure 8.2 shows in more detail the specific steps to be taken in selecting appropriate computational models within the overall process.

Whilst the approach shown on the flow charts is designed to provide a framework for a wide range of estuarine studies, the practitioner should be free to adapt it to his own requirements, be it to a specific estuary or a specific problem within an estuary.

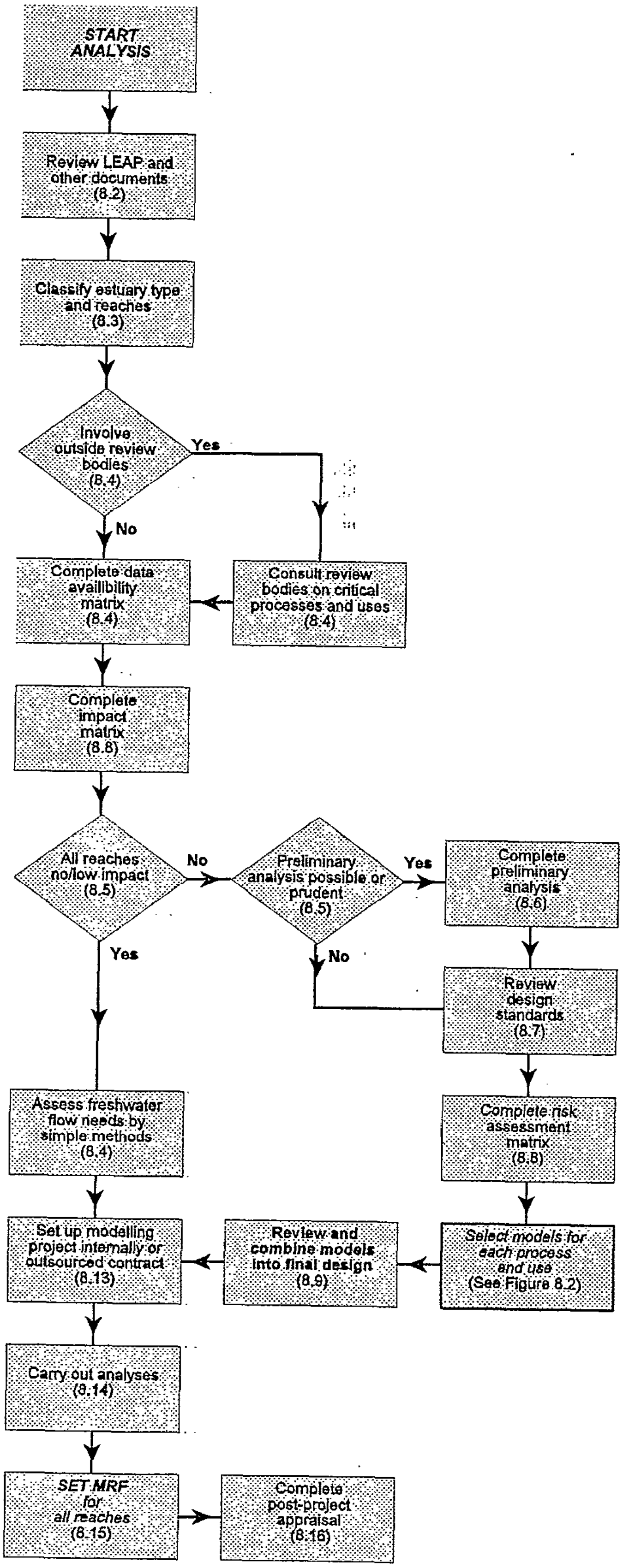


Figure 8.1 - Technical Approach (1)

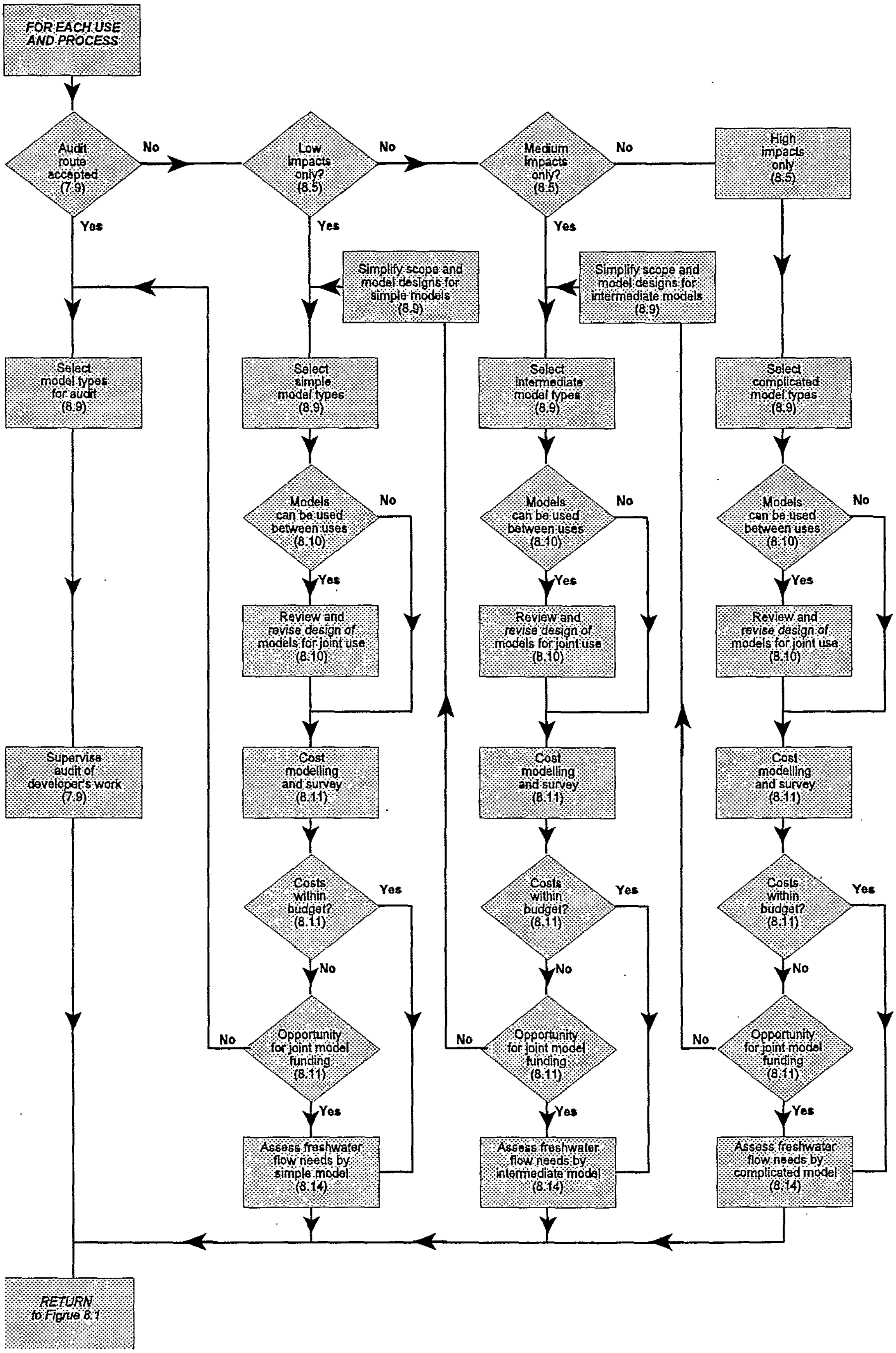


Figure 8.2 - Technical approach (2)

Central to the approach is the use of decision matrices together with elements of risk assessment methodology. In risk assessment terminology:

A Hazard	-	Is a situation with the potential to cause harm.
A Risk -		Is an expression of the potential of a hazard to cause harm. This can be expressed as:

RISK = LIKELIHOOD x IMPACT

where:

Likelihood	-	The probability of the estuarine design standards being derogated, assessed by considering the estuary processes and uses and how close they are to the relevant standard.
Impact	-	The consequence of a hazard occurring.

Abstractions and their associated MRF conditions can then be identified as a *hazard* to the estuarine processes and uses. These techniques can equally be applied to other hazards such as river quality or effluent load. The concept of risk assessment applied to estuary management is described in detail in Chapter 6.

Each step shown on the two flow charts of Figures 8.1 and 8.2 is described in more detail in the following sections of this chapter.

8.2 Review previous work in estuary

Stage 1 - Summary:
Review existing reports
Check data availability

The first step in a study will be to review previous work carried out within the estuary. Although the volume of work may be such as to prevent a detailed review of all areas, care should be taken to identify data that may be re-used for, and conclusions that affect the new study. These may include:

- The relevant LEAP (Local Environment Agency Plan);
- Work and strategies promoted by an Estuary Management Group;
- Work by other interested bodies, such as water companies, port authorities and nature conservation groups;
- Any existing computational models; and
- Any previous reports and studies.

8.3 Classification of estuary type and reaches

Stage 2 - Summary:
Classify estuary type
Select estuary reaches

8.3.1 Estuary type

At an early stage, the estuary should be classified. This classification will be qualitative and to some degree subjective. It is possible that some information on classification may be found in earlier studies.

The aim of classification is to gain an initial understanding of the estuary dynamics. This understanding will both give an indication of the critical processes and uses, but will also give some indication as to the kind of analysis and computational modelling that may be needed.

Four types of classification may be considered:

- Scale;
- Shape;
- Stratification; and
- Human intervention.

Scale refers purely to the estuary's size and importance. Hence the Thames and Humber could be classified as *major* estuaries, both due to their size and importance. The Kentish Stour could be classified as *average*, whereas the nearby Cuckmere and Rother could be classified as *minor*. Of course a small estuary could be classified as *major*, perhaps on conservation grounds. This simple approach thus gives an initial indication of the degree of detail required in a study.

Shape of an estuary gives a guide to the model types necessary for its analysis. The relationship between morphology and process in an estuary is complex and cannot be linked directly with discharge, as with fluvial morphology (HR Wallingford, 1997). For example, tidal inflow affects the estuary form, but the form also affects the tidal inflow.

Despite these complexities, estuaries can be usefully classified by tidal range:

- *Meso-tidal* estuaries (tidal range 2-4m) are usually short and stubby; and
- *Macro-tidal* estuaries (tidal range >4m) are generally long and funnel shaped.

In computational modelling terms, meso-tidal estuaries are more likely to have complex branched or flood and ebb channels and thus to need 2-D modelling. Macro-tidal estuaries are more likely to be adequately represented by 1-D modelling.

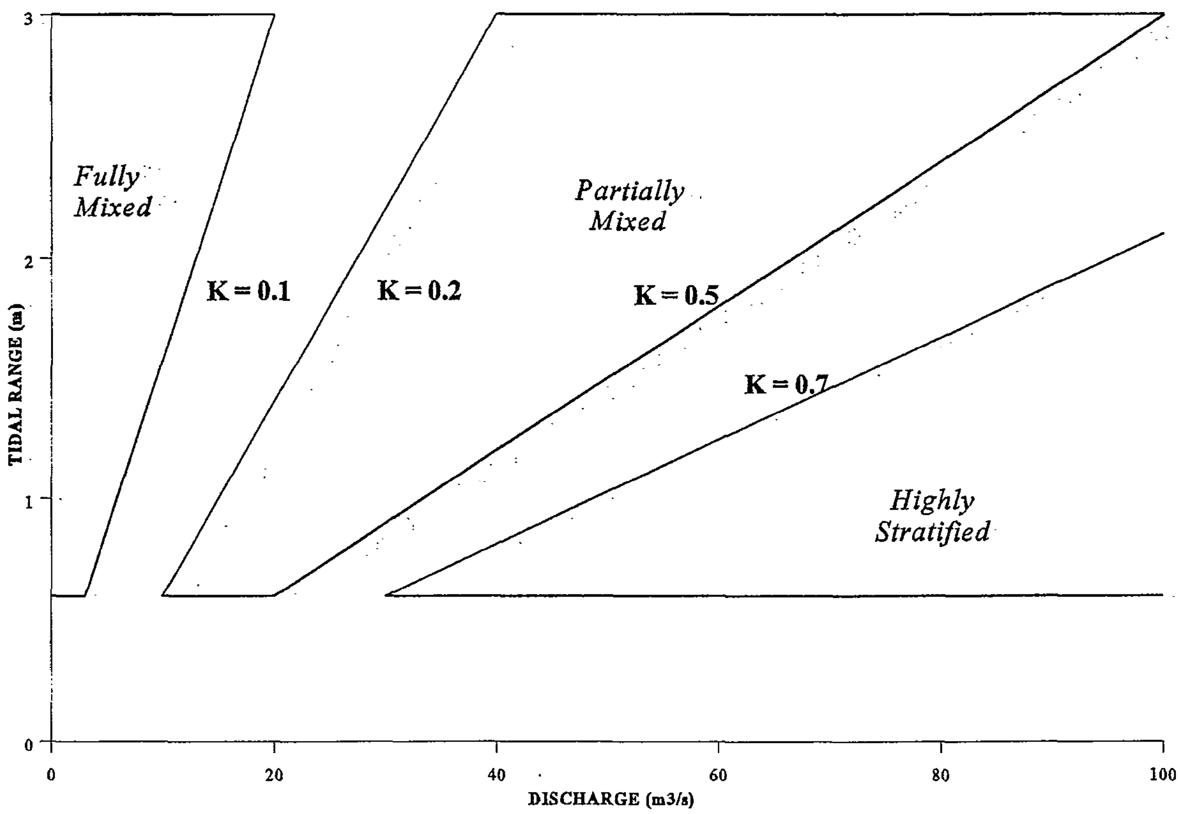


Figure 8.3 - ESTUARINE CLASSIFICATION

Stratification of an estuary also depends to some degree on tidal range. An important factor is the ratio:

K = (Freshwater inflow) / (Tidal inflow)

If the volume of the tidal inflow (prism) and the freshwater inflow can be estimated, the estuary stratification can be classified as shown in Figure 8.3 (from Silvester, 1974). If such data are not available at an early stage of a study general conclusions can be drawn:

- high freshwater flows in a small estuary will encourage stratification; and
- low tidal ranges will encourage stratification.

Where stratification occurs, modelling may require a layered or 3-D approach. It should also be remembered that stratification can vary according to:

- *season*, depending on freshwater flow; and
- *tide*; for example, stratification may occur on neap tides only.

Finally, *human intervention* gives an initial indication of possible complexity in analysis of an estuary. *Low* intervention will show a largely natural estuary, with limited flood works and abstractions. *Medium* intervention may be typical of many of the UK's estuaries. It will show widespread influence by man, but the estuary retains its general form. *High* intervention will show widespread influence by man, but the estuary retains its general form. *High* intervention will show major changes to the estuary, such as reclaimed tidal flats, dredged navigation channels and heavily regulated flows.

This subjective indicator will indicate possible:

- morphological imbalance in the estuary due to earlier engineering works; and
- complex interaction of multiple abstractions, outfalls and the like.

High intervention will indicate that a complex study will be necessary.

The above indicators are used later in this section as part of the risk assessment for the estuary.

8.3.2 Estuary reaches

Following classification, the next step is to divide the estuary system into a series of reaches for the purpose of impact analysis. These reaches are unlikely to be the same as computational model reaches. Each impact analysis reach will contain a number of computational reaches.

The following method can be used to divide the estuary into reaches. It should be remembered that this division is to some degree subjective, and the position of the boundaries between reaches are unlikely to be critical. The estuary should first be divided into the main salinity zones:

- *Freshwater zone*. This zone may include part of the upstream rivers. Although not the main area of investigation, inclusion of part of the rivers may be necessary to include particular uses, such as abstraction, or processes. The limit of the freshwater zone may be the tidal limit shown on the OS map - Teddington Weir on the Thames is an example of this - but is more often further downstream due to the presence of a reach that is tidal but maintained as freshwater by upstream flow.

- *Brackish zone*. This zone is characterised by wide variations in salinity through daily tides and annual variations in river flow. It is often of less interest ecologically, since some species cannot survive such variations. Others species colonise this zone due to the lack of predators and use its high biological production as a nursery area. Nevertheless, it is a zone of high interest for quality and morphology, as the changes in salinity may cause deposition of, for example, sediment, metals, or phosphate. Stratification will occur in this zone.

- *Saltwater zone*. This outer zone is one of relatively constant salinity, with a stable ecology. If no other guide to the inner boundary of this zone is available, the change in the shade of blue on the OS map, from river to sea might be used. An outer, seaward, boundary must also be chosen. This may be at the mouth of the estuary, or may be several kilometres out to sea, depending on the tidal currents and potential morphological changes in this zone.

Apart from OS mapping, the approximate boundaries between these three zones can also be estimated from river form or changes in ecology.

The next step is to subdivide each zone into reaches. Divisions will be made where there are:

- major physical features, such as river tributaries;
- major uses, such as intakes and outfalls, and fisheries;
- areas of nature conservation, such as SSSI's; and
- other areas with known problems or of particular interest to the study.

Alternative methods could, however, be used to divide up the estuary providing they are logically defined and do not overly focus interest on a single use and process.

8.4 Initial matrix reviews

> *Stage 3 - Summary*:
> **Determine external review**
> **Complete data matrix**
> **Complete impact matrix**

8.4.1 Introduction

The next stage will be to carry out an initial matrix analysis to determine the impacts on the estuary and determine the data availability. In a well studied and well known estuary, these impacts may appear obvious. However, the matrix process forms a check list of potential impacts and will ensure that no use or process is omitted from consideration.

8.4.2 Use of external review bodies

An issue to be determined at this early stage is how to involve external review bodies, such as an Estuary Management Group, in the matrix process. The process could be:

- *Internal,* the matrices being filled out by internal consultation in the first pass, and perhaps then reviewed and agreed by an estuary management group, if available; or
- *External,* actively involving external bodies in the matrix process at the earliest stage.

The degree of external involvement will depend on estuary specific factors, including the range of agreeing or conflicting interests and the proposed timescale of the estuary investigation. However, every effort should be made to consult external bodies at an early stage of a project. Such early discussion, compromise and consensus will often prevent entrenched positions at later stages of work.

8.4.3 Data availability matrix

A check should be made on the availability of data concerning the estuary. In particular, the availability of topographic data and other modelling data should be determined. If such data is available either:

- preliminary modelling to scope a full study may be a viable option; or
- survey costs for a full study will be reduced, perhaps allowing a more detailed approach to be achieved with the available budget.

Impact on/by change in freshwater flow	FRESHWATER ZONE			BRACKISH ZONE			SALTWATER ZONE			Comments
	R1	R2	R3	R4	R5	R6	R7	R8	R9	
DATA										
Topographic	L	F	F	F	F	F	F	F	F	
Quality/Salinity										
Flow/Level	F				L	L	L		F	Tide & flow gauges
Sediment			L	L			L	L		Limited data for projects
Ecology	F	L	L			L	L	L		Various studies
MODELS										
Flood	1D	1D	1D	1D	1D	1D				Flood defence design
Quality/Salinity						2D	2D	2D	2D	For outfall design
Resources/operation										
Morphology/sediment										
Ecological/Fish	S	S	S							Flow correlation
CHARACTERISTICS	Meandering lowland river			Wide, shallow, mudflats			Stratified, deep channels			

Key:	Data:	*blank*	No data	Models:	1D	Dimension of model
		L	Limited data		2D	
		F	Full data		3D	
					S	Statistical

Note: Hypothetical example only shown.
R1 to R9 represent estuary reaches.

Figure 8.4 : Data availability matrix

A matrix can then be used to record the existing data and computational models, as shown in Figure 8.4. This approach allows an assessment of data collection needs, and perhaps the potential for a preliminary computational model.

The format of the data availability matrix is not fixed, and would benefit from a large, A3, layout. Data collection is a costly element of a modelling study. It is important to know of any existing data, and also to make best use of this data. This matrix helps these decisions.

Part D - STRATEGY FOR ESTABLISHING FRESHWATER FLOW REQUIREMENTS

8.4.4 Impact matrix analysis

Two matrices are used to carry out the risk assessment, assessing the likelihood and impact of a range of uses and processes, and calculating an average risk for each issue and reach. These matrices are:

- an impact matrix, described in this section; and
- a risk matrix, described in Section 8.6.

The impact matrix is completed first, using a scale of impact to quantify the severity of risk from low estuarine freshwater flows. This scale is described in detail in Chapter 6, but repeated below:

IMPACT		
CATEGORY	DESCRIPTION	SCALE
Catastrophic	Permanent, long term impact on estuary system.	5
Critical	Small permanent or major short-term impact to estuary system.	4
Serious	Significant short-term impact to estuary system.	3
Marginal	Minor impact to estuary system.	2
Negligible	Negligible impact to estuary system.	1

In this matrix, impacts are more closely defined than the data availability matrix described above. All potential uses and processes should be included, but those of known interest should be sub-divided to reveal particular issues that require consideration. For example, the general "fish" category is replaced by three, fish communities, salmonid migration and angling.

The matrix is largely self explanatory. It serves as an initial filter to eliminate processes and uses not critical to the study estuary, and highlight those that will require detailed study. The format of matrix shown above is not fixed, and can be adapted for a particular estuary or study. In particular, the use of a larger A3 format would allow for detailed notes to be made on the matrix itself. The matrix should, however, always include a full range of uses and processes, as a check list to ensure that no impacts are not reviewed during the study.

At this stage, no seasonality has been introduced into the matrix. However, comments can be recorded as shown to record seasonal uses and processes that will need more detailed assessment later in the study.

A typical impact matrix is shown in Figure 8.5.

Use/aspect	FRESH WATER ZONE		BRACKISH ZONE		SALT WATER ZONE		Comments
	R1	R2	R3	R4	R5	R6	
ABSTRACTION/TRANSFER							
Water use	5	5	3	3	2	1	Water supply for urban area
River flow regime	4	4	3	2	2	1	
Salinity	5	5	4	4	2	1	Saline wedge may be critical
Morphological change	4	4	4	4	3	2	Long term effects unknown
DILUTION/FLUSHING							
River water quality	4	4	4	3	3	3	Effluent from STW
NAVIGATION							
Commercial	3	3	3	3	3	3	Dredged channel
Leisure	2	2	2	2	1	1	Summer only
RECREATION & AMENITY							
Recreation	2	2	2	1	1	1	Some sailing and canoeing
Amenity	2	2	4	4	1	1	Visual benefit in urban area
NATURE CONSERVATION							
River plant communities	4	3	3	2	2	1	
Invertebrate communities	4	4	3	2	1	1	
NNR/SSSI	1	1	5	5	1	1	Nature reserves
FISH							
Angling & fisheries	1	1	1	1	2	2	
Salmonid migration	4	4	3	3	2	2	Temperature may be critical
Fish communities	3	3	3	3	3	3	

Key:		
	No impact	1
	Low impact	2
	Medium impact	3
	High impact	4
	Extreme impact	5

Notes: Hypothetical example only shown.
R1 to R6 represent estuary reaches.

Figure 8.5 : Impact assessment matrix

8.5 Use of simple methods to assess freshwater needs

> *Stage 4 - Summary*:
> **All uses/processes low impact**
> **Use simple analysis only**

Following these initial matrix analyses, the results should be examined to assess the level of impact for all uses throughout the estuary. If there is a low impact, throughout the study area, the use of simple models or statistical techniques to determine the freshwater needs of the estuary should be considered. In this case, a full matrix analysis and detailed computational model design will not be needed. The study process may then move directly to the analysis stage (Sections 8.12 & 8.13). An example of a simple statistical approach is included in Chapter 13.

8.6 Preliminary analysis and models

> *Stage 5 - Summary*:
> **Preliminary analysis possible?**
> **If so, carry out analysis**

The use of preliminary analysis and models is discussed fully in Section 6.3. There may be real benefits in this use of preliminary computational analyses to:

- determine the critical processes and uses in an estuary; and
- focus detailed study onto critical areas of the estuary.

However, there are also significant problems in such an approach since:

- use of such a model will increase project costs and times; and
- the results from a simple model may give little added value over existing knowledge of practitioners and from previous studies.

Preliminary models should be considered:

- for major studies, where the cost of the preliminary model may not be significant; and
- where existing models may be quickly used to carry out preliminary analysis.

Preliminary analyses should be carried out in a similar, if simplified sequence, to those presented in following sections

8.7 Design standards

> ***Stage 6 - Summary*:**
> **Review design standards**
> **Set out study standards**

At this stage, the design standards for the study should be determined. These may include:

- a 95% compliance to a water quality standard within the estuary;
- minimum flows for fisheries or to reduce dredging ;
- minimum levels for navigation;
- flows to avoid morphological instability in channels with resulting conveyance changes and effects on existing flood defence capacities; or
- a "no impact" requirement for conservation purposes.

A set of desired design standards should be drawn up for each critical use or process. The selection of standards is discussed in more detail in Chapters 5 and 7.

8.8 Risk assessment matrix

> ***Stage 7 - Summary*:**
> **Complete risk matrix**
> **Consider seasonal variations**
> **Score risk/impact on matrix**

8.8.1 Risk assessment

Having established the need for a comprehensive analysis of the estuary, a full risk analysis should be carried out. In order to quantify risk, a second matrix should be used, of similar form to the impact matrix shown in Figure 8.5. It is now necessary to put a scale to the likelihood of the hazard, reduced freshwater inflows, causing an estuarine event. A scale of 1 to 5 is again used, as described below. The category is qualitative. A guide to frequency is given in the description, but this may need definition for individual uses or aspects.

LIKELIHOOD		
CATEGORY	DESCRIPTION	SCALE
Frequent	Likely to occur on many occasions. (Annual)	5
Probable	Likely to occur regularly. (50%ile)	4
Occasional	Likely to occur occasionally. (95%ile)	3
Remote	Unlikely, but possible. (99%ile)	2
Improbable	Very unlikely, may never occur. (99.9%ile)	1

A typical risk matrix is shown in Figures 8.6, below. The risk is calculated by multiplying the two scales, reach impact and likelihood from Figures 8.5 and 8.6.

A more detailed example of a matrix drawn up to assess hazard to an estuary is shown in Chapter 13.

8.8.2 Assessment of risk matrix

These ratings should then be averaged by both use/aspect and reach, to give an overall picture of the relative importance of the use/aspects and reaches. This is shown in Figure 8.6.

Likeli-hood	Use/aspect	RISK by REACH						Average Risk	Comments
		FRESH WATER ZONE		BRACKISH ZONE		SALT WATER ZONE			
		R1	R2	R3	R4	R5	R6		
	ABSTRACTION/TRANSFER								
4	Water use	20	20	12	12	8	4	13	Water supply
2	River flow regime	8	8	6	4	4	2	5	
3	Salinity	15	15	12	12	6	3	11	
4	Morphological change	16	16	16	16	12	8	14	
	DILUTION/FLUSHING								
4	River water quality	16	16	16	12	12	12	14	Effluent
	NAVIGATION								
3	Commercial	9	9	9	9	9	9	9	Dredged channel
1	Leisure	2	2	2	2	1	1	2	
	RECREATION & AMENITY								
2	Recreation	4	4	4	2	2	2	3	
2	Amenity	4	4	8	8	2	2	3	Visual benefit in urban area
	NATURE CONSERVATION								
3	River plant communities	12	9	9	6	6	3	8	
3	Invertebrate communities	12	12	9	6	3	3	8	
4	NNR/SSSI	4	4	20	20	4	4	9	Nature reserves
	FISH								
2	Angling & fisheries	2	2	2	2	4	4	3	
3	Salmonid migration	12	12	9	9	6	6	9	
4	Fish communities	12	12	12	12	12	12	12	
AVERAGE RISK per REACH		10	10	10	8	6	5		

Notes: Hypothetical example only shown.
R1 to R6 represent estuary reaches.
Risk by reach given by LIKELIHOOD x REACH IMPACT from Figure 8.5.

Figure 8.6 : Risk assessment matrix

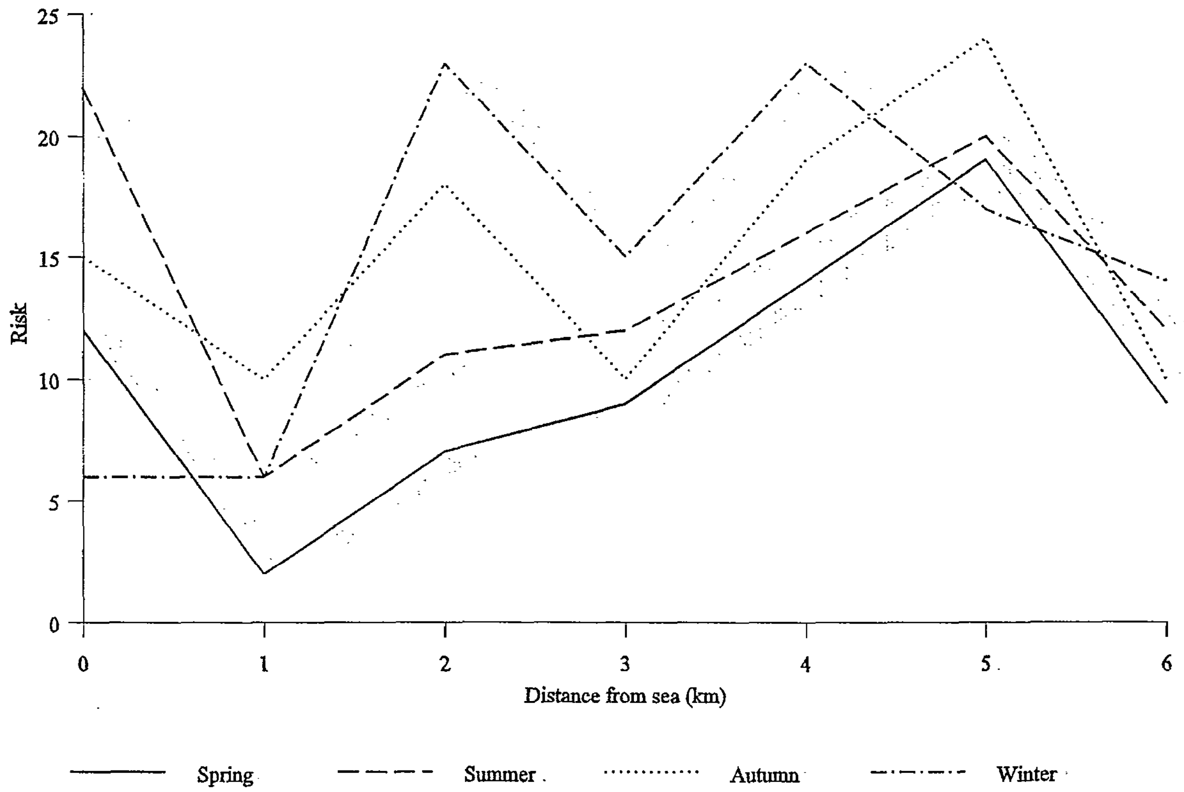


Figure 8.7 - ANNUAL VARIATIONS OF RISK

8.8.3 Seasonal variations

All seasons could be put onto a single matrix. For any other case than the summer/winter split, the resulting matrix would become very large and difficult to read. A better option will be individual matrices for seasons or months - if the matrix is prepared on a spreadsheet, the tabbed page facility could be used to advantage. The resulting weighted sensitivity ratings can then be plotted on a graph, as shown in Figure 8.7, to give a visual indication of variations in rating both seasonal and along the estuary.

The above processes and uses could be sub-divided to express particular, known, concerns of the estuary. For example, fish movement and health could be supplemented by fisheries. Indeed, the fish category could be split up into four, seasonal, classes, namely resident fish, smolt (March to May), upstream movement of adults (May to October), and downstream movement of adults (December to March).

8.8.4 Example of detailed matrix

A detailed matrix analysis was carried out as part of studies on the Kentish Stour (WS Atkins, 1991). Part of this analysis is included as a worked example in Chapter 13.

8.9 Selection of appropriate models

> *Stage 8 - Summary:*
> **For each use and reach, select appropriate analysis method and computational model**

8.9.1 Use, impact and model type

Once the level of analysis for an estuary is determined, it is important to select computational models of appropriate types and complexity. Figure 8.8 shows estuary uses, their potential impacts and the model types that may be used to investigate the impacts.
For all uses, the types of model used will be:

- hydrodynamic (flow and level);
- quality (including salinity);
- morphological (including short term sediment movement); or
- ecological.

8.9.2 Acceptability of impact

With each model type, different levels of analysis can be carried out. Figure 8.9 shows how differing models may be used for a simple, intermediate and complicated level of analysis.

The choice of model will largely depend on the accuracy of the analysis needed. This in turn will depend on the acceptability of the impact of a use on the estuary. If a use is known to have limited impact on the estuary system, or the impact is not considered important, a simple model may be used to quantify this impact in relatively approximate terms. If, however, the estuary impact is to be controlled by a "no impact" standard, complicated modelling will be needed to provide a credible and accurate set of results. Results from the matrix risk analysis should be used to give guidance as to the level of model required as suggested in the table below.

RISK	CLASSIFICATION	LEVEL OF MODEL
1-2	Negligible	None
3-7	Acceptable	Simple
8-12	Undesirable	Intermediate
13-25	Unacceptable	Complex

USE	POTENTIAL IMPACTS	MODEL TYPE 1	2	3	4
ABSTRACTION/ TRANSFER	Reduced flows give:				
	1) Increased saline intrusion.	X			X
	2) Reduction in water quality.	X			X
	3) Long term morphological changes.		X		X
	Possible impacts on:				
	Navigation, nature conservation and fish.				
DILUTION/ FLUSHING	Return flows give:				
	1) Water quality changes, esp. at outfall	X			X
	2) Changes in flow distribution through year.	X	X	X	X
	3) Possible morphological changes.		X		X
	Possible impacts on:				
	Nature conservation and fish.				
NAVIGATION	Navigation requirements give:				
	1) Minimum flows to maintain draft.				X
	2) Morphological changes affect dredging.		X		X
	3) Dredged channels affect morphology.		X		X
	4) Dredged channels affect saline wedge.	X			X
RECREATION & AMENITY	Recreation and amenity may require:				
	1) Water quality for water sports.				
	2) Water quality for fishing.	X			X
	3) Residual flows for visual amenity.	X			X
NATURE CONSERVATION	Nature conservation may be affected by:				
	1) Changes in quality affecting food supplies.	X		X	X
	2) Changes in flow affecting salinity.	X		X	X
	3) Changes in seasonal flow variation.			X	X
	4) Morphology affecting intertidal zone		X		X
	5) Temperature affecting migration	X		X	X
FISH MOVEMENT & HEALTH	Fish and fisheries may require:				
	1) Minimum quality in river.	X			X
	2) Minimum flows to maintain quality.	X			X
	3) Seasonal flows for migratory fish.	X			X
	4) Temperature control.	X		X	X
	5) Preservation of estuarine nurseries.		X		X

Model key: 1 Quality/salinity/temperature; 2 Morphology/sediment; 3 Ecological; 4 Hydrodynamic

Figure 8.8 - USE IMPACT & MODEL TYPE

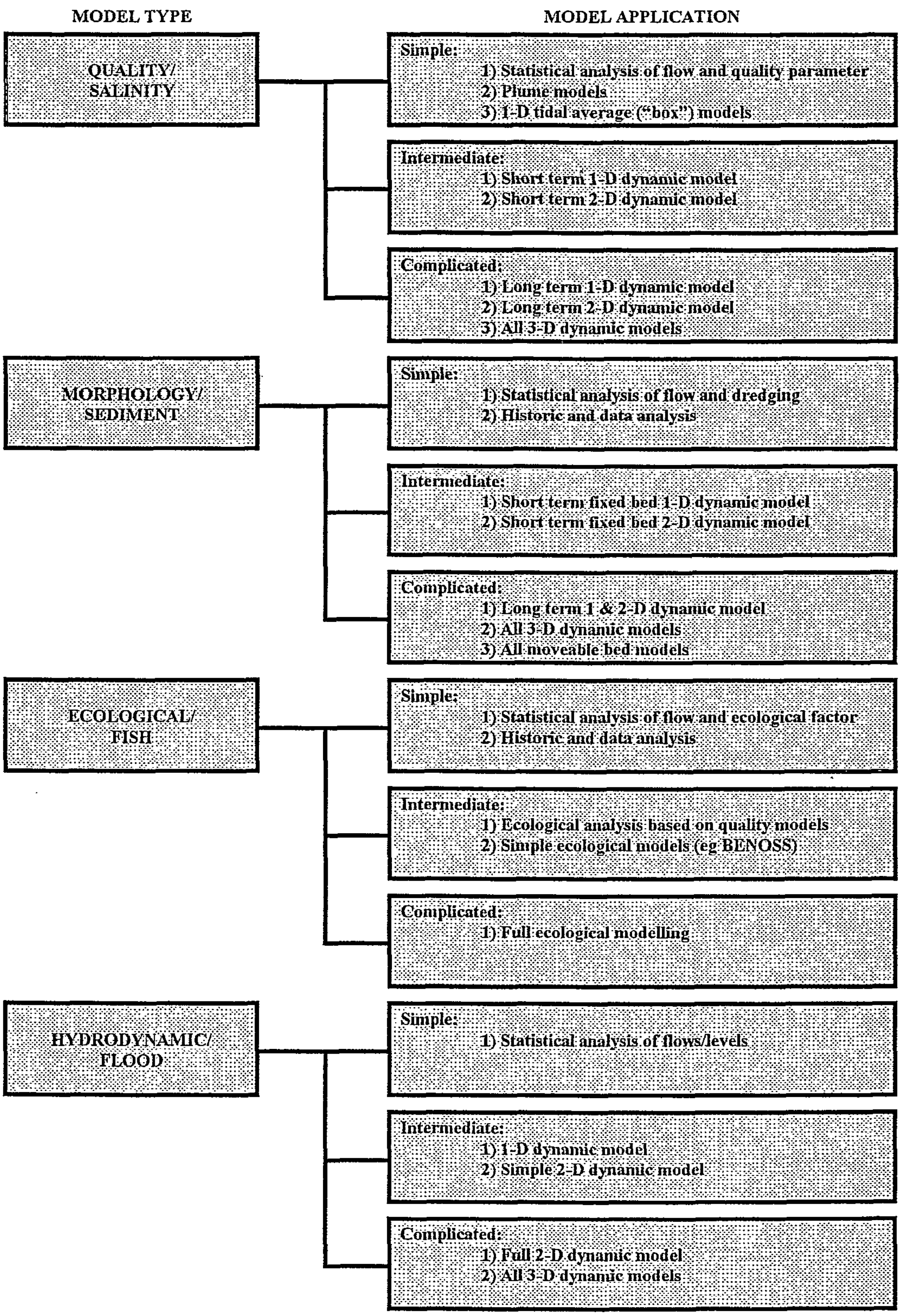


Figure 8.9 - COMPUTATIONAL MODEL APPLICATIONS

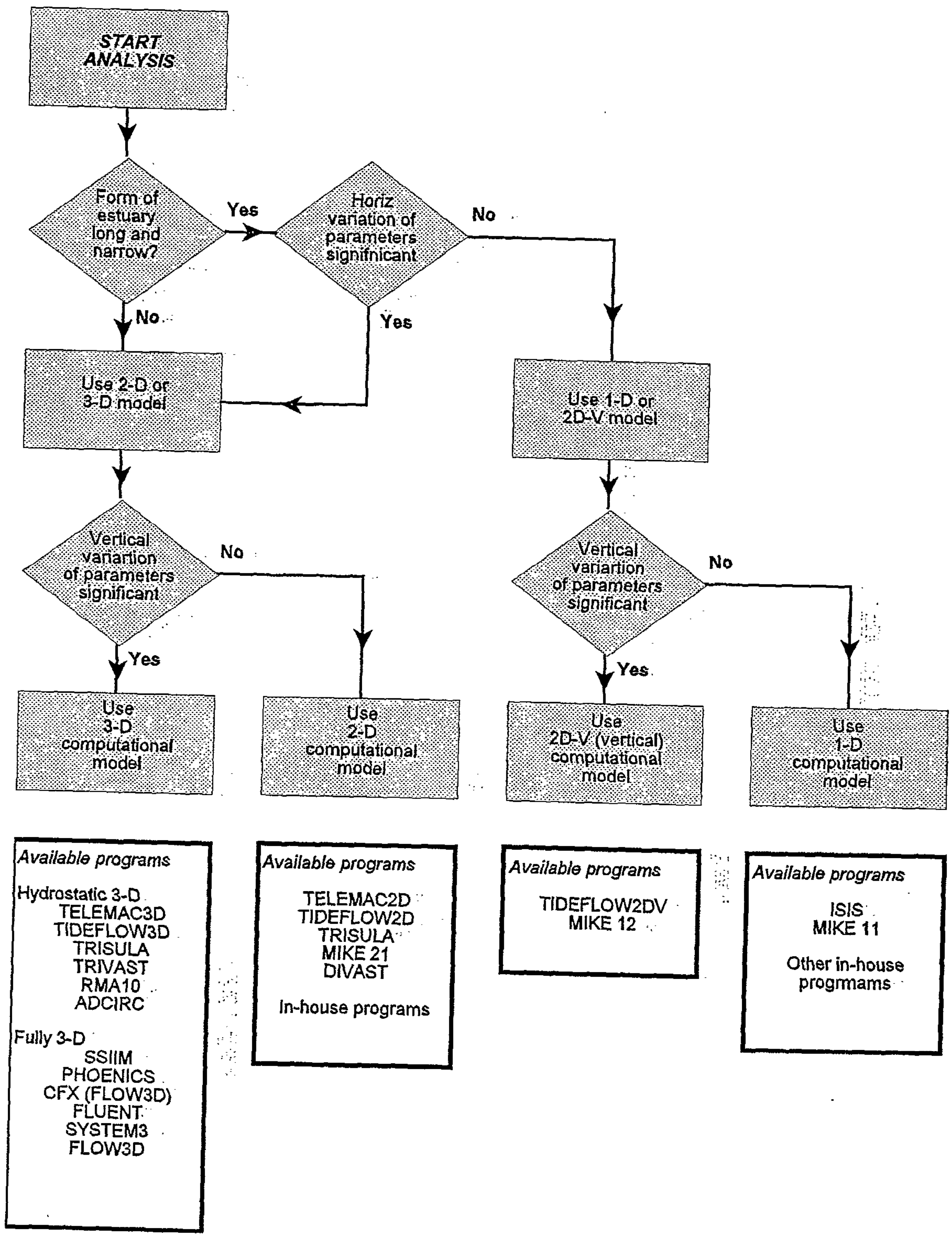


Figure 8.10 - MODEL TYPE SELECTION

Model	Application	Appropriate type
Flow	1) Flow/level alone 2) Floods 3) Storm surge 4) Sea level rise 5) Deltas 6) Large area model & density variations 7) Flow in bends and tidal eddies 8) Intakes (detailed model) 9) Flow over trench or channel	1D/2DH 1D/2DH 2DH 2DH Looped 1D 3DH 3D 3D 3D
Quality	1) Travel distance into estuary. 2) Travel distance into estuary, stratified. 3) Distribution across estuary. 4) Distribution across estuary, stratified. 5) Long term quality models. 6) Plumes. 7) Cooling water.	1D 2DV 2D 3D or 2D2L 2DH or coarse 3D 2DH plus plume or 3D 3D
Sediment	1) 1D models rarely appropriate. 2) Sediment movement due to engineering works. 3) Siltation/flushing of harbour basin. 4) Dredging and resuspension of sediment. 5) Long term morphology.	 2DH or 2D2L 3D Plume 2DH

Adapted from Cooper and Dearnaley (1996)

Figure 8.11 - MODEL APPLICATIONS AND APPROPRIATE TYPES

On completion of this matrix risk assessment, there is clear direction as to the aspects of the estuary that require investigation by computational modelling, and to the level of modelling. The level of modelling may be further guided by the estuarine classification of Section 8.3. If the estuary is classified as mixed or stratified, or the human intervention is medium or high, the level of risk should be considered. If the risk is close to the upper limit for that classification, the practitioner may consider using the next level of model.

Figure 8.10 presents a decision flow chart that can be used to assist in the model selection for a range of estuary forms. Figure 8.11 indicates what type of model should ideally be used for different types of analysis.

8.9.3 Seasonally varying/constant minimum residual flow scenarios

When the choice of models for a study is made, consideration must be made of the types of flow scenarios that will be considered. These may include:

- constant minimum residual flows determined by snapshots of, say, spring and neap tides.
- seasonally varying scenarios, allowing for flow variations, say for fish migration.

8.9.4 Model applications

Hydrodynamics

The hydrodynamic model itself may be of marginal use for water resources studies, except perhaps in navigation studies.

However, a hydrodynamic base model often forms the basis of other, for example quality, studies, the results from one forming an input to the second model.

Features of estuarine hydrodynamic models are shown in Table 8.1.

Quality/salinity

The simulation of water quality by computational models, is an established analysis technique. Simulation may be of conservative parameters, such as salinity, or may include algorithms for the decay or reaction of parameters, such as biological oxygen demand (BOD).

Features of estuarine quality models are shown in Table 8.2.

Morphology/sediment

Short term modelling of sediment movement is well established.

The choice of sediment transport equation used in an analysis often has a significant effect on the volume of material transported. Calibration of the model is often difficult, as care must be taken to obtain representative field measurements.

Long term morphological modelling is a growing science. The extrapolation of short term models can only give indicative results. Long term, moving bed, models that can, say, simulate the effect of a dredged channel must be considered approximate in nature at present. Any such model may at present include a degree of research.

Features of estuarine morphological models are shown in Table 8.3.

Ecology/Fish

Ecological modelling is still in its infancy. Although models that simulate biological processes have been written, their use should, at present, be considered complicated, possibly with a degree of research included in the project.

However, simpler methods will give an insight into the ecological impact on an estuary.

Quality models may be used where a quality parameter is directly associated with ecological factors, for example temperature and the migratory fish.

Features of estuarine morphological models are shown in Table 8.4.

Notes on tables and costs

Tables 8.1 to 8.4 should be read with the Computational Model Quality Assurance manual.

In particular, detailed information on model costs are included in the Quality Assurance manual, and in Chapter 13 of this report.

	SIMPLE MODEL	INTERMEDIATE MODEL	COMPLICATED MODEL
MODEL TYPE	Simple "hydrodynamic" models general consist of statistical analysis of flow or level records. Correlation of this record with other records, such as fish counts or dredging quantities, can provide a reliable basis for decision making.	Traditional 1-D, depth and width averages dynamic hydrodynamic model. Simple 2-D model, built from existing data or Admiralty charts. Large grid size.	Detailed 2-D hydrodynamic model. Small grid size. All 3-D models.
DATA NEEDS	Basic data needs are flow or level records. If statistical analysis is to be carried out, as long a record as possible should be used.	Topographic data. Flow and level data for boundary conditions and calibration.	Topographic data. Flow and level data for boundary conditions and calibration.
ASSUMPTIONS	The hydrological or tidal data used follows a known statistical distribution. If this data is correlated with other parameters, it is assumed that there is a real correlation between these parameters, and that the system is independent of other data.	For 1-D model, depth and width averaged flows assumed to be a good approximation. For 2-D model, coarse grid assumed to capture character of tidal currents to a good approximation.	For 2-D model, grid assumed to capture character of tidal currents to a good approximation. For 3-D model, assumptions may need to be made for horizontal slices between the saline and freshwater layers of the model, or the mechanisms for vertical interchange of water between the layers.
UNCERTAINTY IN RESULTS/ DATA	Results will only be as accurate as the confidence limits of the statistical analysis. Results will only be as accurate as the data sets; care should be taken in checking the quality of gauged records.	Results will be accurate as input data to model. For 1-D, and to a lesser extent 2-D models, local variations in flow and level may not be correctly modelled.	Results will be accurate as input data to model. For 2-D, and to a lesser extent 3-D models, local variations in flow and level may not be correctly modelled.
EXAMPLE	Statistical correlation has been carried out between flow and fish numbers in the River Severn.	1-D flow models have been used successfully on the Norfolk Broadland, where extensive flood banks and urbanisation at Great Yarmouth have limited the width of the estuary.	2-D models, for example the series of models used in Poole Harbour, Dorset, have been used to capture the complex two dimensional layout of the estuary and the differing ebb and flood tidal channels. 3-D models should be considered for stratified estuaries.
TIMESCALE AND COST	Timescale will be low - analysis will take less than a month. Cost in the range £2,000 to £5,000.	Typical analysis time will be 2 months for the modelling. Modelling costs in the range £10,000 to £20,000. Survey costs in the range £20,000 to £30,000.	Typical analysis time will be 4 months for the modelling. Modelling costs in the range £40,000 to £80,000. Survey costs in the range £30,000 to £60,000.

Table 8.1 - MODEL APPLICATIONS - HYDRODYNAMIC

	SIMPLE MODEL	INTERMEDIATE MODEL	COMPLICATED MODEL
MODEL TYPE	Statistical analysis of quality records may be used to show seasonal variations, or correlation of quality with flow. Plume models for pollution outfalls, or sediment sources. The 1-D tidal averaged ('box') model for a simple quality study.	Short term 1-D model. Short term defined as model where all calibration and scenario testing carried out over a short period, such as a few "snapshot" tides. Short term 2-D model.	Long term 1-D models. Long term defined as model is run for an extended period, perhaps to simulate seasonal changes in quality. Long term 2-D models. All 3-D models.
DATA NEEDS	For statistics, quality records. For plume models, current data from float tracking or hydrodynamic modelling. For box model, the volume data of each reach modelled, and basic information on the tidal excursion. Field data for calibration.	Topographic data. Flow and level data for boundary conditions and calibration. Quality data for boundary conditions and calibration	Topographic data. Flow and level data for boundary conditions and calibration. Quality data for boundary conditions and calibration
ASSUMPTIONS	For statistical analysis, if quality data is correlated with other parameters, it is assumed that there is a real correlation between them.	For 1-D model, depth and width averaged flows assumed to be a good approximation. For 2-D model, coarse grid assumed to capture character of tidal currents to a good approximation.	For 2-D model, grid assumed to capture character of tidal currents to a good approximation. For 3-D model, assumptions may need to be made for horizontal slices between the saline and freshwater layers of the model, a salinity profile, or the mechanisms for vertical interchange of water and pollutant/salinity between the layers.
UNCERTAINTY IN RESULTS/ DATA	Results will only be as accurate as the confidence limits of statistical analysis. In all cases, results will only be as accurate as the data sets.	Results will be accurate as input data to model. For 1-D, and to a lesser extent 2-D models, local variations in quality may not be correctly modelled. A particular case here is the concentration of effluent in the plume at an outfall.	Results will be accurate as input data to model. For 2-D, and to a lesser extent 3-D models, local variations in concentration may not be correctly modelled.
EXAMPLE	A box model was used to investigate the impact of cooling water for the new Barking power station on the tidal Thames.	1-D salinity models have been used on the Norfolk Broadland, where stratification is not a major concern, but the penetration of the saline wedge during spring tides may have severe ecological impact.	2-D models, for example the series of models used in Poole Harbour, Dorset, have been used to simulate the impact of effluent from the treatment works around the estuary.
TIMESCALE AND COST	Timescale will be low - analysis will take less than a month. Cost in the range £2,000 to £5,000.	Typical analysis time will be 3 months for the modelling. Modelling costs in the range £15,000 to £30,000. Survey costs in the range £30,000 to £40,000.	Typical analysis time will be 4 months for the modelling. Modelling costs in the range £40,000 to £80,000. Survey costs in the range £50,000 to £60,000.

Table 8.2 - MODEL APPLICATIONS - QUALITY/SALINITY

	SIMPLE MODEL	INTERMEDIATE MODEL	COMPLICATED MODEL
MODEL TYPE	Statistical analysis of records such as dredged volume may show correlation of deposition with flow. Plume models conform a simple approach for sediment modelling close to sediment sources.	Short term fixed bed 1-D model. Short term defined as model where all calibration and scenario testing carried out over a short period, such as a few "snapshot" tides. Short term fixed bed 2-D model.	Long term 1-D and 2-D models. Long term defined as model run for an extended period, perhaps to simulate seasonality in quality. All 3-D models. All moveable bed models.
DATA NEEDS	For statistics, sedimentation data and flow. For plume models, current data. If possible, field data for calibration	Topographic data. Flow and level data for boundary conditions and calibration. Sediment data for boundary conditions and calibration	Topographic data. Flow and level data for boundary conditions and calibration. Sediment data for boundary conditions and calibration
ASSUMPTIONS	For statistical analysis, if sediment data is correlated with other parameters, it is assumed that there is a real correlation between them. Analysis may, however, show that there is no correlation.	For 1-D model, depth and width averaged flows assumed to be a good approximation. For 2-D model, coarse grid assumed to capture character of tidal currents to a good approximation. For all models, sediment transport formulae.	For 2-D model, grid assumed to capture character of tidal currents to a good approximation. For 3-D model, assumptions may need to be made for horizontal slices between the saline and freshwater layers of the model, a salinity profile, or the mechanisms for vertical interchange of water and sediment between the layers.
UNCERTAINTY IN RESULTS/ DATA	Results will only be as accurate as the confidence limits of statistical analysis. In all cases, results will only be as accurate as the data sets.	Results will be accurate as input data to model. For 1-D, and to a lesser extent 2-D models, local variations in sediment flux may not be correctly modelled. Seaward boundary sediment flux may be difficult to define.	Results will be accurate as input data to model. For 2-D, and to a lesser extent 3-D models, local variations in sediment flux may not be correctly modelled.
EXAMPLE	Estimates for the tidal reaches of the river Trent suggest that reducing the freshwater flow by $1m^3/s$ may increase dredged volumes by $15,000m^3$ per year (Binnie & Partners 1993).	A 1-D hydrodynamic and sediment model was used to estimate the impact of a tidal power barrage in the River Duddon.	In Kelantan, Malaysia, a moveable bed 1-D model was used to simulate the change in river and estuarine bed profiles for the next 100 years, using a 1-D moveable bed sediment model.
TIMESCALE AND COST	Timescale will be low - analysis will take less than a month. Cost in the range £2,000 to £5,000.	Typical analysis time will be 3 months for the modelling. Modelling costs in the range £15,000 to £30,000. Survey costs in the range £30,000 to £40,000.	Typical analysis time will be 5 months for the modelling. Modelling costs in the range £60,000 to £80,000. Survey costs in the range £50,000 to £60,000.

Table 8.3 - MODEL APPLICATIONS - MORPHOLOGY/SEDIMENT

	SIMPLE MODEL	INTERMEDIATE MODEL	COMPLICATED MODEL
MODEL TYPE	Statistical analysis of flow/quality against ecological parameters. Historic and data analysis of flow/quality against ecological parameters such as population. Correlation with flow, quality and other parameters.	Use of 1-D and 2-D water quality models. Ecological impacts are assumed to be accurately assessed by changes in quality parameters. Simple ecological models, such as BENOSS. These are one step beyond a quality based study, but only model certain, simple, aspects of the ecology of the estuary.	Any full ecological model. Extension of models such as PHABSIM into estuaries.
DATA NEEDS	Ecological data, such as fish counts or bird counts. For statistical analysis, if ecological data is correlated with other parameters, it is assumed that there is a real correlation between them.	Topographic data. Flow and level data for boundary conditions and calibration. Quality and/or ecological data for boundary conditions and calibration.	Topographic data. Flow and level data for boundary conditions and calibration. Ecological data for boundary conditions and calibration
ASSUMPTIONS	Results will only be as accurate as the confidence limits of statistical analysis.	Ecological impact can be adequately assessed by quality impacts.	Ecological impact can be adequately expressed by model algorithms.
UNCERTAINTY IN RESULTS/ DATA	In all cases, results will only be as accurate as the data sets.	Many ecological processes are poorly understood, in terms of cause and effect from flow and water quality. Interpretation of results must reflect these unknowns.	Many ecological processes are poorly understood, in terms of cause and effect from flow and water quality. Interpretation of results must reflect these unknowns.
EXAMPLE	In the river Severn, Agency research has shown good correlation between salmon movement and salinity. In the Wash, however, it has proved difficult to correlate bird and invertebrate numbers with freshwater flow from the Ouse.		
TIMESCALE AND COST	Timescale will be low - analysis will take less than a month. Cost in the range £2,000 to £5,000.	Similar to an equivalent quality model.	Modelling costs high as R&D element likely to be included.

Table 8.4 - MODEL APPLICATIONS - ECOLOGY/FISH

8.10 Joint use of models

> *Stage 9 - Summary:*
> **Consider how models may be used to analyse more than a single use or process**

Having chosen the appropriate level of analysis and computational model for each use and reach, these choices should be carefully rationalised to achieve the most efficient and economic approach. This may involve:

- design of models to allow a single hydrodynamic model to provide data for quality, sediment and ecological models; and
- extending more complex models to cover isolated reaches that were to be analysed by a simpler analysis. It will usually be more economic, and far easier to manage, a complex model than any two simpler models.

It should, however, be remembered that a water resources study will often involve investigation of changes of flow regime in the estuary. Such a study will require information on long term changes in quality and morphology. A model built for short term events, such as flooding, may not be useable for such long term investigations.

8.11 Costing of models

> *Stage 10 - Summary:*
> **Cost modelling studies**

The proposed analysis and computational modelling should then be costed. Guidelines for model costs are given in the Tables 8.1 to 8.4 and Chapter 12. The model costing should include:

- realistic modelling costs;
- adequate survey costs; and
- adequate costs for project management.

Modelling projects are often costed optimistically low. Although a low budget may be met if all aspects of the modelling run smoothly, it is usual for there to be unforseen problems at some point, be it in data collection, calibration, or in completing the model design runs. A contingency of perhaps 10% should be allowed in the project budget.

8.12 Joint funding or simplification of models

> *Stage 11 - Summary:*
> **Consider joint funding of modelling with other practitioners.**
> **Consider simpler models.**

If the study costs are above the project budget, the following options should be considered:

- Increase the budget (should be considered, even if unlikely to be viable);
- Consider joint funding of the models by other organisations; or
- Simplify the models.

Joint funding of computational modelling work is considered in Chapter 7. Possible partners with the Agency in such an alliance are:

- Estuary management groups;
- Other users, such as Port Authorities;
- Proponents of schemes, such as abstractors or producers of effluent; and
- Nature conservation bodies.

The advantages of such a joint approach are that:

- More detailed studies can be achieved by a joint study than through studies carried out by the individual organisations;
- A high agreement in modelling results and technical output from the study should be achieved; and
- There will be an implicit high level of consultation between critical parties at an early stage of the study.

Disadvantages may be:

- Added administration costs;
- Transparency of all studies to all proponents; and
- Potential conflict as to the direction taken by studies.

If joint funding of the computational modelling is not considered a viable option, the study costs can be reduced by the use of simpler analysis techniques. This iterative process is shown on Figure 8.2. The reduced modelling costs will also result in reduced accuracy of and confidence in the study results. Care must be taken that the pressure to meet a budget does not result in the study providing no new knowledge about the estuary, or insufficient results and information to support a management decision, or face detailed questioning at a public enquiry.

8.13 Modelling contracts

> *Stage 12 - Summary:*
> **Set up internal or outsourced modelling contracts**

Modelling may be carried out internally by the Agency or outsourced to consultants. In either case, a detailed project definition and model specification should be drawn up, including:

- the scope of work;
- background to the project;
- model types to be used and the extent of modelling;
- a detailed technical specification;
- data collection needs; and
- reporting requirements and deliverables.

The specification will be written to achieve definition of minimum freshwater flow needs for the estuary, as discussed in Section 8.15. The following outputs, or similar, may be specified:

- the impact of different freshwater flow options (hazards) on the estuarine processes and uncertainty estimates. For example, a table of mean, 95% and 5% chloride statistics may be presented for each specified reach for a dry year, an average year and a wet year; and
- the likelihood of estuarine standards being derogated for different freshwater flow options (hazards) in terms of number of exceedances.

These issues are described in more detail in Chapter 7 of this report, and in the Computational Modelling Quality Manual published with this report .

8.14 Modelling analyses

> *Stage 13 - Summary:*
> **Carry out/manage all modelling studies**

The modelling studies will now be carried out, ensuring that:

- all modelling work is managed to ensure appropriate model results are produced; and
- all modelling work is quality assured to an agreed system.

These issues are described in more detail in the Computational Modelling Quality Manual published with this report .

A range of model runs will be required to analyse the impacts of changed freshwater flows to the estuary. Typical model runs will be for:

- Existing MRF or residual flow rules (baseline);
- MRF = observed Q99;
- MRF = observed Q99 plus reservoir releases to flush out estuarine sediment;
- MRF = observed Q95;
- MRF = 10% of ADF (mean flow);
- MRF = maximum of monthly observed Q95 and flow needed for dilution;
- no MRF;
- maintained flow equal to Q99; or
- % of reservoir release to go to the estuary (low flow support).

The aim of these runs will be to find an MRF that will maintain the estuarine standards relating to, for example, water quality, dilution, sediment. The runs must take into account flow variability, therefore including seasonal variations, and also typical dry, average, wet and extreme years in an extended (10 year or more) flow sequence. These runs may be iterative and will include sensitivity analysis.

A final set of results for presentation in the study modelling report will typically include 7 runs:

- Baseline;
- Constant MRF;
- Constant MRF - 10%;
- Constant MRF - 20%;
- Seasonal MRF;
- Seasonal MRF - 10%;
- Seasonal MRF - 20%.

8.15 Setting of freshwater flow needs and/or MRF

***Stage 14 - Summary*:**

Analyse model results to determine freshwater flow needs of estuary. Set MRF if appropriate.

Following analysis, the results should be processed to determine the freshwater flow needs of the estuary, and set a resulting MRF. The MRF should be set as follows, using model output:

- Set an initial value. This may be the existing MRF or Q95 for the estuary;
- Modify the value to meet uses, but maintain quality and salinity constraints;
- Modify the value to satisfy morphological and ecological criteria;

- Modify the value seasonally to meet seasonal variations in freshwater needs for all processes and uses; and
- Hence derive a final seasonally varying residual flow.

8.16 Post-project appraisal

> ***Stage 15 - Summary*:**
> **On completion of project, appraise studies carried out.**

On completion of the project, a post project appraisal should be carried out. This should review a number aspects of the project:

- Success - Has the project met its objectives?
  - Have any mistakes been made? Consideration of the modelling and management process may reveal wasted effort in the study.
  - Was the data collection carried out adequate?

- Data - Is additional long term data collection needed?
- Archiving - Has all project data been placed for later retrieval?

9.0 CONCLUSIONS AND RECOMMENDATIONS

9.1 Existing relevant R&D

Relatively little R&D has been directed towards the freshwater flow needs of estuaries and the determination of residual flows. There is, however existing and ongoing research into:

- Aspects of computational modelling, providing support to residual flow determination;
- Residual flows in rivers. The Surface Water Abstraction Licensing Policy procedure is designed to assess applications for surface water abstractions.
- Morphology. Current MAFF research is looking at methods for the prediction of long term morphological change caused by changes in the estuary.
- Fisheries research into minimum acceptable flows and the effect of temperature on migratory fish.
- Risk assessment. Research into risk assessment methods in management decision making and long term corporate planning. A risk assessment approach has been used in the determination of freshwater flow needs in this study.

9.2 Understanding of estuarine processes

Most short term estuarine processes are well understood and can be simulated by computational models or other analytical methods. However, there are major gaps in knowledge in:

- Long term morphological change;
- The relationship of sediment and ecology; and
- Ecological mechanisms.

9.3 Best practice in estuarine management

Estuary management should be interactive and based on a combination of technical studies with interest groups. This approach applies equally to establishing the freshwater flow needs of estuaries and to other estuarine issues. Management strategies must be developed that are both:

- technically viable; and
- understood by all those affected, as to the issues and impacts of the possible strategies.

In addition, the estuary must be managed holistically. This will require consideration of:

- all possible estuary processes and their interaction. This may imply use of more complex analytical techniques, and MRFs that varying with season and flow;
- all estuary users, perhaps by formation of estuary management groups; and
- the whole estuary and perhaps its associated river basin to ensure consideration of the impact of all processes and uses.

9.4 Present and future use of modelling techniques

Computational modelling is closely linked to the computing power available. It is certain that the power available on the average modeller's desk at low cost will continue to escalate. It will become possible to create models that are:

- more realistic, using more complex algorithms to simulate hydrodynamic, chemical or ecological functions;
- more detailed in space and longer in time;
- more integrated, with a single model being used for a range of functions; and
- simulates morphology and ecology with confidence.

Modelling is widely used in the Agency for flow and quality analyses. Less advance has been made in the use of modelling for the determination of freshwater flow needs of estuaries.

Computational modelling has significant cost. The Agency does not have the budget to carry out all modelling that may be required. It may then carry out its regulatory function for license applications and other issues by:

- carrying out its own modelling;
- building jointly funded models with other parties; or
- auditing models built by proponents of schemes.

The above alternatives raise a number of questions of Agency policy. These are:

- Does the Agency wish to maintain its capability in computational modelling? If credible estuary models are to be built increased budgets will be required.
- If modelling is no longer carried out by the Agency, is a credible regulatory role possible through review and audit of others work alone?
- To what extent does co-operating with other interested parties in developing estuary models compromise the independence of the Agency as a regulator?

These points should be considered by appropriate functional groups and brought before high level policy makers to ensure that the implications of the above options are not ignored.

9.5 Methodology for determining freshwater flow needs

This report sets out a management and technical approach to freshwater flow need studies. The approach is designed to make best use of existing and emerging technology. The approach also allows the manager to use simple methods of analysis where budget dictates, although it should be stressed that the use of such simple methods should be seen as less than ideal, adding little to one's knowledge of the management or needs of an estuary than the methods used to fix the last round of MRFs a generation ago.

The management approach stresses the need for a coherent data management policy. At present data collected by the Agency may not always be easily retrievable for future studies. A policy is needed that:

- Encourages project teams to archive data; and
- Creates a simple, yet comprehensive, database to allow retrieval of this data.

It is envisages that such a policy will make extensive use GIS databases.

Data collected by the Agency does not include data sufficient for the building of morphological models to predict long term changes in an estuary. It is expected that the ongoing MAFF sponsored research will give guidance on the collection of this long term data.

A technical approach for the determination of freshwater flow needs is proposed, using concepts from risk assessment. This approach is shown below:

STAGE 1	Review existing reports and check data availability.
STAGE 2	Classify estuary type and select estuary reaches.
STAGE 3	Determine external review, complete data and impact matrices.
STAGE 4	For low impact uses and processes, use simple analysis methods.
STAGE 5	If appropriate, carry out preliminary analysis.
STAGE 6	Review design standards and set out study standards.
STAGE 7	Complete risk matrix, seasonal variations and risk assessment.
STAGE 8	For each use and reach, select appropriate analysis method.
STAGE 9	Rationalise and optimise model design.
STAGE 10	Cost modelling studies.
STAGE 11	Consider joint funding of modelling, or simpler models.
STAGE 12	Set up modelling contracts.
STAGE 13	Carry out or manage modelling studies.
STAGE 14	Analyse model results and set MRF.
STAGE 15	Post-project appraisal.

9.6 Recommendations

The following future R&D needs are recommended:

- The technical approach described should:

  a) be trialed; and
  b) its application to disciplines other than water resources considered.

- Each region should develop a strategic computational modelling plan that:

  a) indicates the management approach for each estuary, as to whether modelling will be carried out in-house, jointly, or by audit only;
  b) proposes a strategic programme for in-house modelling; and

- Data collection and management should be reviewed, then:

  a) a fully integrated and focused data monitoring strategy adopted;
  b) a consistent policy on data adopted between regions;
  c) a minimum specification database to archive estuarine data developed; and
  d) a GIS should be used for this data archive.

- An overview should be kept of advances in morphological and estuarine modelling techniques to identify any future R&D needs.

- Data collected by the Agency does not include data sufficient for the building of morphological models to predict long term changes in an estuary. The Agency should:

  a) keep the ongoing MAFF sponsored research on morphology in view; and
  b) implement a morphological data collection programme as soon as is practicable.

- Agency functional groups and policy makers should consider whether:

  a) the Agency's computational modelling budgets are adequate for the Agency to maintain its capability in computational modelling;
  b) the Agency's regulatory role if carried out through review and audit of others work alone, if modelling is no longer carried out; and
  c) whether the Agency loses its independence as a regulator if it co-operates with other interested parties in developing estuary models.

PART E - SUPPORTING INFORMATION

10. LIST OF CONSULTEES

10.1 Environment Agency

Name	Title	Type of consultation
Ken Allison	Flood Defence Manager, Southern Region	P
Ian Barker	Regional Water Resources Manager, Welsh Region	P,W
Gary Beamish	Flood Defense, Southern Region	P
Geoff Bell	Abstraction Control Manager, Thames Region	P
Simon Bingham	Thames Region	N
Dr Paul Crocket	Senior Resources Engineer/Modeller, Midland Region	P,W
Keith Davies	Welsh Region	N
John Ellis	Regional Resources Management Officer, Southern Region	P
Adrian Fewings	Fisheries Scientist, Southern Region	P,W
Richard Freestone	Environmental Modelling Principal Officer, North East Region	P,W
Rob Grew	Senior Planner, South Western Region	P,W
Trevor Hardy	North East Region	N
Gordon Hargreaves	Regional Licencing Officer, Anglian Region	P
Catherine Holman	Southern Region	N
Carolyn Hopper	Anglian Region	N
Pete Jonas	Senior Scientist (WQ Modelling) South Western Region	P
Aileen Kirmond	Headquarters	P
Dave Lowthion	Southern Region	N
Nigel Milner	Area Environmental Appraisal Manager, Welsh Region	P
John Morgan	Area FRCN Manager, Southern Region	W
Neil Murdoch	South West Region	P,N
Dr Betty Ng	Environmental Modeller, Welsh Region	P,M,N
Oliver Pollard	Hydrologist, Southern Region	P,M,W
Alaistair Pratt	Water quality modeller, Southern Region	P
Brian Repton	Licencing and Monitoring Manager, North West Region	P
Sheila Sowerby	North West Region	N
Cameron Thomas	Licensing and Transfers Manager, Anglian Region	P
Dr Roger Wade	Area Water Resources & Planning Manager, Midlands Region	P
Dave Willis	Thames Region	P
Tony Warn	Anglian Region	N
Ann Watts	Midlands Region	N
Stephen Worral	Coastal Processes Manager, Anglian Region	M

Key to consultation types:

- P Telephone conversation
- M Meeting
- W Written submission
- N Consultation at NAMOG seminar

10.2 Other UK Organisations

Name	Title	Type of consultation
Roger Falconer	Department of Civil Engineering, University of Cardiff	P
Kathy Kennedy	Project Manager, Thames Estuary Project, English Nature	M
Frank Law	Institute of Hydrology	P.M
Nicholas Odd	Hydraulics Research Wallingford	P,M,W
Tony Polson	MAFF	P,M
Paul Samuels	Hydraulics Research Wallingford	P
Peter Whitehead	ABP Research & Consultancy Ltd	P,W
Richard Whitehouse	Hydraulics Research Wallingford	W

Key to consultation types:
- P Telephone conversation
- M Meeting
- W Written submission

10.3 Overseas Consultees

Name	Title	Type of consultation
Neal Armstrong	Professor, University of Texas	P
Ted Burgess	Director, Binnie Black & Veatch, Indonesia	W
Gerald M Hansler	Executive Director, Delaware River Basin Commission	M
Vic Hobcroft	Project Director, Binnie Black & Veatch, Thailand	M,W
Karsten Havno	Danish Hydraulic Institute	P
Gerald R Miller	Black & Veatch (Kansas City)	W
Geoff Piggott	Country Director, Binnie Black & Veatch, Singapore	W
Beth Quinlan	Black & Veatch (Kansas City)	W
Andries Roelfzema	Manager Marine Environment Group, Delft Hydraulics	W
Nick Townsend	Director, Binnie Consultants Ltd (Hong Kong)	M,W

Key to consultation types:
- P Telephone conversation
- M Meeting
- W Written submission

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12. COST DATA TABLES

12.1 Basis of tables

Section 8 provides approximate modelling costs for a range of model complexity, given at 1997 prices, and summarised in Table 12.1. However, the cost of modelling work varies with supply and demand. A more constant measure is the estimated man-day input by staff with the appropriate experience. The tables in this chapter are therefore presented in man-day format.

Even so, in the case of modelling, the amount of staff time to complete a given task varies depending mainly on the quality of the data and whether it is provided in digital form. The staff input is therefore based on the assumption that the model is fully packaged and user friendly. No allowance is made for the cost of purchasing the model.

12.2 Project costs

Table 12.1 provides approximate modelling and survey costs for a range of model complexity, given at 1997 prices. It should be noted that these costs are an estimate, and real tender costs will depend on market conditions.

12.3 Staff costs

The following tables of staff input are given in the following pages:

- Staff time to complete a 1-D intertidal modelling study.
- Staff time to complete a 2 or 3-D intertidal modelling study.
- Staff time to establish a functional relationship between an estuarine phenomema and river flow predictive and other variables.
- Staff time to execute low flow surveys.

The tables should be used with the following guidelines:

- The experience required for staff of a given grade for a given task relates to experience applying mostly that type of model to mostly the same type of problem and not general experience. However, staff with longer but more general experience may be substituted.
- The experience should relate mostly to UK estuaries and not general experience. Staff with longer but more general overseas experience may be substituted.
- It should be recognised that there is a balance of experience here. Detailed experience of a type of model on a type of problem will usually provide an efficient approach to a project. However, when wider experience is applied to a task, it often provides external insights that improve the results from the task.
- In general, Graduate staff may be substituted by MSc staff with slightly less or more general experience. Technician staff may be substituted by junior Graduate staff with appropriate experience, depending on the task to be completed.

A table of typical staff rates are also included, at 1997 prices. These rates are indicative only.

12.4 Survey costs

The same principles apply to the method of estimating staff time required to execute surveys in UK estuaries.

In the case of field surveys there are many other significant costs besides staff time. Downtime is usually not a problem in the sheltered waters of the upstream part of most UK estuaries.

Boat hire costs and sample transport and analysis costs vary from region to region, and often on availability.

Equipment hire costs are often expressed as a fraction of their capital costs.

To emphasis the variation in survey costs, Table 12.10 gives budget costs quoted by West (1995) for modelling studies into the flow requirements in the tidal Trent.

All figures quoted, except where stated, refer to short term, snapshot, data collection. Long term data collection costs will depend largely on the extent and methods of collection. However, typical costs will be typically 50% of snapshot costs per annum.

Table 12.1 -APPROXIMATE PROJECT COSTS

Model type	Timescale (months)	Modelling cost (£)	Survey cost (£)
Hydrodynamic			
Simple	1	2 - 5,000	-
Intermediate	2	10 - 20,000	20 - 30,000
Complicated	4	40 - 80,000	30 - 60,000
Quality/Salinity			
Simple	1	2 - 5,000	-
Intermediate	3	15 - 30,000	30 - 40,000
Complicated	4	40 - 80,000	50 - 60,000
Morphology/Sediment			
Simple	1	2 - 5,000	-
Intermediate	3	15 - 30,000	30 - 40,000
Complicated	5	60 - 80,000	50 - 60,000
Ecology/Fish			
Simple	1	2 - 5,000	-
Intermediate	3	15 - 30,000	30 - 40,000
Complicated	High	High	High

Notes: All costs from late 1997.
Long term survey costs are typically 50% of snapshot costs per annum.

Table 12.2 - ESTIMATES OF STAFF TIME REQUIRED TO APPLY 1-D INTER-TIDAL MODELLING FOR SHALLOW TURBULENT NARROW CROSS-SECTIONALLY WELL MIXED ESTUARIES

TIDAL FLOW AND SALINE INTRUSION (FS)

No.	Task	Estimate of Man-day input	Grade/experience using model (min years)
FS1	Collate and check cross-sectional data*	4-8 per 100 cross-section	Tech/5 years
FS2	Schematise UK estuary	1-2	Specialist/10 years
FS3	Input cross-sectional data to model	3-5 per 100 cross-section	Tech/2 years
FS4	Input sea boundary harmonic tidal level constants. Check-predictions*	1	Tech/10 years or Grad/2 years
FS5	Collate, check and input daily fluvial inflows*	2-4 per 1 year hydrograph	Tech/10 years Grad/2 years
FS6	Collate, check and input tidal level, velocity and salinity calibration data*	2-4 per record (Total 10-30)	Tech/10 years Grad/2 years
FS7	Estimate bed roughness type specify calibration accuracy targets	0.5	Specialist (10 years)
FS8	Simulate period of intensive inter-tidal survey compare with tidal level and tidal velocity data and optimise bed roughness	2-4 per test (Total 10-20)**	Grad/2 years or Tech/10 years
FS9	Use salinity data under steady flows to estimate coefficient of longitudinal dispersal Set empirical constants in equation defining coefficient of longitudinal dispersion	3 5	Specialist/10 years Tech/10 years
FS10	Simulate annual cycle and compare with long term salinity observations. Optimise longitudinal mixing	3-6 per test. (Total 10-30)	Tech/10 years
FS11	Validate model on independent set of data	3-6 per test	Tech/10 years
FS12	Carry out sensitivity tests on calibration constants for low flows. Estimate error bar on position of 0.5ppt and 5ppt salinity fronts	5-10	Grad/2 years
FS13	Prepare calibration report	4-8	Grad/2 years
FS14	Predict design low flow year and analyse results	2/test year 1/test year	Tech 2 years Grad 5 years
FS15	Technical Management	5-10	Specialist 10 years

* excludes measurement or purchase of data

** most time needed if bed sediment fine sand (<0.25mm)

Table 12.3 - ESTIMATES OF STAFF TIME REQUIRED TO APPLY 1-D INTER-TIDAL MODELLING FOR SHALLOW TURBULENT NARROW CROSS-SECTIONALLY WELL MIXED ESTUARIES

Sand transport, siltation and erosion (S) (refined flow model)

No.	Task	Estimate of Man-day input	Grade/experience using model (min years)
S1	Collate long term bed level data	10-30	Tech/10 years
S2	Collate sediment size fraction data	5-10	Tech/2 years
S3	Select appropriate sand transport function	5	Specialist/10 years
S4	Test model	5 5	Grad/5 years Tech/2 years
S5	Simulate observed drought and compare with bed level changes. Adjust coefficients to obtain best fit	5/test (Total 20-30)	Grad/5 years
S6	Validate modelagainst independent data	5/test (Total 10-15)	Grad/5 years
S7	Carry out sensitivity tests and evaluate error bar (ie ± 0.5m)	3/test (Total 10-15)	Grad/5 years
S8	Prepare calibration report	1-3 1-4	Tech/2 years Grad/5 years
S9	Predict design low flow year and analyse results	3/test year 2/test year	Tech/5 years Specialist/10 years
S10	Technical management	10-15	Specialist/10 years

Note: 1D model will not simulate trapping of sand in lower estuary by saline wedge at high flows

Table 12.4 - ESTIMATES OF STAFF TIME REQUIRED TO APPLY 1-D INTER-TIDAL MODELLING FOR SHALLOW TURBULENT NARROW CROSS-SECTIONALLY WELL MIXED ESTUARIES

WATER QUALITY INCLUDING SUSPENDED SOLIDS (Q) (requires flow model)

No.	Task	Estimate of Man-day input	Grade/experience using model (min years)
Q1	Collate daily fluvial pollution loading data	3-6 1	Tech/5 years Grad/5 years
Q2	Determine diurnal, weekly and seasons variations in effluent flows and pollution loads	2-10 1-2	Tech/5 years Grad/5 years
Q3	Collate sea boundary data	1-3 0.5	Tech/5 years Grad/5 years
Q4	Collate calibration data	5-10 2-3	Tech/5 years Grad/5 years
Q5	Input loading, sea boundary and calibration data	5-10 1-2	Tech/2 years Grad/5 years
Q6	Review bio-chemical processes and set rate constants and specify calibration targets	2-4	Specialist/10 years
Q7	Simulate period of intensive survey and compare with observations and optimise rate constants to obtain best fit	5-15 2-6	Tech/5 years Grad/5 years
Q8	Simulate whole annual cycle and compare with sparse data and make further adjustment if necessary	5-10 1-2	Tech/5 years Grad/5 years
Q9	Carry out sensitivity tests on critical constants	5-10 1-2	Tech/5 years Grad/5 years
Q10	Prepare calibration report	5 5	Tech/2 years Grad/5 years
Q11	Predict design low flow year and analyse results	4/test year 2/test year	Tech/2 years Grad/5 years
Q12	Technical Management	10-15	Specialist/10 years

Note: 1D models will not simulate turbidity maximum caused by gravitational circulation in the deeper parts of many estuaries.

Table 12.5 - ESTIMATES OF STAFF TIME REQUIRED TO APPLY MULTI-LAYERED INTER-TIDAL MODELLING FOR DEEP NARROW PARTIALLY MIXED ESTUARIES

TIDAL FLOW AND SALINE INTRUSION (FS)

No.	Task	Estimate of Man-day input	Grade/experience using model (min years)
FS1	Collate and check cross-sectional data*	4-8 per 100 cross-section	Tech/5 years
FS2	Schematise UK estuary	2-3	Specialist/10 years
FS3	Input cross-sectional data to model	6-10 per 100 elements	Tech/10 years
FS4	Input sea boundary harmonic tidal level constants. Check predictions*	1	Tech/10 years or Grad/2 years
FS5	Collate, check and input daily fluvial inflows*	2-4 per 1 year hydrograph	Tech/10 years Grad/2 years
FS6	Collate, check and input tidal level, velocity and salinity calibration data*	3-5 per record (Total 10-40)**	Tech/10 years Grad/2 years
FS7	Estimate bed roughness type and specify calibration accuracy targets. Select appropriate turbulence closure model	1-2	Specialist/15 years
FS8	Set empirical constants in equation defining longitudinal dispersion within layers	1	Specialist/15 years
FS9	Simulate period of intensive inter-tidal survey and compare with tidal level and tidal velocity and salinity profile data and optimise bed roughness. Check stratification and gravitational circulation is correctly reproduced. Make fine adjustments to coefficients	3-5 per test (Total 15-40)***	Grad/5 years or Tech/15 years
FS10	Simulate annual cycle and compare with long term salinity observations. Fine tune longitudinal mixing and turbulence closure model	3-6 per test. (Total 10-30)***	Tech/15 years Grad/5 years
FS11	Validate model on independent set of data	3-6 per test	Tech/10 years
FS12	Carry out sensitivity tests on calibration constants for low flows. Estimate error bar on position of 0.5ppt and 5ppt salinity fronts	5-10	Grad/5 years
FS13	Prepare calibration report	4-8	Grad/5 years
FS14	Predict design low flow year and analyse results	2/test year 1/test year	Tech 2 years Grad 5 years
FS15	Technical Management	5-10	Specialist 15 years

* excludes measurement or purchase of data

** most time needed if data not recent

*** most time needed if degree of saline stratification varies widely with tidal range and river flow or field data is not simultaneous

Table 12.6 - ESTIMATES OF STAFF TIME REQUIRED TO APPLY MULTI-LAYER INTER-TIDAL MODELLING FOR DEEP NARROW PARTIALLY MIXED ESTUARIES

WATER QUALITY INCLUDING SUSPENDED SOLIDS (Q) (requires flow model)

No.	Task	Estimate of Man-day input	Grade/experience using model (min years)
Q1	Collate daily fluvial pollution loading data	3-6 1	Tech/5 years Grad/5 years
Q2	Determine diurnal, weekly and seasons variations in effluent flows and pollution loads	2-10 1-2	Tech/5 years Grad/5 years
Q3	Collate sea boundary data	1-3 0.5	Tech/5 years Grad/5 years
Q4	Collate calibration data	7-15* 2-3	Tech/5 years Grad/5 years
Q5	Input loading, sea boundary and calibration data	5-10* 1-2	Tech/2 years Grad/5 years
Q6	Review bio-chemical processes and set rate constants and specify calibration targets	2-4	Specialist/10 years
Q7	Simulate period of intensive survey and compare with observations and optimise rate constants to obtain best fit	10-25* 4-12	Tech/5 years Grad/5 years
Q8	Simulate summer season and compare with sparse data and make further adjustment if necessary	7-15* 2-3	Tech/5 years Grad/5 years
Q9	Carry out sensitivity tests on critical constants	7-15 2-3	Tech/5 years Grad/5 years
Q10	Prepare calibration report	4-8 4-8	Tech/2 years Grad/5 years
Q11	Predict design low flow year and analyse results	4/test year 2/test year	Tech/2 years Grad/5 years
Q12	Technical Management	10-20*	Specialist/10 years

Note: Most time needed if pollution loads or boundary conditions are poorly defined or results are sensitive to algal kinetics.

Table 12.7 - ESTIMATES OF ADDITIONAL STAFF TIME REQUIRED TO APPLY MULTI-LAYER INTER-TIDAL MODELLING TO DEEP NARROW PARTIALLY MIXED ESTUARIES

TIDAL FLOW AND SALINE INTRUSION WITH A TIDAL BARRAGE (refined model)

No.	Task	Estimate of Man-day input	Grade/experience using model (min years)
B1	Analyse discharge characteristics and operating procedure of barrage, including automatic control	2-4* 6-10 6-10	Specialist/15 years Grad/5 years Tech/10 years
B2	Write bespoke barrage operating sub-routine	1-3 5-10	Specialist/15 years Grad/5 years
B3	Modify multi layer model to accomodate exchange flows and pollution fluxes	1-3 5-10	Specialist/15 years Grad/5 years
B4	Test model over full range of barrage operations as regards flows, saline stratification and pollution transport	1 per test 2 per test (Total 10-20)	Grad/5 years Tech/10 years
B5	Technical management	5-10	Specialist/15 years

Note: Most time needed with compound moving structures.

Table 12.8 - ESTIMATES OF STAFF TIME REQUIRED TO ESTABLISH A FUNCTIONAL RELATIONSHIP BETWEEN AN ESTUARINE PHENOMENA AND RIVER FLOW PREDICTIVE AND OTHER VARIABLES

No.	Task	Estimate of Man-day input	Grade/experience using model (min years)
F1	Assess estuarine phenomena and define processes linking dependent variables. Collate field data	3-6**	Specialist/15 years
F2	Extract and collate time series of dependant variables	10-20* 2	Tech/2 years Grad/5 years
F3	Apply suitable multiple cross correlation	5-10	Grad/5 years
F4	Test for sensitivity to phase lag and time integration effects	2 5-10**	Specialist/15 years Grad/5 years
F5	Reassess original hypothese and check for spurious correlations and missing processes	3-6*	Specialist/15 years
F6	Test models capability to predict independent time series	2-4	Tech/2 years
F7	Test for sensitivity and define accuracy of model and limits of application	2	Specialist/15 years
F8	Apply model to predict a scenario	0.5-1 per test series	Tech/2 years
F9	Technical Management	3-6**	Specialist/15 years

* Most time needed to analyse bathmetric charts.

** Most time needed in case of complex correlations.

Table 12.9 - ESTIMATES OF STAFF TIME REQUIRED TO EXECUTE LOW FLOW SURVEYS IN UK ESTUARIES

Survey type	Methodology	Equipment	Tasks	Estimated man-day input	Staff grade and experience
Long term monitoring of salinity variations in an estuary (continuous or during droughts)	Deployment of salinity recording and logging instrumentation at a fixed position over an extended period. To measure temporal variations in salinity at a given site.	Battery powered multi-point monitoring system with integral data logging and at least six separate measurement channels.	installation presentation	4-10 1/ 2 (monthly) 0.5-1 (monthly) Savings could by expected with multiple sites	Tech specialist 5 years
Rapid HW slack surveys (regular or ad hoc during droughts)	Rapid drop profiles through water column for insitu measurement of salinity, temperature, dissolved oxygen and turbidity to measure the maximum landward movement of salt at HW slack spring tides	Fast survey vessel. Multi-parameter sonde or sensor with integral data logging.	lisation [Savings expected by using local craft] presentation per survey	3 5 1 1 1 1	Hydrographic surveyor 10 yrs Technician 5 yrs Hydrographic surveyor 10 yrs Technician 5 yrs Hydrographic surveyor 10 yrs Technician 5 yrs
Detailed surveys of water quality in an estuary at 5-10 fixed stations (For calibration purposes)	In site measurement of current year and direction, salinity, temperature, dissolved oxygen and turbidity at 30 minute intervals through tide cycle. Collection of 1.5 water samples for laboratory determination of suspended solids, BOD content at HW, LW and mid tide times. To measure inter-tidal variations at a single vertical.	Suitable survey vessel. Multi-parameter sonde or sensor array and current meter or ADCP, both with integral data logging. Water samplers, water sample containers, suitable sample handling facilities and rapid transport to accredited laboratory.	lisation presentation (1 station day)	3/station 3/station 5/station 1/station 1/station 1/station 1/station 6-10/station 2/station	Hydrographic surveyor 10 yrs Skipper 5 yrs Technician 5 yrs Hydrographic surveyor 10 yrs Skipper 5 yrs Technician 5 yrs Hydrographic surveyor 10 yrs Technician 5 yrs Specialist 10 yrs

Notes: Position fixing assumed to be based on landmarks rather than differential GPS.
Boat and equipment hire costs not estimated as they vary.
Sample transport and analysis costs not estimated.
Survey of effluent inflows and loads not included.

Table 12.10 - EXAMPLE OF RANGE OF MODELLING AND SURVEY COSTS

COMPONENT	Timescale (months)	Modelling cost (£)	Survey cost (£)
Desk study for first estimate conclusions	1	10,000	
1-D sediment transport model	3	10 - 30,000	
Use above model as basis of morphological model	2	15,000	
Fieldwork for all above modelling work	2		10 - 75,000

Notes: From West (1995), for tidal Trent
All costs from late 1995.

Table 12.11 - APPROXIMATE STAFF RATES

Staff member	Cost (£/day)
Specialist	
15 years experience	450
10 years experience	400
Graduate/MSc	
5 years experience	275
2 years experience	225
Technician	
10 years experience	225
5 years experience	175
2 years experience	125

Note: All rates from late 1997.

13. WORKED EXAMPLES

Two examples of flow need derivation are included in this report:

- An example of matrix analysis developed for the River Stour, based on work carried out for the Broakoak Reservoir study (WS Atkins, 1991).
- An example of statistical correlation of saline intrusion and freshwater flow in the Severn Estuary. This is based on an Internal Report for Severn Trent Water Authority, written by Roger Wade in 1983.

13.1 Matrix analysis

13.1.1 Introduction

During the early 1990's, extensive studies were carried out into the construction of a new reservoir north of Canterbury, on a tributary of the Kentish Stour. One part of this study was an impact matrix analysis using a method simpler, but similar, to that proposed in this report.

The following example has been adapted from the matrix presented in the report. Where possible, the example has followed the steps in the proposed methodology. Those steps were not used in the Broakoak study have been omitted from the example.

13.1.2 Initial reviews

Review existing reports and check data availability

The proposal to build a reservoir at Broad Oak has been considered on a number of occasions. The 1991 study referred extensively to the earlier reports, but placed greater emphasis on protecting the downstream environment and downstream users of the river.

Classify estuary type and select estuary reaches

The estuary reaches were selected as shown diagrammatically in Figure 13.1, below. They represent the main areas of interest on the river.

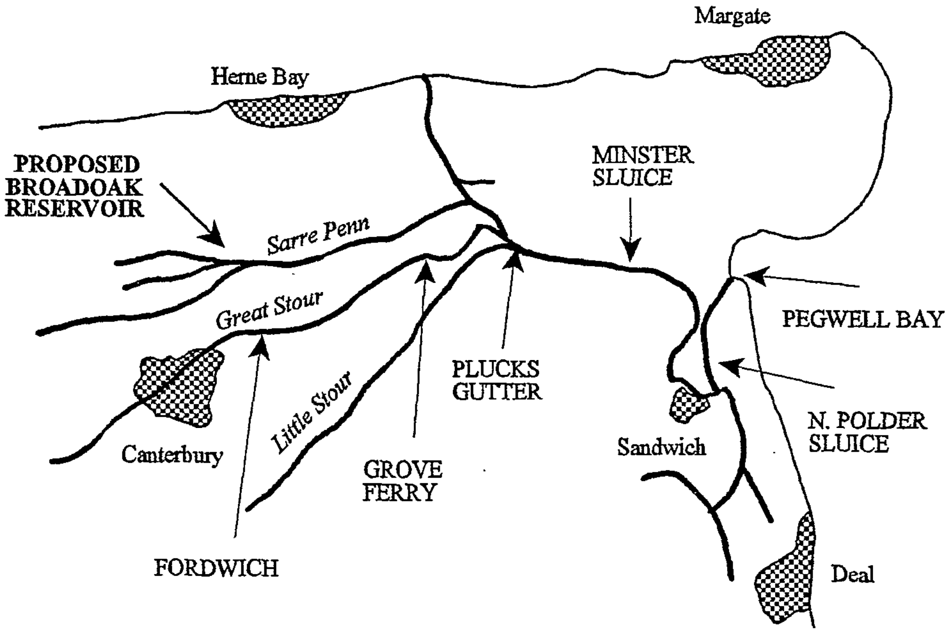

Figure 13.1 - RIVER STOUR REACHES

13.1.3 Matrix analysis

Determine external review, complete data and impact matrices

Comprehensive external consultation was carried out during the project, although external bodies did not participate in the matrix risk assessment. A data matrix was not completed. The impact matrix was drawn up as below. It should be noted that slightly different uses and aspects were used to categorise the matrix, and that summer and winter conditions have been included in a single matrix.

For low impact uses and processes, use simple analysis methods

Not considered in this study.

If appropriate, carry out preliminary analysis

No preliminary analysis was carried out.

Use/aspect	Fordwich Intake to tidal limit		Grove Ferry reach from Fordwich		Plucks Gutter from Grove Ferry		Minster Sluice from Plucks Gutter		N. Polder Sluice from M Sluice		Pegwell Bay from N. Polder		Comments
	S	W	S	W	S	W	S	W	S	W	S	W	
River character	5	4	4	3	3	3	3	3	3	3	3	3	Water supply for urban area
River flow regime	5	5	4	4	4	4	3	2	3	3	3	3	
Water use	5	5	5	4	5	4	4	3	4	4	3	3	Irrigation, water supply, cooling water
River water quality	5	5	5	5	4	3	3	2	2	3	4	4	Effluent, quality standards
River plant communities	5	3	4	3	3	2	2	1	1	1	1	1	
Invertebrate communities	5	3	4	3	3	2	2	1	1	1	1	1	
River sediment characteristics	5	5	3	3	3	2	3	2	4	5	4	5	Siltation, scour
Fish communities	5	5	4	3	3	3	2	1	1	1	1	1	
Salmonid migration	4	5	4	4	3	3	2	2	1	2	1	3	
Angling	5	5	4	3	3	2	1	1	1	1	1	1	
NNR/SSSI	1	1	4	4	1	1	1	1	1	1	1	1	Nature reserves
Navigation and boating	3	3	3	3	3	3	2	2	1	1	1	1	Level dependant
Amenity	3	3	3	3	2	2	1	1	1	1	1	1	

Key:

No impact		1
Low impact		2
Medium impact		3
High impact		4
Extreme impact		5
Summer	S	
Winter		W

Figure 13.2 : River Stour - Impact assessment matrix

Likeli-hood	Use/aspect	Fordwich Intake to tidal limit		Grove Ferry reach from Fordwich		Plucks Gutter from Grove Ferry		Minster Sluice from Plucks Gutter		N. Polder Sluice from M Sluice		Pegwell Bay from N. Polder		Average Risk
		s	w	s	w	s	w	s	w	s	w	s	w	
2	River character	10	8	8	6	6	6	6	6	6	6	6	6	7
2	River flow regime	10	10	8	8	8	8	6	4	6	6	6	6	7
4	Water use	20	20	20	16	20	16	16	12	16	16	16	16	17
4	River water quality	20	20	20	20	16	6	12	8	8	12	16	16	15
3	River plant communities	15	9	12	9	9	6	6	3	3	3	3	3	7
3	Invertebrate communities	15	9	12	9	9	6	6	3	3	3	3	3	7
2	River sediment characteristics	10	10	3	6	6	4	6	4	8	10	8	10	7
4	Fish communities	20	20	16	12	12	12	8	4	4	4	4	4	10
3	Salmonid migration	12	15	12	12	9	9	6	6	3	6	3	9	9
3	Angling	15	15	12	9	9	6	3	3	3	3	3	3	7
4	NNR/SSSI	4	4	12	12	4	4	4	4	4	4	4	4	5
3	Navigation and boating	9	9	9	9	9	9	6	6	3	3	3	3	7
2	Amenity	6	6	6	6	6	6	3	3	3	3	3	3	5
RISK per REACH		13	12	12	10	9	8	7	5	5	6	6	7	

Key: Summer S
Winter W

Notes: Risk by reach given by LIKELIHOOD x REACH IMPACT from Figure 13.2

Figure 13.3 : River Stour - Risk assessment matrix

Review design standards and set out study standards

The proposed design standards for the study were to take the form of a seasonally varying flow. The standards imposed by this flow took account of the environmental and user interests downstream of the intake.

Complete risk matrix, seasonal variations and risk assessment

The completed risk matrix, together with seasonal variations is shown in Figure 13.3.

13.1.4 Model studies

For each use and reach, select appropriate analysis method
Rationalise and optimise model design

Following the risk analysis, the modelling and field studies were proposed as shown in Table 13.1, below.

Cost modelling studies
Consider joint funding of modelling, or simpler models
Carry out or manage modelling studies

Carried out at study stage only.

13.1.5 Set MRF

Analyse model results and set MRF
Post-project appraisal

Not carried out for operations, as scheme has not gone ahead.

Interest	Study	Outside Consultations	Fieldwork	Modelling
Water use	Marsh feeding requirements (current and future, with climate change) Richborough Power Station	Farmers Powergen	Survey of marshes -	Water levels and quality with tidal influence Water quality
Fish communities	Water quality and flow to maintain fisheries	Angling bodies	Undertaken	Water quality
River water quality	Effluent dilution and maintenance of WQOs - class 2 NWC and A	-	NRA routine sampling + model requirements	Water quality
Salmonid migration	Details of incidence and requirements for migration of salmonids	-	Feasibility of installing fish counter upstream of Canterbury	Seasonal flow and quality requirements
Angling	Water level requirements	Angling bodies	-	Water levels
Invertebrate communities	Consider sensitivity to water quality, flows, depths	-	-	Water quality, levels and flows
River sediment	Establish volume and location of sediment deposition and scour	-	As required by model	Tidal and river flows & sediment transport
River plant communities	Consider sensitivity to water quality and depth	-	-	Water quality and levels
River character and flow regime	Note dependancy of river nature on flows	-	River quality sketch	Water levels
Navigation and recreation	Effect on duration of boating hours	Boatowners Boating Co's	-	Water levels
NNR/SSSI	Importance of frequency of flooding and water quality	NCC, KTNC	Survey of bankside connections	Frequency of fluvial and tidal flooding; water quality

Table 13.1 - PROPOSED MODELLING STUDIES AND FIELDWORK

13.2 Statistical analysis - Saline Intrusion in the Severn Estuary

13.2.1 Introduction

Background

The extent of saline intrusion in the Severn Estuary is of concern to water abstractors near the tidal limit and has also been of interest recently for estimating the agricultural benefits of a proposal to position a tidal exclusion barrier in the upper estuary.

The abstraction of water from the Severn at Gloucester Docks to the Gloucester-Sharpness Canal (See Figure. 13.4) provides a major source of water for Bristol. During the drought of 1976 a peak chloride concentration of 880mg/l was recorded at Gloucester Docks and on the same spring tide the chloride concentration exceeded 150 mg/l over the whole tidal cycle, compared with a mean chloride level in the region of 60 mg/l. Abstraction of brackish water to the canal resulted in the WHO. recommended chloride concentration for water in supply (200mg/l) being exceeded on two samples at the Purton Waterworks intake. The ability to predict saline intrusion would thus be of direct use in the day to day control of pumping at Gloucester Docks, to prevent estuary salt entering the canal.

During 1976 the flow in the River Severn at Gloucester fell below 700 Ml/d compared with a normal summer flow in excess of 2,000 Ml/d. As the summer flow in the river is supported by releases from reservoirs in Mid Wales, to compensate for licensed abstractions, the influence of river flow on the saline intrusion may b e relevant to the cost effective use of such storage facilities. There are several reported examples of the setting of minimum river flows to limit saline intrusion. In the United Kingdom residual flows have been set to protect abstractions for industrial purposes (River Medway), for domestic supply (River Ancholme) and for irrigation (Kent River Stour).

Predictive Methods

Most predictions of salinity distributions within estuaries are made from theoretically derived mathematical models. The derived relationships for the saline intrusion and concluded that, for well mixed estuaries, the intrusion would be inversely proportional to flow rate, while for partially mixed estuaries the relationship should be an inverse proportionality to the square of flow.

The one dimensional dynamic simulation model (Hydrobase) developed by the Institute of Marine Environmental Research 1975 (IMER) to predict salinity gradients along the Severn Estuary produces results in agreement with observations but to a relatively course distance scale, which is inappropriate to the accurate prediction of saline intrusion and was not intended for this purpose. The model average salinity over 5km sections and also incorporates a simplified boundary condition at Gloucester, which is likely to lead to errors at this end of the estuary.

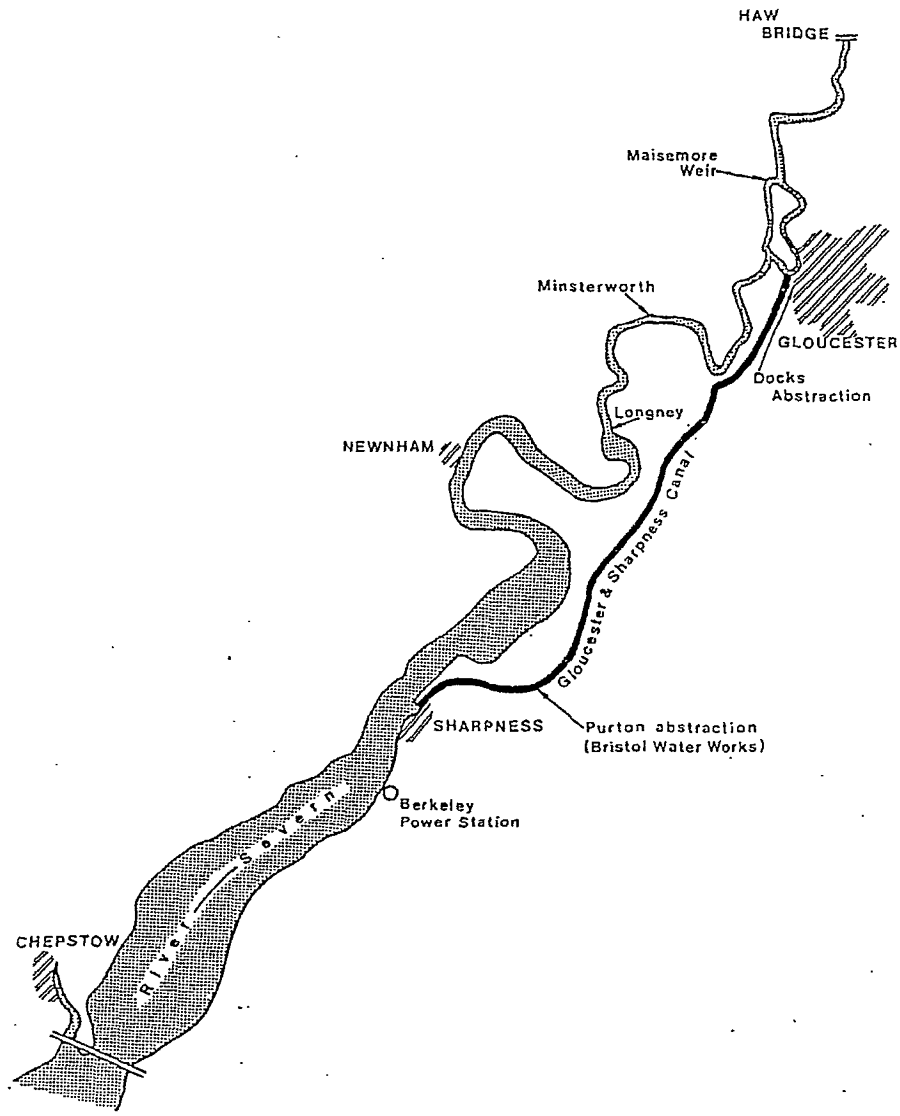

Figure 13.4 - THE UPPER SEVERN ESTUARY AND TIDAL RIVER

An alternative approach is the statistical analysis of actual salinity variations with flow and tidal parameters. An example of this approach is that of Dyer, who determined a linear regression equation for salinity against river discharge and tidal amplitude for a station on Southampton Water. The river discharge used was the mean value over the Severn days prior to the survey and the salinity values were averaged with depth throughout the tidal cycle.

In the present study, a statistical approach has been used to analyse the recorded position of the salt water/fresh water boundary at its maximum landward point under varying river flows and tidal ranges.

13.2.2 Area of Study

Data for this study has been obtained from surveys on which the maximum saline intrusion was observed between Haw Bridge and Longney (see Figure 13.4) This section of the tidal river is relatively uniform in width and depth. At Longney Sand the configuration of the river channel changes significantly, limiting the usefulness of data on intrusions below Longney. At Gloucester the river divides into two dissimilar channels, each with a weir, for about 3km. The additional energy dissipation through this system may be expected to affect the tidal inflow above Gloucester and give actual saline intrusions less than those predicted. The use of saline intrusion data from above Gloucester in establishing correlations is discussed further in the results section.

13.2.3 Data

Flow Data

The most accurate estimate of fresh water flow to the Estuary was thought to be obtained by summing the measured flows at the Severn-Trent Water Authority gauging stations at Haw Bridge (River Severn), Slate Mill (River Chelt) and Wedderburn (River Leadon), with a allowance for other smaller tributaries and for the pumped abstraction at Gloucester.

For predictive purposes, however, a single flow measurement or estimate is obviously much simpler and correlations have been derived using the River Severn Flow gauged at Haw Bridge and Saxons Lode. The latter point is upstream of the River Avon, but is less affected by tidally induced flow reversal and has the advantage of recorder which can be interrogated by telephone.

Most of the surveys included in this study were undertaken between 09:00 nd 12:00 hours on the day of the survey which corresponds to the morning local high slack water in the upper estuary. As the river flow day is taken from 09:00 to 09:00 hours the most appropriate one day flow figure for use in correlation determinations was thought to be that of the day previous to the survey. This decision was supported by the fact that the flow measuring points used are some distance upstream of the intrusion area. Two further measure of flow have been used in calculations which were thought may include some measure of longer term flow fluctuations. A 3-day flow was calculated from the mean of the flows on the day of the survey and the two previous days and 7 day flow from the mean of the flow on the day of the survey and the six pervious days.

Tidal Data

Recording tidal gauges exist at Minsterworth and Berkeley Nuclear Power Station intake. The Minsterworth gauge records the entire tidal cycle while Berkeley goes off the scale at low water and thus give only high water levels.

Published Tide Tables (Bristol Channel Tide Tables, J.W. Arrowsmith Ltd., Wineterstoke Road, Bristol) include predictions for Sharpness Dock, some 3km upstream of Berkeley, and to facilitate comparison of observed and predicted heights the data recorded at Berkeley had been corrected to Sharpness.

For surveys included in this study the low water levels predicted for Sharpness are all within 0.1m of the local datum so that Sharpness High Water readings are very close to the tidal range, which has physical significance as a measure of the potential energy of the tidal oscillation.

Tidal Cycle Effects

There is evidence from the Minsterworth tidal record that an accumulation of water can occur in the upper estuary as the tidal range increases. This might be expected to affect the saline intrusion and, to study this, surveys were grouped according to the temporal relationship to the peak tide of the cycle.

Measurement of Saline Intrusion

Surface water samples were taken by boat from mid-stream sites at local high slack water. This condition occurs some 15-30 minutes after local high water and 'moves' up river at a rate which can be followed by boat. Samples so taken corresponded to the maximum saline intrusion.

Conductivity and Temperature were measured on site and samples were collected for laboratory analysis of chloride. Surveys commenced at a site where a conductivity reading correspnd9ing to at least 1,000 mg/l of chloride was measured. Samples were then taken at 0.5-1.0 Km intervals until a steady fresh water conductivity level was reached (normally corresponding to a chloride concentration of 50-120 mg/l). The position corresponding to a chloride level 100 mg/l above fresh water was then dete3rmined by graphical interpolation and the distance of this point in kilometres below Maisemore Weir was taken as the 'Saline Intrusion' for the survey.

13.2.4 Results

33 surveys were undertaken between 1976 and 1980 which gave saline intrusions above Longney Sands (17.5 km below Maisemore weir). The observed tidal heights at Sharpness ranged from 7.33 to 9.97 m and the flow to the estuary on day prior to the survey ranged from 620 to 5620 Ml/d. The maximum saline intrusion was 7.0km above Maisemore Weir and was the only intrusion to reach above the weir, occurring towards the end of the drought in 1976. The point has a marked effect on the statistical response of saline intrusion (I) to tidal height (H) and river flow (F) and figures considerably in the discussion below.

Figure 13.5 - SALINE INTRUSION v. OBSERVED TIDAL HEIGHT

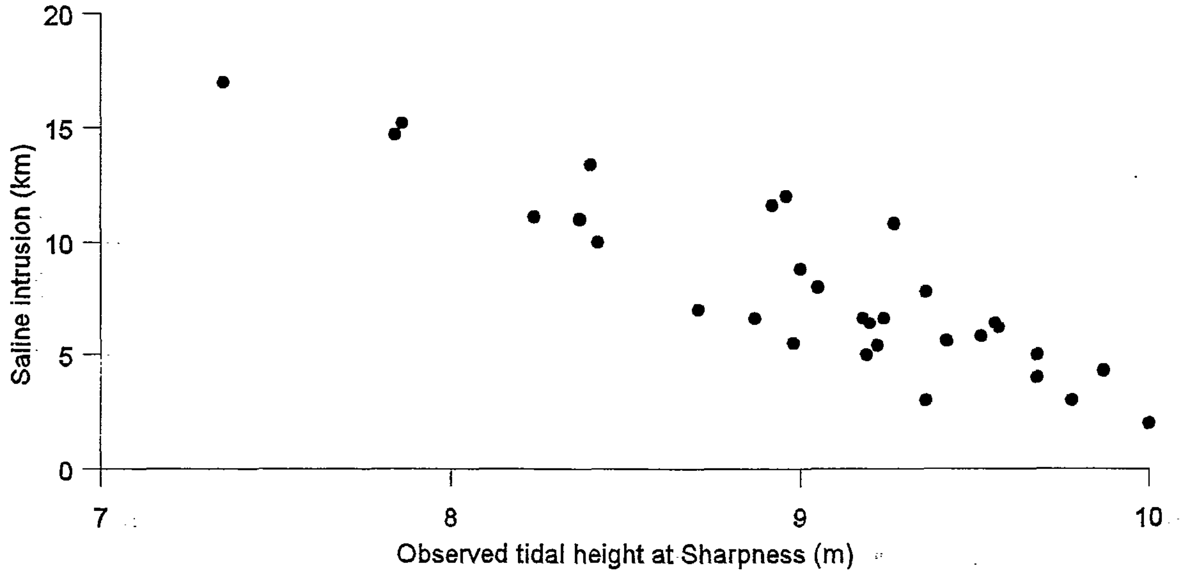

Figure 13.6 - RESIDUALS AFTER FITTING HEIGHT AND FLOW

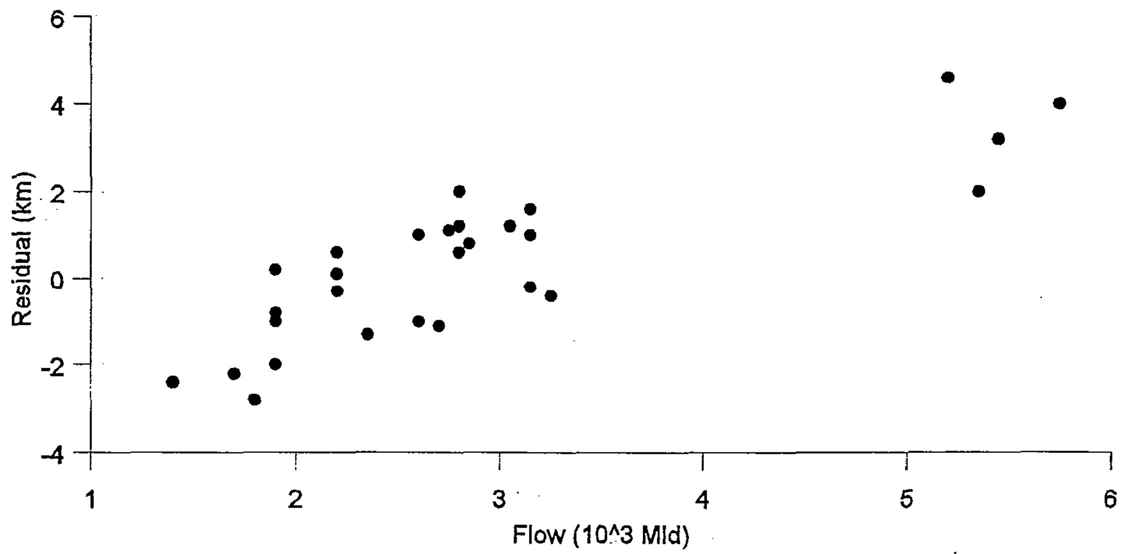

Figure 13.5 shows the relationship between I and H_0 (observed tidal height at Sharpness), and it can be seen that the relationship is a strong one particularly if I = 7.0 is omitted. The result of plotting the residual after fitting H_0 with F_3 (previous day's flow at Hawbridge) is shown in Figure 13.6. The inclusion of I = - 7.0 suggests a non-linear relationship with flow, and an inverse flow term would seem intuitively consistent. Nevertheless a simple linear term might suffice if the value were excluded, given the limited range of flows considered.

Table 13.2 shows the residual standard deviations (rsd's) of various combinations of flow (F) and tidal height (H) fitted to saline intrusion (I) by regression analysis; figures in brackets are the corresponding rsd's with I = -7.0 excluded.

Table 13.2 - FLOW AND TIDAL HEIGHT FITTED TO INTRUSION

	F_1	F_2	F_3	F_1^{-1}	F_2^{-1}	F_3^{-1}	-
H (obs.)	1.838 (1.007)	1.803 (0.984)	1.840 (0.996)	1.095 (1.110)	0.946 (0.963)	1.057 (1.071)	2.723 (1.733)
H (pred.)	2.288 (1.545)	2.164 (1.437)	2.259 (1.510)	1.657 (1.672)	1.435 (1.454)	1.607 (1.603)	2.952 (1.975)
-	4.024 (3.510)	3.932 (3.454)	3.984 (3.479)	3.713 (3.681)	3.550 (2.562)	3.665 (3.632)	4.450 (3.672)

The suffices 1, 2 and 3 refer to Lower Parting, Saxon's Lode and Haw Bridge respectively. Similar rsd's are obtained for the flows are replaced by 3-day flows (i.e. day of survey and two previous days). Use of Minsterworth tidal range data in place of Sharpness height at Sharpness provided a consistently better fit than predicted height as might be anticipated; there was little to choose between the three measuring stations, though the Saxon's Lode values were marginally better in all cases. The particularly interesting feature of the above table is how markedly the rsd of the equations using direct flow is affected by censoring the data compared with the inverse flow equations. The major reason for this is that with the value of I = -7.0 excluded, the range of flows is restricted enough for the inverse function to be adequately approximated by a simple linear function. However, given that our particularly interest is with intrusions approaching or passing beyond the weir it seems more sensible to use all the data. The equations for observed tidal height and the three measures of flow as defined earlier as shown below:

(1) $I = 64.0 - 5.78\ H\ (obs) - 10.01\ F_1^{-1}$; rsd = 1.10, $R^2 = 0.943$

(2) $I = 63.9 - 5.58\ H\ (obs) - 11.49\ F_2^{-1}$; rsd = 0.95, $R^2 = 0.958$

(3) $I = 64.4 - 5.72\ H\ (obs) - 12.99\ F_2^{-1}$; rsd = 1.06, $R^2 = 0.947$

No evidence was found that the temporal relationship of a particular survey to the peak tide of the cycle had any effect on saline intrusion.

Figure 13.7 shows the required combinations of flow and tidal height to give intrusions of varying degrees between -10.0 to 10.0km as calculated from equation 1.

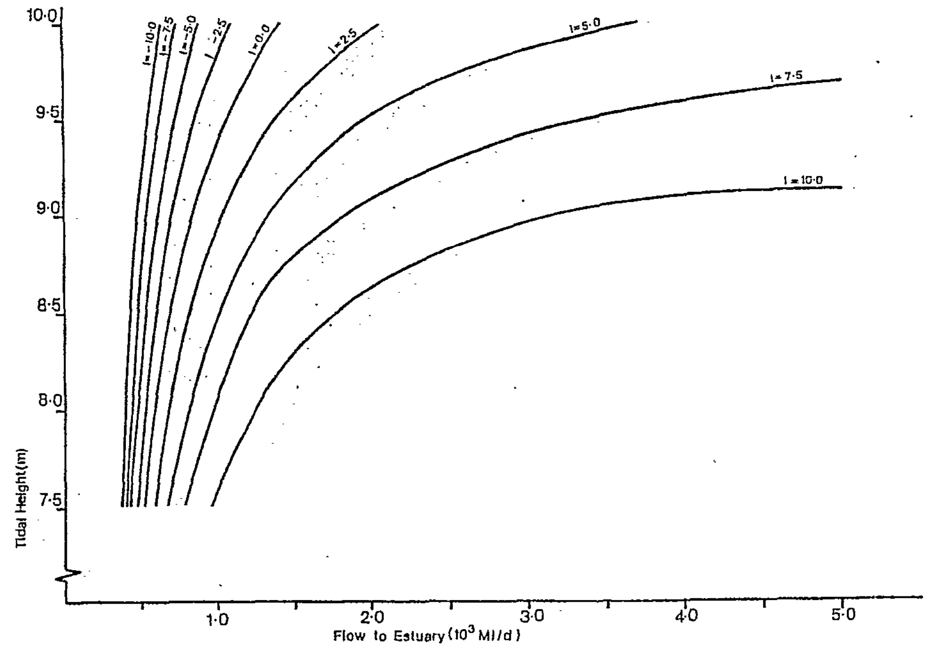

Figure 13.7 - INTRUSION FOR COMBINATIONS OF FLOW AND TIDE

13.2.5 Discussion

Good correlations between observed tidal heights, river flows and saline intrusions have been established such that the position of a salt water-freshwater boundary can be described to within 2km (2 standard deviations) with a 95% confidence. For predictive use the prevailing river flow at Saxons Lode (without any allowance for inflows and abstraction below this point) does not introduce any further error, but use of published tide table height at sharpness may lessen the accuracy. Over the period of our study the mean discrepancy between observed and predicted tidal height at Sharpness was found to be 0.15m with a maximum discrepancy of 0.45m. These correspond to a mean error of 0.82km and a maximum error or 2.5km in predicted intrusion. For short-term maximum error or 2.5km in predicted intrusion. For short-term prediction it may sometime be possible to reduce this error by incorporating tidal surge predictions supplied by the Meterological Office.

13.2.6 Application

The main management requirement of the models produced is to predict occasions when brackish water is likely to penetrate to the water abstraction point at Gloucester Docks (an equivalent distance below Maisemore Weir of 1.3km). Allowing for a possible error of up to 3-4km an arrangement has been established whereby the intake is warned of predicted saline intrusion of 5km and 10km. These values are calculated from Equation 2 using prevailing Saxons Lode river flows and predicted heights at Sharpness. On four occasions during 1981 when predictions of 10km or less were made surveys were undertaken to determine the actual intrusion position. The observed and predicted intrusion lengths together with river flows and tidal heights are listed in Table 13.3.

Table 13.3 - OBSERVED AND PREDICTED INTRUSION LENGTHS

Date	Predicted Tidal Height (m)	Observed Tidal Height (m)	River Flow Ml/d	Predicted Intrusion km	Observed Instruction km
2/7/81	8.9	8.91	2,350	9.3	8.5
19/8/81	8.8	8.76	1,610	7.6	6.3
14/9/81	8.8	8.81	1,990	9.0	9.2
16/9/81	9.3	9.39	2,130	6.6	5.6

13.2.7 Predicted intrusion from historic data

A record of tidal height at Avonmouth exists from 1931 to the present and as Sharpness tidal heights are determined directly from those at Avonmouth, it is straightforward to transform the prediction equation for intrusion. Measured flows of the River Severn at Saxon's Lode and Haw Bridge have been made since 1970, but a simulated record of flows back to 1930 was created by Manley (1977) using the model HYSIM. The two records have been combined for the years 1931 to 1980 and used to predict the expected saline intrusion over that period. The prediction equations for the two river sites are:-

(4) Haw Bridge: $I = 92.73 - 5.938\ H(obs) - 13.55\ F_{1_1}^{-1}$ rsd = 1.25

(5) Saxon's Lode: $I = 91.81 - 5.814\ H\ (obs) - 12.04\ F_1$ rsd = 1.10

Where F_1 is the previous day's flow in '000 Ml/d and H(obs) is observed tidal height at Avonmouth. The Saxon's Lode equation is preferred because it exhibits a lower residual s.d. than that for Haw Bridge. The predicted number of intrusions above Gloucester Docks for the years 1931 to 1980 is shown month by month in Table 13.4; also included are the number of intrusions which came within 5km of the docks. Over the 50-year period the number of tides was just over 35,000 so the total number of 117 and 969 for the two categories correspond to 0.3% and 2.8% respectively. The majority of intrusions occur in the months August, September and October reflecting the co-incidence of high spring tides with summer low flows. If equation 4 (Haw Bridge flows) is used then the number of predicted intrusions above Gloucester is only 65 though the figure of 1009 for intrusions within 5 km of Gloucester is similar to that above.

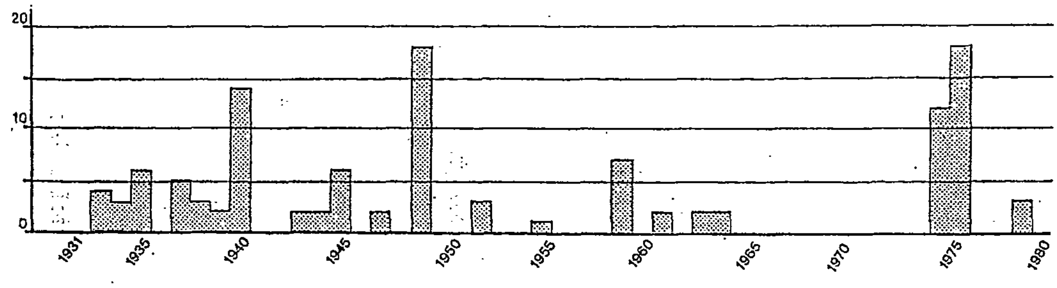

Figure 13.8 - PREDICTED INTRUSIONS ABOVE GLOUCESTER DOCKS

The annual distribution of intrusions above Gloucester is shown in Figure 13.8. The first feature of the figure that is worthy of comment is that a predicted intrusion occurs in only 21 of the 50 years, and then 53% of all intrusions occurred in only four years: 1940, 1949, 1975 and 1976. For the rest of the most obvious feature is the dearth of intrusions between 1949 and 1975 with the possible exception of 1959. Table 13.4 shows the predicted number of intrusions (i) above, and (ii) within 5km of Gloucester Docks for the years 1931 to 1980, tabulated by month of the year.

Table 13.4 - PREDICTED INTRUSIONS TO GLOUCESTER DOCKS, BY MONTH

	JAN	FEB	MAR	APR	MAY	JUN	
Above Glos.	0	0	1	0	1	1	
within 5km	4	20	57	30	22	39	
	JUL	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**	**TOTAL**
Above Glos.	5	28	55	24	2	0	117
within 5km	93	207	278	278	33	1	969

13.2.8 Implications for Required River Flow at Gloucester

Flow at Gloucester

Although the number of occasions where saline intrusion would appear to reach the Gloucester Docks is small it is nevertheless instructive to calculate the river flow required to prevent these intrusions. During the period of our study the highest predicted tide at Sharpness was 10.4m and if this figure is inserted into the derived equations together with other relevant parameters it is found that a flow of 2,500 Ml/d is required at Saxons Lode (76%idle) and 3,600 Ml/d at Haw Bridge (69%ile) to prevent saline intrusion under all conditions.

A more practical calculation may be made by including storage potential in the canal and optimum pumping at Gloucester in the equation. Optimum storage in the canal at present obviates the need for pumping over 5 consecutive tides. The critical tidal height then becomes that of a tide immediately before or after the 5 highest consecutive spring tides. For the 10.4m tide considered above these tides have heights at 9.7m.

Adequate pumping to the canal is thought to be achieved at present during 3 hours of each tide so the river needs to be free of salt over the last 1/4 of a tidal cycle. Assuming a tidal excursion of 8km and allowing a margin of error of 2 standard deviations an intrusion of -2.7km has been used in this calculation together with the tidal height of 9.7m. This gives flow figures of 920Ml/d at Saxons Lode (99.6%ile), 1.120Ml/d at Hawbridge (99.5%ile) and 945Ml/d as a flow to the estuary. (The discrepancy between the last two figures may be due to the abstraction at Gloucester itself).

It may be concluded from the above figures that a correct combination of pumping and storage should be sufficient to protect the Gloucester intake under present flow conditions in the river.

Theoretical Considerations

The inverse proportionality observed between intrusion and river flow is in agreement with Harleman and Ippen although attempts to relate our results with the actual equations derived by Harleman and Ippen have not proved successful.

As mentioned above, the equations derived using one day flows and 3 day mean flows have similar rsd's and are better than equations derived using a 7 day mean flow. Dyer has suggested that the best correlation with river flow is likely to equate to the residence time of water at the point of interest. In these surveys, however, we have not considered a single station and the residence time of water in the upper estuary is very dependent on the position of the springs - neaps cycle. It would seem inappropriate to draw much significance from our preferred use of one day flows and we present the relationship as the best empirical one.

The tidal height data from Sharpness, remote from the section of estuary above Longney gave a far better statistical correlation with intrusion than tidal range data from Minsterworth - a site within the zone of study. An explanation for this variation may be that tidal amplitude measurements at Minsterworth are dependent on river flow so that a more complicated relationship exists between intrusion, river flow and tidal range at this point.

13.2.9 Conclusions

Under most conditions observed the dominating influence on saline intrusion is tidal heights. The inverse correlation noted between intrusion and flow, however, suggests tat the effect of flow increases considerably under low flow conditions.

Equations formulated from observed intrusions, tidal heights and river flows can be used to predict the position of the salt water - freshwater boundary using prevailing river flow and predicted tidal height data. The predicted intrusion can be used to help control pumping at Gloucester to the Gloucester-Sharpness Canal and so prevent brackish water from entering

Bristol's water supply.

With the present flow in the Severn, saline intrusion to Gloucester is likely to be a rare event and control of pumping at Gloucester is adequate to protect water supplies. Any major new abstractions from the Severn, however, will have to be considered in the light of their implications on saline intrusion.

14. GLOSSARY OF TERMS

1-D hydrodynamic model	Computational model, usually used for rivers and narrow estuaries where all flow is assumed to be depth and width averaged
2-D hydrodynamic model	Computational model, usually used for open sea and wide estuaries where flow is assumed to be depth averaged only
3-D hydrodynamic model	Computational model, usually used for stratified estuaries where all flow is simulated in three dimensions
Automatic calibration	Calibration of a computational model by algorithms within the computer software to select optimum model parameters
Barrage	Structure built across a *river* or *estuary*, comprising a series of *gates* designed to regulate the upstream water level and pass flood water without an appreciable rise in the upstream water level
Baseline	The present condition of the *river* or *estuary*
Bathymetry	Topography of the bed of the sea, *estuary* or other water body
Beach	*Shore* of sand or shingle
Benthic	Referring to life in or on the sea bed
Biochemical Oxygen Demand (BOD)	Is the amount of dissolved oxygen consumed by chemical and microbiological action when a sample effluent is incubated for 5 days at 20°C
Calibration	The adjustment of parameters in a computational model to achieve agreement between the model and observed results
Catchment	The land which drains (normally naturally) to a given point on a *river* or drainage system
Catchment area	The area of a *catchment*
Channel	(1) Natural or man-made open passage designed to contain and convey water (2) The part of a body of water deep enough to be used for navigation through an area otherwise too shallow for navigation (3) The deepest part of a body of water through which the main volume of current passes
Coastal defence works	*Flood defence works* in a coastal area, designed to protect the land against *erosion*, encroachment or *flooding* by the sea (includes *coast protection works* and *sea defence works*)
Coastal lagoon	Shallow body of water close to the sea, usually with a shallow restricted connection to the sea
Coastal zone management	The process of ensuring that all the problems within a coastal zone relating to the environment are presented within a management framework which aims to promote the well-being of the coastal zone
Coast protection works	Works to protect land against *erosion* or encroachment by the sea

Combined sewerage overflow (CSO)	Overflow from municipal sewerage network that carries both foul sewage and stormwater runoff
Compensation water	Water released by law or custom from a *reservoir* or diversion structure to the downstream *watercourse* to meet the needs of downstream water users and satisfy environmental requirements
Computational model	*Statistical* or *deterministic* numerical simulation of reality, often in the form of computer software
Control structure	Device constructed across a *channel* or between water bodies or water passages, used to control the discharge passing the device and/or the water level on either side of the device
Deterministic model	A *computational model* that uses mathematical descriptions of physical laws and provesses
Ebb tide	That part of the *tide* in which the water level is falling; also the outflow of water from coastal bays and *estuaries* during the falling *tide*
Empirical model	Mathematical expression that is fitted to observed conditions without consideration of physical laws
Environmental Quality Objectives (EQOs)	Are categories relating to the use of particular stretches of water. For each use an associated series of quantitative standards applies
Environmental Quality Standards (EQSs)	Are concentrations of substances in the receiving water which must not be exceeded if the water is to be suitable for a particular purpose or use, or to achieve a certain level of protection for aquatic life
Estuary	The mouth of a *river* connected to the sea, where both *fluvial* and *tidal* effects occur and interact
Estuarine	Relating to an *estuary*
Fish kill	Localised high mortality of fish population caused by lack of oxygen or other pollution
Flood tide	That part of the *tide* in which the water level is rising; also the flow of water into coastal bays and *estuaries* during the rising *tide*
Freshwater flow need	The *residual flow* required in the *estuary* to maintain required uses and habitats
Flushing time	Is the time taken for the freshwater and associated contaminants to pass out to sea. It depends to a large extent on the size of estuary and the relative volume of freshwater discharging into it
Fluvial	Relating to a *river*
Geographical Information System (GIS)	Computerised database that can visualise and analyse data in a spacial or geographical form.
Heavy metals	A general term for those metals which are toxic when present in elevated concentrations. These include elements such as zinc, copper, lead, nickel and mercury, all of which are commonly used by industry
High water	Highest water level reached by each *flood tide* (see also *tides*)

Holistic catchment management	Recognition that many parameters within a *catchment* interact, and a management approach that takes an overview of these parameters
Hydrodynamic model	Mathematical model of water movement using the laws of motion
Hydrograph	Graph that shows the variation with time of level or discharge of water in a *river*, *channel* or other water body
Hydrography	The study of water bodies and their movements
Intertidal	Between the levels or lines of *low tide* and *high tide*
Intake	Structure through which water is drawn out of a *river* or other body of water
Invertebrate	Animals without a backbone
Low water	Lowest water level reached by each *ebb tide* (see also *tides*)
Minimum residual flow	The lowest *residual flow* allowed in a *river* or *estuary* to satisfy downstream users
Morphology	The study of change of form of a *river* or *estuary*
Neap tides	Tides on the two occasions per lunar month when the predicted range between successive *high water* and *low water* is least.
Outfall	Structure through which water is discharged into a *channel* or other body of water
Reach	A length of *channel* between defined boundaries
Residual flow	Flow remaining in a *river* or *estuary* after all users have taken water
Risk assessment	Decision making methodology that considers the likelihood of an event and the potential impact resulting from the event
River	Any natural *watercourse* (including modified watercourses) carrying perennial flow
Salinity	The extent to which salts are dissolved in water.
Salmonid	The family of migratory fish that include salmon and trout
Saltation	*Sediment transport* in which the particles remain close to the bed and are bounced along
Salting (or salt marsh)	Area of land adjacent to the sea or *estuary* which is periodically covered by saline water and usually supports vegetation
Sand dune	Hillock of wind-blown sand
Sea defence works	Works to prevent or alleviate *flooding* by the sea
Sea level rise	Increase in mean sea level due to global warming
Seawall	A shoreline structure, usually parallel to the coast, designed to prevent *flooding*, *erosion* and other damage caused by high sea levels or *waves*
Sediment	Fine material transported in a liquid that settles or tends to settle

Sediment transport	Movement of *sediment* under the action of *waves* and currents
Semi-diurnal tides	*Tides* with a period of about 12½ hours between two successive *high* or *low waters*
Sensitivity analysis	Variation of *computational model* parameters to assess impact of each parameter on model results
Shoal	Localised area of *siltation* or *sediment* deposition
Shore	Strip of land at the edge of the sea, *lake* or *coastal lagoon*
Siltation	Deposition of *sediment* onto the *river* or *estuary* bed
Spring tides	*Tides* on the two occasions per lunar month when the predicted range between successive *high water* and *low water* is greatest (see also *tides*)
Statistical model	A *computational model* that uses linear regression analysis to relate empirically the observed values of variables
Stratification	The separation of fresh and salt water into separate layers in an *estuary*
Tidal	Relating to the *tides*
Tidal barrier	Gated structure located in an *estuary* or coastal area that can be closed to prevent high *tides* and/or *surges* reaching inland areas vulnerable to *flooding*.
Tidal excursion	The distance travelled by a body of water between *low* and *high tides*
Tidal limit	Furthest upstream point on an *estuary* or *river* where there is a tangible *tidal* influence
Tidal prism	Volume of water contained in estuary or other tidal body of water between the levels of the *high* and *low tides*
Tidal range	Is the difference in height between *high* and *low tide*
Tidal sluice	Structure designed to prevent or control the ingress of seawater into a coastal *watercourse*, whilst allowing seawards flow to occur at times of *low water*
Tides	Periodic rising and falling of water resulting from the gravitational attraction of the moon, sun and other astronomical bodies, together with the effects of coastal aspect and *bathymetry*
Highest astronomical tide (HAT) and lowest astronomical tide (LAT)	Highest and lowest levels respectively which are predicted to occur under average meteorological conditions and any combination of astronomical conditions, excluding any *surges*
Mean high water springs (MHWS) and mean low water springs (MLWS)	Annual average, during year when average maximum declination of the moon is 23½°, of the elevations of two successive high waters and low waters respectively, at the times (approximately once per fortnight) when the tidal range is greatest
Tide-locked	Situation where flow into the sea is prevented by the level of the *tide*
Verification	Testing of a *calibrated computational model* with alternative data sets to confirm that the model is fit for purpose
Waterway	*Channel* used, previously used, or intended for the passage of vessels

Wave	(1) Short period oscillation of a water surface caused by the action of wind or by the passage of vessels (see *wake*) (2) Long period movement of water surface due to *tide*, *surge* or the passage of a flood *hydrograph*
Wave amplitude	Half the *wave height*
Wave energy spectrum	Graph showing the distribution of the kinetic energy content of *waves* in relation to *wave period*
Wave forecasting	Estimation of future *wave* characteristics likely to be associated with particular meteorological conditions
Wave height	Vertical distance between the crest and trough of a *wave*
Wave hindcasting	Use of historical weather data to estimate the characteristics of *waves* which have already occurred
Wavelength	Distance between two successive *wave* crests
Wave period	Time for two successive *wave* crests to pass a fixed point
Wave protection	Material applied to *flood defence works* to provide protection against *wave* attack
Waverider buoy	Floating device used to measure water level fluctuations due to *waves*
Wave setup	Tilting of mean water level profile near a sloping *shore* associated with the conversion of wave energy to potential energy
Wave steepness	Ratio of *wave height* to *wavelength*
Wave train	Group of *waves* originating from the same fetch (see *group velocity*)
Wave velocity	Speed of advance of an individual *wave* (see *group velocity*)