

**Estuaries Research Programme, Phase 1
MAFF Contract CSA 4938**

EMPHASYS Consortium

Modelling Estuary Morphology and Process

Final Report



Research by the EMPHASYS Consortium for MAFF Project FD1401

December 2000



**ENVIRONMENT
AGENCY**



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For further information on the Estuaries Research Programme Phase 1
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Contract

This report describes work commissioned by the Ministry of Agriculture, Fisheries and Food, the Environment Agency (national R&D programme) and English Nature under MAFF Project FD1401 (Estuaries Research Programme, Phase 1). The Funders Nominated Project Officer was Peter Allen-Williams (MAFF). The HR Wallingford job number was ICS0030. The work was carried out by members of the EMPHASYS Consortium led by HR Wallingford. The views expressed are those of the individual authors. Publication implies no endorsement by the Funding Agencies of the conclusions or recommendations of the report.

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Prepared by
(name)

.....
(Title)

Approved by
(name)

.....
(Title)

Date

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Members of the EMPHASYS Consortium

HR Wallingford Ltd
Howbery Park
Wallingford
Oxon OX10 8BA

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

Posford Duvivier
Rightwell House
Bretton Centre
Peterborough
PE3 8DW

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

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

Proudman Oceanographic Laboratory
Bidston Observatory
Birkenhead
Merseyside
L43 7RA

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

Plymouth Marine Laboratory
Prospect Place
West Hoe
Plymouth PL1 3DH

British Geological Survey
Kingsley Dunham Centre
Keyworth
Nottingham NG12 5GG

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

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

CEFAS
Lowestoft Laboratory
Pakefield Road
Lowestoft
Suffolk NR33 0HT

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

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Executive Summary

Estuaries Research Programme, Phase 1
MAFF Contract CSA 4938

EMPHASYS Consortium Final Report on Modelling Estuary Morphology and Process

Research by the EMPHASYS Consortium for MAFF Project FD1401

Report TR 111
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HOW YOU CAN BENEFIT FROM THIS REPORT

The morphology of an estuary (its shape and underwater contours) affects, and is in turn affected by, issues relating to *flood defence, water quality, conservation and navigation*. This report, and companion reports¹, provide answers to some of the key questions that face those concerned with such issues: estuary managers, stakeholders and interest groups. The reports result from Phase 1 of the UK Estuaries Research Programme undertaken by the EMPHASYS² consortium, which comprises 13 partners including practitioners and researchers with widely varying and complementary areas of expertise. Links are made between the understanding and prediction of changes in estuarine morphology and the resulting changes in the ecology and water quality that are subject to legislative constraints, policy and directives.

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

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

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

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

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

- *How “healthy” is this estuary?*

¹ Reports (listed in the Bibliography below) on: Guide to Prediction of Morphological Change, Legislative Context, Directory of Predictive Methods, Research Recommendations, and Database

² Estuarine Morphology and Processes Holistic Assessment SYstem

Executive Summary continued

To help provide answers to all these questions, predictions need to be made about how the estuary might alter if the project goes ahead, compared with how it would alter in the absence of the project (since natural changes will occur anyway). The focus of this report is on predicting changes in the short term (up to one year) or the long term (some years to decades) in the morphology of the estuary, at both the local and the whole-estuary spatial scales, together with the changes to the ecology and the water quality. Many varied techniques have been developed to make these predictions, ranging from expert opinion based on analysis of the behaviour over time of a large number of estuaries, to highly complex computer-based models. As with weather forecasting, no one method is indisputably superior to the others – all have their strengths and weaknesses, and their suitability to the kind of problem, the kind of estuary, and the time and space scale. This report brings together many of the available techniques and tests them against data from selected representative estuaries, chosen on the basis of (a) adequate availability of data, and (b) complementarity of types of estuary.

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

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

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

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

Executive Summary continued

The present report acts as a supporting document to the report “A Guide to Prediction of Morphological Change within Estuarine Systems” (see below), which offers a structured approach to tackling these types of estuarine problems.

PROJECT BIBLIOGRAPHY OF OTHER KEY REPORTS

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

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Synopsis

MORPHOLOGICAL MODELLING

1. BACKGROUND

For the purposes of Phase 1 of the Estuaries Research Programme available methods of simulating or predicting the evolution of estuarine morphology have been evaluated and assessed. Each approach has its strengths and weaknesses, and many of these have been illuminated by the use of common data sets from a small number of representative estuaries. Crucial to the whole philosophy of prediction of estuarine morphology is the concept that the morphology will evolve to achieve a balance between the forcing of the tidal currents in moving sediment and the resulting form of the estuary created by that movement. (Some models also include other forcing factors such as waves, wind-driven currents, and river inputs.) This equilibrium can be examined from a number of points of view; from consideration of the gradual topographic development of the estuary, in terms of the hydraulics of the water flows, and in terms of sediment budgets.

So far there has been no proof that any estuarine system is actually in long-term equilibrium, though a number appear to have dimensional characteristics that suggest they might be. Though sediment can be in transport throughout the estuary, equilibrium will only hold if there is no net erosion or deposition anywhere when averaged over a time-scale similar to the sedimentary response time. Indeed, an equilibrium would only be expected to exist if all the boundary conditions were constant. In practice, we would expect to observe some form of dynamic equilibrium, in which the estuarine system is constantly trying to “catch up” with the continuously changing boundary conditions. However, measurements are generally not accurate enough to confirm that slow underlying trends do not exist, and measurements are not extensive enough to average through time the very large variability that the tides, winds, barometric pressure, and river flow impose.

Consequently, it is very difficult to quantify how close, or how far, an estuary is from an equilibrium morphology. Also, it is possible that there may be several possible equilibria. Thus equilibrium according to any one particular definition may be a necessary, but not essential state. Nevertheless, the equilibrium concept is a very attractive one as it has a useful simplicity and assumes the existence of the normal natural feed-back processes common in sedimentary systems. Use of these models has aided understanding of the critical processes involved in morphological change, and the response of the systems to advance considerably, so that we are now in a better position to be able to carry out predictions with some confidence that the models have realism.

It has been beneficial in the project philosophy to distinguish between Bottom-up, Top-down and Hybrid methods. These are defined in subsequent sections. The Predictive Methods Report (Ref. 1), undertaken as part of the EMPHASYS project in March 2000, collated a number of models and methods and gave a synopsis of their strengths and their limitations. The report identified the potential for future development and recommended tests both to validate the methods where possible and to extend our understanding. The present report contains a set of summary papers that present the results of the tests and comparisons carried out on a number of representative estuaries for which the project established that there is good data coverage.

Synopsis continued

Six key estuaries were selected as having adequate data to provide for the modelling tests by the EMPHASYS consortium (see Paper 1). Of the models listed in Ref.1, 16 were selected for the testing programme with a good balance between Bottom-up, Top-down and Hybrid models. A matrix of models tested versus the estuaries they were tested on is given in Table 1. In all, 29 combinations of models and estuaries were tested. All the six key estuaries had at least three model tests, and the Humber and Mersey had seven and eight tests respectively.

2. BOTTOM-UP MODELS

Bottom up models, designed to simulate the physical properties of estuaries, rely on solving the basic shallow water equations for water flow and sediment transport. Most approaches to the modelling use finite elements and finite difference grids but other approaches include both 1-D vectors and statistical models. The models can be 1, 2, or 3D, offering results of increasing realism, but with increasing difficulties in calibration and validation. They cannot be used for long term prediction because the errors accumulate during the repetitive iterations to dominate the outcome.

Other bottom up models include those with ecological components, which predict impacts of biota on cohesive sediment behaviour, or relating human and physical impacts in estuaries to bird populations. These use semi-empirical approaches, or empirically derived statistical equations. These models differ widely in their subject and in their approaches to the predictive process.

One of the major difficulties facing a bottom-up approach is the definition of feedback links between morphology and process, an issue addressed by several of the studies. Another issue addressed in the work has been the possibility that small but persistent processes not adequately represented in models can be the key factors in determining long-term morphology. These problems are so acute that feedback loops may be followed for periods of between 14 days to one year but are not stable over the long term.

Six bottom-up models were tested. In each case, verification of the model outputs was achieved using one or more of the sample estuaries. The verification of a large-scale morphological model demands that a range of morphological types can be predicted with accuracy. Such a range of morphology can be found in an inter-estuary comparison, but such a comparison also involves major changes in environmental controls (geology, tides, sediments, ecology) which themselves must therefore be included as control variables in the model. An alternative, less demanding, approach is to use intra-estuary, temporal changes in morphology, so that independent environment controls are held constant, and this has been the dominant method used within the project.

EstBed (Paper 7)

This approach uses the Mike21 hydrodynamic and sediment transport model. The model is run sequentially with the bathymetry being updated at intervals, in order to simulate the changing patterns of morphological change. The verification process used comparison with several data sets. Changes in the inner-estuary channels of the Humber in response to the construction of training walls were simulated. Results show that the approach can reproduce many of the general patterns of bathymetric change, but that the sudden avulsions of the Humber channels were not reproduced. However, waves are not included.

Synopsis continued

POL 1-2- & 3-D models (Papers 4 & 6)

This suite of models is intended to simulate estuarine process rather than morphology, but they have important and interesting links with the POL top-down models. The models simulate tidal propagation and suspended sediment transport. Validation was achieved using data sets from the Mersey estuary. Results of the validation demonstrate that 1-D provide good prediction of fine-grained suspended sediments, but do not simulate coarser, bed-load sediment movement. The 2-D model improves simulation of both coarse and fine sediment sizes. The study concludes, however, that 3-D models offer the only realistic possibility for the simulation of erosion, transport and deposition in estuaries and should be developed further to allow progress towards prediction of morphological change.

ISIS (Paper 9)

Isis is a 1-D model simulating the response of process (flow characteristics) to change in estuarine bathymetry. The study used time-series data sets from the Mersey and concentrated on the response of flow characteristics to bathymetric changes set up by the construction of the Liverpool Bay training walls, and the resultant morphological changes due to increased sediment inputs to the estuary. Further investigation was made into the impacts of reclamation and sea level rise in the Mersey. The results showed increased ebb dominance over the time period, but it was concluded that it is difficult to distinguish between cause and effect in the model simulations. The model results showed, however, that no changes in flow characteristics occurred as a response to reclamation or sea level rise.

TELEMAC 2D/3D (Paper 5)

TELEMAC-2D and TELEMAC-3D are hydrodynamic models, simulating the response of process to changes in estuarine bathymetry. The study used three historical bathymetric data sets from the Mersey and Liverpool Bay and derived the resulting tidal flow for each historic scenario. These flow fields were used as a basis for an examination of the changes in sand transport into the Mersey estuary over the last century. The changes in historic sand transport were shown to be consistent with the observed morphological changes within Liverpool Bay and the Mersey Estuary. As a further exercise a sediment budget analysis of the system was undertaken which suggested strongly that other processes were also important to the system, such as dredging and disposal, wave activity, and mud transport.

Transverse (Paper 10)

This model was designed to investigate the distribution of flows and bed shear stresses on a cross section of an estuary. It was set up for a cross section of the Tavy estuary, using data from spring tide observations at three stations on the cross section. The depth averaged longitudinal density distribution was estimated from the tidal cycle variations, and the surface water slope was deduced by constraining the model to simulate the depth averaged tidal currents in the central channel. The longitudinal eddy mixing and the lateral water slopes were assumed negligible. The computations showed that the ebb currents and ebb shear stresses were dominant over the upper intertidal mudflats, but the flood currents and shear stresses were dominant in the central channel and on the lower intertidal mudflats. The shear stresses were less than the estimated erosion threshold, but less than the threshold for deposition, and were consistent with deposition of suspended sediment over the high water period. It is planned to extend the model by incorporating a sediment transport module in order to investigate long term changes in channel shape.

Synopsis continued

BIOTIDE (Paper 8)

This is a 1-D transect model of an estuary inter-tidal bank that uses the well-established EcoS framework. It produces a tidal cycle prediction of net deposition and erosion along the transect. It incorporates standard algorithms for erosion and deposition, while cross-shore velocities are calculated from tidal elevations. The model is unique in that it assesses the impact of biota (specifically *Macoma* and microphytobenthos) as stabilisers in the erosion and deposition processes. Verification used data sets showing observed temporal changes in inter-tidal morphology over a 30-year period from the outer Humber and the Mersey. Results were qualitatively correct for both Mersey and Humber. The model shows that variations in biota can increase upper shore deposition equivalent to doubling offshore sediment supply, and change the profile of net intertidal accretion during low wind periods. Extension of the model to the estuarine scale will demand a statistical approach to changes in biota.

BIRD-POP (Paper 26)

This model predicts the response of bird condition and population size to human and physical impacts in estuaries, by calculating the body condition and overwinter survival of birds from their known behavioural responses to environmental change. The model has been parameterised for a full range of bird species on one estuary and one species on a range of estuaries. The work has concentrated on the one-way causal relationship between morphology and bird populations and as such is an important addition to the morphology models.

The studies appear to indicate that existing bottom-up models do not provide a tool for the prediction for the long-term morphological evolution of estuaries. They do however offer an important and accurate predictive ability for the response of flow and sediment processes to morphology change over short time-scales and, in so doing, provide a qualitative indication of the evolution of the morphology. Consequently they are a valuable and widely used tool for predicting the local, short-term (up to one year) hydrodynamic and morphological changes resulting from localised engineering projects.

The application of the models across a wide range of environmental variation has been limited by the extent to which major independent variables are included in model design. This, together with the considerable data demands of a bottom-up approach, has meant that the validation of the models in a range of estuaries has been restricted.

The provision of long-term feedback loops was identified at the outset as the major problem facing this approach to modelling estuarine morphology and this remains true at the conclusion of this phase of the research. Many of the models described in the work involve only one-way paths from bathymetry to process and have no feedback, others incorporate only short term loops. The development of long-term feedback loops is perhaps dependent on a top-down approach in which a functional directionality is introduced into the relationship between process and form and should be the goal of the next phase of the work.

3. TOP-DOWN MODELS

Top-down predictive methods can take two approaches; an expert analysis of data, and consideration of regime type concepts. The former uses all available data, determines trends, and extrapolates the trends for prediction. It can also examine

Synopsis continued

relationships between events in the driving processes and the observed system response, in order to determine probable future changes. The regime approach develops empirical relationships between the dimensional features of the estuarine topography, and some measure of the tidal flow, such as cross-sectional area and tidal volume. The majority (other than those with an ecological bias) are aimed at predicting the long-term physical response of an estuary to natural changes in forcing (e.g. sea level rise) and also, to a varying degree, changes in morphology following human interference such as engineering works or dredging.

It is most valuable to be able to use the methods on several bathymetric data sets to make hindcast predictions of estuary morphology, thus allowing comparison between the results and observed data. The methods or models, in general, do not utilise iterative techniques, and are large scale and long term.

Historical Trend Analysis (Paper 14)

Expert Geomorphological Assessment (Paper 15)

Historical Trend Analysis involves consideration of historical changes in estuarine morphology and sediment accretion/erosion patterns through analysis of historical and archaeological evidence. This method can be improved by additional Expert Geomorphological Assessment where the physical, chemical and biological processes, and geological constraints and sediment properties are considered. Additionally, relationships between events and morphological responses can be included. Through this, an understanding can be gained of the morphological changes that have occurred within an estuary, along with a prediction of future changes. Both methods were tested separately.

Historical Trend Analysis was tested on the Ribble, Mersey, Southampton Water, Blackwater and the Humber. Validation was effected by analysing historical data, and comparing predictions from past data to the most recently available data set. An error assessment was also made through a comparison of the available sediment volume in relation to a fixed datum plane.

Testing showed that the method is valuable in predicting morphological changes within an estuary, but that it is constrained by the limited amount of available data. Errors arose because of the interpolation necessary when comparing incomplete surveys. Greater confidence could be placed on the trends relating to general morphological changes such as channel depth and position. Due to the cyclic nature of some estuarine morphological changes, and changes in boundary conditions, simple linear extrapolation is not appropriate. However, long term data sets, of sufficient resolution, combined with an understanding of the cause of morphological change, can give relatively accurate predictions.

The Expert Geomorphological Assessment approach was tested on the Ribble and Mersey by comparing data for at least two historical periods as a basis for prediction, and using the data set for a third period to assess the accuracy. Test analysis concluded that through a combination of Historical Trend Analysis and an understanding of process quite accurate predictions could be made of the future morphological development of an estuary. However, the method is not appropriate for assessing detailed local changes. The method also depends on the quality of the data used in the predictions and the expertise of the user.

Synopsis continued

Conceptual Estuarine Model (Paper 16)

This is essentially the same technique as the Historical Trend Analysis/Expert Geomorphological Assessment. The model uses analysis of historical trends and sediment budgets within an estuary to predict future morphological changes. It aims to provide an understanding of an estuary in terms of hydrodynamics, sediment dynamics, morphology, sedimentology and anthropogenic influences.

The method was tested on Southampton Water to assess the diagnostic and predictive ability of the model. Changes in the area of tidal flats and salt marshes were calculated and the cause of the morphological changes was extrapolated, based on the observed changes and knowledge of the forcing processes. This allowed a prediction of future morphology to be made.

In addition to the above, a strong relationship was found between water quality / biology and hydrodynamics and between biological factors and sedimentary processes, particularly over the estuarine fringing environments.

Accommodation Space (Paper 11)

Accommodation space is the volume of the estuary available to “accommodate” the sediment being brought into it. This method aims to predict morphological development of an estuary as a result of sea level fluctuations and utilises the relationship between changes in the amount of depositional accommodation space and sedimentation patterns. As sea level rises the volume of the estuary increases by flooding of the marshes.

Values for sea level rise compared with sedimentation volumes were determined for the Humber and Mersey estuaries, and Southampton Water. The incremental accommodation space for each 200year sea level elevation was established over the past 8000 years. Curves were produced depicting the annual increase in accommodation space versus time.

Large differences were found in the accommodation space volume increase between the estuaries. The value for the Humber peaks at 54 times the equivalent peak for Southampton Water. These plots have been attributed to two factors: (1) sea level rise and (2) cross-sectional form.

The effect of a 500mm sea level rise, constrained within the existing flood defences, was also examined. It was found that the flood defences reduce the increase in accommodation space, by up to 79% in the Humber, requiring a very much smaller supply of sediment to fill the space available in an estuary. This inevitably affects the sediment balance and the morphological development of an estuary. The testing determined that the method could provide invaluable information on the ability of an estuary to accommodate sediment and hence assist in the long-term prediction of the estuarine morphology.

Regime model (Paper 13)

This method uses the empirical relationship between estuarine gross morphology and tidal prism, using simple power law relations. Predictions, of the effect of sea level rise and managed retreat of flood defences, are made in terms of the resulting changes in estuary cross-section.

Synopsis continued

This method was tested on a number of UK estuaries, including all six of the EMPHASYS selected key estuaries, and it was found that results could be grouped in terms of regions. The groupings also corresponded to the particle size of the sediment within the estuary and wave energy at the coast. In addition, testing determined that the rate of change of tidal prism against mouth area remained similar for all regions.

The introduction of a shear stress component allowed the prediction of the depth needed to give critical erosion, or deposition, at any given location along an estuary. Thus since cross section could be determined, the width could also be predicted.

It can be concluded therefore that the relationship between tidal prism and cross sectional area can assist in predicting changes to the overall morphology of an estuary. The relationship shows regional trends.

Roll-over (Paper 13)

Based on the Regime Theory, this method investigates the landward transgression of the estuary with sea level rise. The change in shape, elevation or position of the estuary may be predicted. However caution must be exercised to account for anthropogenic effects. By the same token its application to certain schemes avoiding major change to estuary shape is questionable.

The method was tested, for validation purposes, on the Humber, Blackwater and the Crouch / Roach estuaries. In general, results showed that the estuaries would migrate landward by 1m per 1mm rise in sea level. Landward migration was accompanied with a change in the planimetric shape of the estuaries which tended to become more flared. However, lateral constraints, such as flood defences, resulted in the erosion and deposition, associated with rollover, occurring in the sub-tidal zone. Testing also illustrated that estuaries can migrate in the opposite direction, to that which would be predicted by rollover. This was attributed to adjustment from previous reclamation that had affected the tidal prism.

POLANT/ANST/ANSE (Paper 18)

These methods were developed to provide a framework of estuarine responses for tidal propagation, salinity intrusion and bathymetric evolution.

The objectives of testing were:

to indicate the range of dynamic salinity and sedimentary regimes to be anticipated in UK estuaries.

to interpret these against underlying causative mechanisms

to deduce inferences for estuarine bathymetries, namely likely size, relative stability and hence bathymetric evolution.

It was found that the framework for tidal propagation and salinity intrusion, appropriate for the shallow UK estuaries, could be determined using a 1 D numerical model with a simplified cross section and bathymetry. Maximum tidal currents were effectively controlled by bottom friction in water depths of less than 10m. Flushing time for an estuary varied from greater than 15 days (spring neap tidal cycle) to hours for a shorter estuary. Shorter estuaries are, therefore, more susceptible to sedimentary changes as a result of tidal range and river flow.

Synopsis continued

It was found that the relative stability of an estuary could be determined by comparing the net flux of sediment on the flood tide with the existing estuary volume. It was deduced that longer estuaries are generally more likely to be associated with fine sediments and lower tidal ranges, while the converse is true for short estuaries.

SHAPE-SED (Paper 17)

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

This model was not tested as part of the EMPHASYS study but research was undertaken in 1994–95. It was found that estuaries on the east and south coast of the UK were generally much muddier than those on the west coast. Sediment size also seemed to be influenced by estuary shape and the mean spring tidal range. The wider the estuary and the greater the tidal range, the sandier the sediment. The study also found that sediment tended to be sandier at the lower reaches of the estuary.

Generally, therefore, it is possible to predict reasonably well the overall sediment composition of an estuary (muddiness) through estuary shape, region and tidal range.

The Expert Analysis of data is a powerful method of prediction, since it can take into account many facets of the processes and responses that are not otherwise included in models. However, the method is only as good as the expert, and there may be considerable divergences in the predictions of several people. Nevertheless, it is essential that such analyses are used to complement and in some cases control the results obtained from other techniques.

In regime type models there are no explicit processes which transport the sediment and cause the morphological changes. Morphological readjustment is considered solely to result in some way from tidal current action, without any contribution from waves. There are no direct connections, or pathways, between areas of erosion and deposition. Waves can be particularly important in eroding sediment from inter-tidal areas, the main areas of sediment accumulation. Additionally, the effect of high river discharge and floods in enhancing currents near the heads of the estuaries are not considered. Many applications would also require inclusion of the effects of salinity on the currents and the tidal elevations. Gravitational circulation is important in the mean transport of fine suspended sediment, and comparative modelling has shown that tidal elevations can differ by several centimetres with and without the density effect of salinity. Consequently, the regime models give orders of magnitude calculations that are approximations of varying and unknown accuracy. Nevertheless, these can be of immense importance for general guidance and testing alternative scenarios.

4. HYBRID MODELS

Hybrid models are a combination of empirical top-down, regime models, together with detailed bottom-up models based on physical principles and data. The general mode of operation is to use the bottom-up models to generate close coverage of tidal elevations, current velocities and, in some cases, suspended sediment

Synopsis continued

concentrations. These are then used in regime theories, with volumetric or dimensional estimates derived from bathymetric data, to explore how close or how far the system may be from equilibrium. Time series of results allow consideration of whether the system may be converging on a stable equilibrium condition, and how fast it may respond to perturbations created by forcing events. Hybrid models are thus ideal for integrating the short time-scales inherent in the bottom-up models with the long time-scales of the top-down models.

EstEnt (Paper 19)

This proposes the theory that the morphology of an estuary will evolve so that the tides do minimum work as they progress along the channel, ie. the entropy production reaches a minimum state. This is an assumption, so far without rigorous proof. This model has been tested on six different estuaries. Bathymetries measured at various times are used with 1D modelling to determine the historical tidal energy distribution. The results show that each estuary has different energy and dissipation distributions. However, two major patterns of distribution are shown, one being exponential and the other linear. These appear to conform to funnel-shaped and canal-like estuaries, respectively. This may demonstrate that there is not a single equilibrium shape. It appears that at the moment the theory is not predictive, in that it is not clear what the end equilibrium situation is that the estuary is evolving towards. Of course, attempts to obtain equilibrium are also constrained by geological features and by the fact that man has been altering estuaries continually. Nevertheless the concept is a valuable one that needs to be developed further, particularly in the situation where it can be compared with other concepts of equilibrium and other models.

ESTMORF (Paper 22)

This model also utilises empirical relationships together with results from a 1D model, and is applied to the Humber. The flow field is calculated from the tidal volumes and high and low tide water levels derived from a 1D model. The model works with a cyclic representative tide, rather than the full spring-neap cycle. Specific relationships are assumed for the profiles of the intertidal and subtidal areas so that predictions can be made of the development and the respective areas of the channel and flats. Constant suspended sediment concentrations are imposed at the river and outer boundaries, and an equilibrium concentration field calculated. Transport of this concentration field allows development of the topography. The model produced a dynamic equilibrium after about 35 years of simulated running, with a sea level rise rate of 0.2m per century. The sediment demand required to create this equilibrium was consistent with present day sedimentation rates. The model has been tested for various scenarios of reclamation, and reasonable patterns of morphological change result. It is obvious that there are a number of factors that affect the realism of the results, in particular the derivation of the equilibrium concentration field. As an extension into ecological modelling the ESTMORF model is used to determine various intertidal parameters of inundation time, current speed, salinity and water depth, which control biological responses. These are used to define a series of different physiotopes. This valuable addition to predictive ability is not yet well proven – for the Humber it is based on the physiotope characteristics defined for the Netherlands. Nevertheless it does give reasonable comparison with observations. The approach holds distinct promise if it can be refined by iterative use with a series of comprehensive measurements.

Synopsis continued

HYMORPH (Paper 21)

HYMORPH was applied to the Tollesbury Creek managed realignment experiment. Regime theory is used to relate cross-sectional area, width and depth with discharge, calculated using a 1D hydrodynamic model. After extensive analysis of the regime relationships, one considering discharge at peak velocity and area at peak velocity was chosen as it best represented initial changes. Calculations were made before the breach in the dyke was made, and then following the breaching and the flooding of the backing salt marsh, the evolution of the creek system was predicted. This is a very small-scale system and 2D effects are likely to be very significant, and pose problems of resolution. The results benefited from using small topographic time-steps in the iterations. Additionally there are several unresolved problems in coping with extensive wetting and drying areas within hydrodynamic models. After the initial period there were major differences of the predictions from the later observed changes. Nevertheless, it is apparent that, as it was the first time that this sort of problem had been attempted, it was more of a simulation exercise than a prediction. The experience gained, however, will be invaluable in attempting future modelling of this sort.

As can be seen from the above comments, the results of hybrid modelling can only be evaluated qualitatively by comparison with what the expert thinks looks reasonable. Considerably more effort will need to be put into obtaining comprehensive data sets over considerable times to be able to provide quantitative evaluation. In particular before and after monitoring of imposed changes where the response is likely to be fast would be most useful.

The main weakness in the hybrid approach stems from that inherent in the regime theory, which is basically a dimensional relationship, without specific mechanisms for transporting sediment and modifying the morphology. The ideal test of equilibrium would be to determine the morphological conditions under which the gradient of the tidally averaged sediment transport rate is zero over the whole estuary. In that case no net erosion or deposition would occur.

There are errors in the 1D tidal modelling in that such models simplify the topography and the consequent friction, which can only be adjusted by calibration against water elevation data. Additionally, no account is taken of the modification to the elevations that may be caused by the salinity distribution in the estuary.

5. ADDITIONAL SYNTHESSES

In addition to the individual modelling reports, syntheses of the work on the Humber and the Mersey are given in Papers 2 and 3 respectively. Further considerations of a general synthesis nature are given in Papers 12 (Gross properties of UK estuaries), 20 (Fluxes of suspended sediment), 23 (Importance of physical, biological and geological influences), 24 (Linkage to end-user needs for water quality and ecology) and 25 (Conclusions and recommendations from POL).

Synopsis continued

6. CONCLUSIONS

It is evident that no one model and no one approach will provide adequate prediction of morphological evolution in estuaries. Though it has been beneficial to distinguish between Bottom-up, Top-down and Hybrid methods, future development is likely to combine the methods as required for specific tasks. It will be necessary, therefore, to relax the boundaries between the groupings and only to consider the methods to be more conceptual or more analytical.

The way forward in developing improved techniques appears to be to incorporate bottom-up models as modules in a hybrid approach that first specifies the long-term outcome of estuarine morphology evolution. The bottom-up models may then be used to assess the rate at which such evolution may occur, or indeed whether a steady-state outcome can be attained at all. Such a development in modelling must be based on an assumption that estuarine evolution is a form of progressive movement towards equilibrium, rather than a series of random steps that arrives at a steady-state outcome by probabilistic means. Such an assumption is by no means accepted and here the application of historical trend analysis may offer a means of verification.

Top-down methods generally assume that an estuary will adjust to equilibrium. This allows for short-term adjustment, such as channel location and even sediment distribution, but assumes that an estuary is stable over a longer period of time. The methods tend to be conceptual and empirical, but are relatively effective in making predictions on a comparatively long-term estuary-wide basis. However, they are not as effective with short term or localised changes.

Bottom-up models are valuable tools for assessing local, short-term hydrodynamic and morphological change, and they are an essential element of water-quality modelling. They also offer an important component of a large-scale approach to the prediction of change in estuarine morphology. When used with top-down models to give a hybrid approach they can provide the quantification of rates of change needed by estuarine managers. As such, the work carried out by the EMPHASYS teams has demonstrated both the range and the accuracy of the approach.

The problems of model application across space and time remain at the end of this phase of the research. Wide scale application across a range of estuarine environments is here perhaps less of a problem for bottom-up simulation than the problem of long-term prediction and the major issue of feedback.

Testing has shown that all the methods have strengths and limitations. For applications and problem solving it is possible to predict a morphological trend with only a limited amount of information, but with unknown accuracy. Where data of greater quantity and quality is available a more accurate prediction is likely to be possible through Expert Assessment. This method should always be adopted as the only means at present of providing rational judgement of the validity of the other methods. The final method adopted will depend on the prediction requirements, the funds and time available to undertake the study, as well as the quantity, type and quality of the information available. It is also advisable that more than one method is utilised to provide a comprehensive understanding of the processes affecting the morphology of the estuary under consideration, and to predict future changes.

Synopsis continued

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Table 1 Tests of models versus estuaries (Paper numbers are indicated)

No	Promoter	Name	Type	Blackwtr	Humber	Mersey	Ribble	Soton Wtr	Tamar
1	HR	TELEMAC	BU			5			
2	HR	ISIS	BU			9			
3	PML	BIOTIDE	BU		8				
4	PML	TRANSVERSE	BU						10
5	POL	POlest	BU			4, 6			
6	ABP	EstBed	BU		7				
7	UoN	Regime	TD	13	13	13	13	13	13
8	UoN	Rollover	TD	13	13				
9	POL	POLant/anst/anse	TD			18			
10	BGS	Accom Space	TD		11	11		11	
11	RHC	HTA/EGA	TD			14, 15	14, 15		
12	UoS	Conceptual model	TD					16	
13	DH	ESTMORF	HY		22				
14	HR	HYMORPH	HY	21					
15	ABP	EstEnt	HY	19	19	19	19	19	19
Total on each estuary				4	7	8	3	4	3

EMPHASYS DATABASE

Ian Townend

email: IHT@research.abports.co.uk

ABP Research & Consultancy Ltd, Pathfinder House, Maritime Way, Southampton SO14 3E, UK

1. THE DATA TASK

One of the aims of the Estuaries Research Programme, Phase 1 is to deliver a system which will assist estuarine managers to make informed decisions regarding flood defence and related issues using the best knowledge and techniques that are presently available.

During this phase of the programme, the estuarine predictive modelling techniques presently implemented by the consortium members are to be applied to a number of estuaries in order to compare their relative merits and to recognise the conditions to which they are best suited.

The model testing is to be undertaken using three general approaches, namely bottom-up, top-down and hybrid.

The data requirements for the techniques vary greatly. For the bottom-up and hybrid modelling, highly detailed data are needed to simulate estuarine hydrodynamic and physical processes, while for the top-down modelling, more general data are required.

At the outset of the Estuaries Research Programme an initial, data gathering period was identified by the consortium as being the most effective and productive means of meeting the data requirements of the model testing to be undertaken during Phase 1.

2. THE ESTUARIES

The Consortium selected 18 UK estuaries that are known to have reasonable data coverage or are particularly suited to model testing. All known sources of data and references for these estuaries were catalogued in a data inventory. The inventory was produced to facilitate the selection of the six most suitable estuaries for the application of bottom-up and hybrid modelling and to provide a useful catalogue of available data to the project throughout its duration.

The estuary selection was based upon data availability and estuarine characteristics. The six selected estuaries are presented in Table 1.

An intensive data acquisition period was undertaken to gather detailed data for the six selected estuaries and more general summary data for all other UK estuaries.

3. THE NEED FOR A 4D GIS

To facilitate its transfer within the consortium, the data acquired was aggregated into a single database. A geographical information system (GIS) was chosen as being the most desirable front end to the database since such systems put data into spatial context and incorporate powerful tools for data analysis. Estuaries exhibit large variations in properties both longitudinally and transversely, advocating the use of GIS. However, estuaries can also exhibit significant variations in properties with depth, which can be difficult to represent in a conventional GIS.

Estuaries are very dynamic environments driven principally by tidal and fluvial forcing, both extremely variable over time. It is critical to our understanding and ability to model estuaries that the dynamics of their properties must be represented fully in three spatial dimensions with comprehensive records of their change through time.

In order to store the estuary data in a system in which it's full four dimensional nature could be exploited, the Spatio-Temporal Environment Mapper (STEM) was selected for the EMPHASYS Database. STEM is a mapping system designed to store, access, visualise and analyse large volumes of diverse data that vary in both 3D space and time (Morris *et al.* 1999).

Table 1 Key characteristics for the selected six estuaries

Estuary Name	Geographical Location	Morphological Description (JNCC)	Tidal Description	Indicative Use
Blackwater	England, East Coast	Coastal Plain	Mesotidal	Rural
Humber	England, East Coast	Coastal Plain	Macrotidal	Industrial
Mersey	England, West Coast	Coastal Plain	Macrotidal	Industrial
Ribble	England, West Coast	Coastal Plain	Macrotidal	Urban
Southampton Water	England, South Coast	Coastal Plain	Mesotidal	Urban
Tamar	England, South West	Ria	Macrotidal	Rural

4. THE STEM DATA MODEL

There are two basic parts to STEM, the front-end including the visualisation components and the database that stores and manages the data. The database is based on a generic data model capable of holding many types of data through space and time.

The database design provides a simple conceptual model that helps to visualise how data are stored. It allows the history of any feature to be recorded as it changes through space and time. Descriptions of features and the events observed at them are recorded in terms of properties or attributes. Thus, to store river water quality data, an individual monitoring site might be classified as a feature and the variables which describe or are observed at the site, such as its position, the site name, a unique reference number, river flow, pH values and so on, would be its attributes. Other examples of features could include a river network, land use map, and remotely sensed images. The data model supports a wide range of spatial and non-spatial data types permitting the storage of most types of variables. Both features and attributes can be customised and user definitions are held in data dictionaries. One of the significant advantages of the data model is that all attributes or properties are assumed to be potentially time variant as are features and positional properties.

Figure 1 provides a pictorial view of the STEM data model. The model could be visualised as a cube where the axes represent features (where observations are made), attributes (what has been observed) and time (when the observations are made). Each cell contains a value of an attribute describing a feature at some moment in time. For example, one cell might contain a real value representing the rate of flow in the river Thames at Kingston on the 20th May 1993. There are no

constraints on the number of features, attributes or occasions that can be stored by the cube other than those imposed by the physical limits of the hardware.

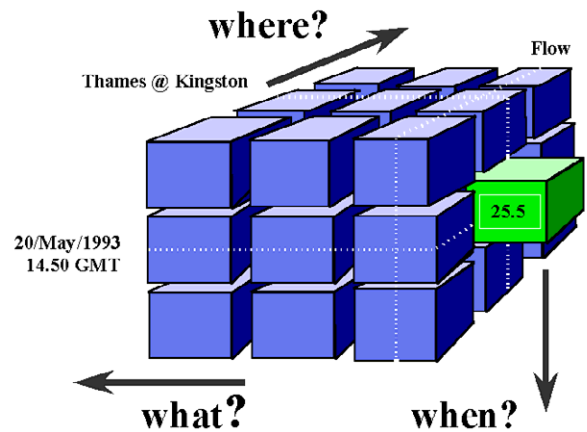


Figure 1 The STEM data model

Listed below are the key properties of the STEM data model:

- A feature may have any number of attributes;
- The same attribute may be observed at any feature;
- Any number of values may be recorded for an attribute over time at a feature;
- The values may be recorded at fixed or random time intervals;
- The data model does not distinguish between spatial and temporal data;
- The cube is infinite in all directions;

The significance of the cube is that it provides a completely generic data independent structure around which to build equally generic tools for data visualisation, analysis, retrieval and loading.

5. DATA VISUALISATION AND MAPPING

Data are accessed via a query wizard that guides the user through the query procedure. At each stage SQL³ queries are made to the database to retrieve the relevant information. After choosing an area of interest on the map, up to five feature types may be chosen during a query. This is important when investigating the transfer of materials between different environments. For instance, chlorophyll data could be retrieved for a number of different types of measurement sites, including river monitoring stations, marine monitoring stations, intertidal monitoring stations and so on. The next stage in retrieving data is to select the attributes that are required. Again, a maximum of five may be selected, which is useful when comparing attributes, *e.g.* nitrate versus salinity. The desired time range is then specified.

When displaying time variant data on a map, it makes little sense to plot every value on the map at the same time. Later data may mask out earlier data and in a marine environment where the media will have moved in the intervening period the map will be misleading. A solution to this is to aggregate the data into periods of time (Kraak & MacEachren 1994). STEM enables data to be aggregated on the fly into any desired time periods from seconds through to centuries, providing complete flexibility in the temporal scale. Similarly, it is necessary to aggregate the data in terms of depth, where present, to a specified interval. Where there is no data within a time period or depth interval, there is no aggregation. Also, there is no process to increase data density to fill temporal gaps (*i.e.* no temporal interpolation).

At the end of the query all attribute data throughout the time and depth ranges are retrieved into one map layer. The data are aggregated into a statistical array associated with the map layer. Any time/depth combination may be chosen for display. This means that one map layer may represent the equivalent of up to 100,000 (200 times x 100 depths x 5 attributes) of what might be described as conventional GIS map layers.

There are several ways in which the time and depth dimensions are visualised within STEM.

The main access to these dimensions is via the time/depth bar that appears below the map window. The time/depth bar (Figure 2) is made up of an array of segments, each of which represents a time or depth interval of the data based on the intervals selected when the layer was retrieved from the database. Initially, the data displayed on the map shows the first period in a time sequence. Different segments in the time/depth bar may be selected to change the period or depth of the data being displayed in the map. The segments are coloured according to the mean value for all sites in that time or depth interval. Hence, the time bar itself provides a useful summary of temporal variations in the dataset. Other statistics, including measurement frequency, minimum, maximum and standard deviation can be displayed in the map and the time/depth bar. A toggle button is used to switch the time/depth bar between the two dimensions relatively seamlessly.

The second visualisation method is to produce time series or depth plots of the data. This is achieved by simply clicking on a site in the current map layer. Up to five sites and five attributes may again be compared within the graphing tool. At this stage it is also possible to display the full time or depth series in addition to the calculated statistics.

A further method, which applies to both point and raster data, is that of animation. An animation tool provides control of the speed, direction and extent of the animation. Animation of point data (*e.g.* concentrations of suspended sediment at fixed sites) may result in pulsating proportional symbols on the map or fixed-sized symbols that vary in colour during the animation. Alternatively, if more than one attribute has been retrieved it is possible to animate bar charts at each site, providing a comparison of all attributes throughout the time sequence. Raster animations may include a set of remotely sensed images or the results of a model run.

Depth is also visualised through depth profiles and perspective views. Depth profiles are achieved by drawing a transect on the map and then performing an interpolation through depth.

³ Structured Query Language

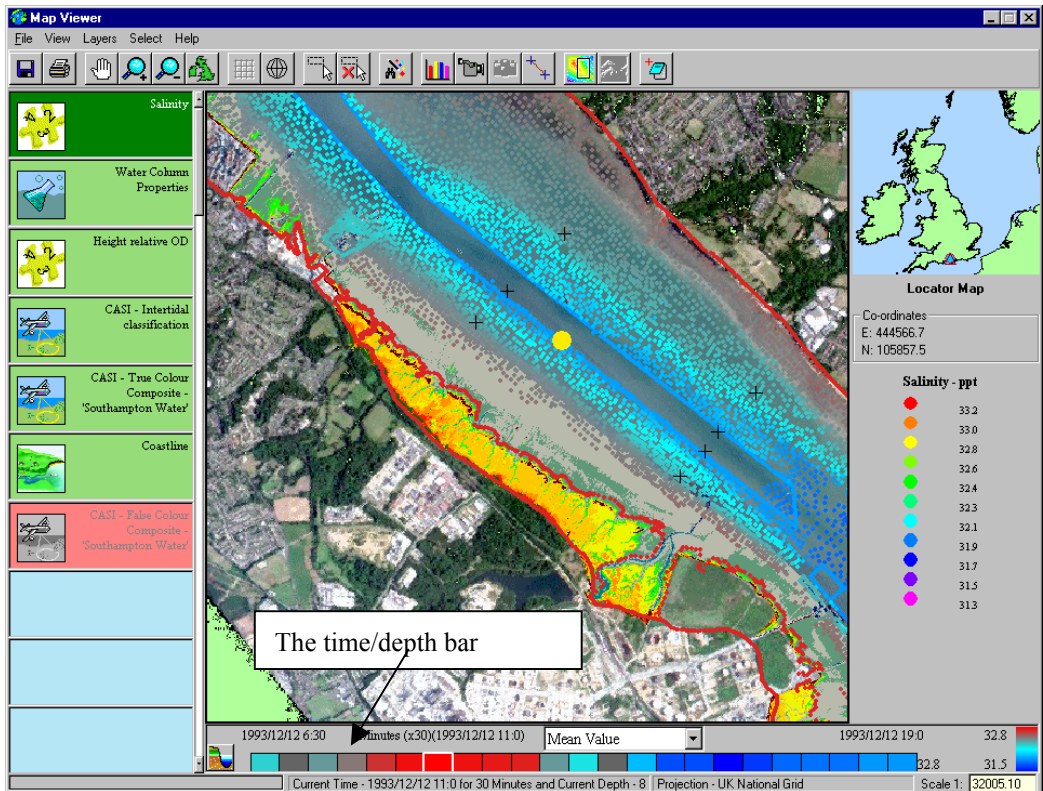


Figure 2 The time/depth bar

The data model used for any project is entirely flexible and can be expanded or modified as required. There are no limits to the number of feature types, features, dictionaries or attributes that can be used and the names, terms, units, icons and default symbology can be fully customised throughout the database.

6. THE EMPHASYS DATABASE

The EMPHASYS Database contains over 575Mb of data. It holds many of the attributes of importance in the estuarine zone, including bathymetry, currents, tides, freshwater flows, salinity, turbidity, temperature, chemical data, nutrient data, biological data, sediment data and Compact Airborne Spectrographic Imager (CASI) imagery. Since estuaries are highly dynamic environments, the majority of the data within the database is considerably variable with time and many of the attributes also exhibit depth

variable properties. The use of a 4D GIS has enabled much greater control with the storage and analysis of this type of data than has been previously achieved using conventional database and GIS systems.

One of the major benefits of using STEM for the EMPHASYS Database is the temporal control of data. Data is stored as instantaneous values, which negates the usual requirement to determine the temporal scales of interest before the storage of data and the limitation of being fixed with the selected time interval thereafter. Once the measured data is held within the database, there is complete flexibility with the temporal period at which to analyse the data. Figure 3 presents a time series plot of mean seasonal freshwater flows for five of the tributaries that flow into the Solent, calculated from the mean daily freshwater flows in the database.

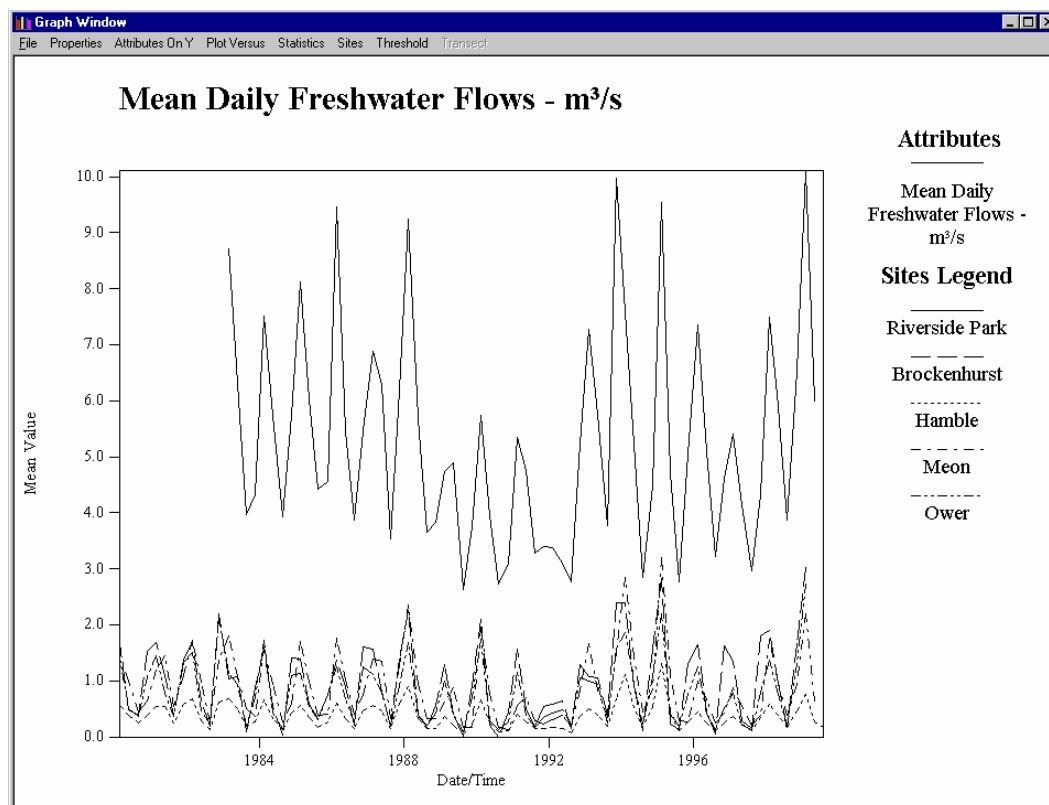


Figure 3 Time series of fresh water flows for 5 tributaries of the Solent

The handling of bathymetric datasets within STEM is of particular value to the EMPHASYS Consortium. Early on it became evident that the STEM generic data model would not be suitable for the volume of bathymetric data required by the EMPHASYS consortium. The problem to be solved was to improve the storage capacity and retrieval times for these data. In the generic data model, each measurement site is a feature at which a series of attributes can be stored. When this model is used for bathymetry data, each xy pair is assigned a unique feature identity and the elevation or sounding is stored as an attribute of the feature. With bathymetric datasets often exceeding 30,000 soundings and in any particular estuary and a large numbers of surveys available, it was clear that the technique for handling bathymetric data in STEM needed to be revised for the EMPHASYS database.

The problem was successfully resolved by treating bathymetry as a distinct attribute with a unique data structure. The data are stored as a series of surfaces each of which is a feature in the STEM data model. The data within each surface are stored as an array of compressed x, y, z coordinates. This technique has enabled substantial compression ratios to be achieved and

has dramatically improved the time taken to retrieve data from the database into the map view. The use of surfaces as a data management technique is done ‘behind the scenes’ and is therefore transparent to the user who would obtain a bathymetry map as a series of colour banded survey points in the usual way.

The database currently stores 30 bathymetric datasets for the six selected estuaries dating from 1783 to 1999. All of the bathymetric surveys for a particular area can be stored in a single map layer with each discrete bathymetric survey being represented under separate intervals of the time/depth bar. The data are displayed in the map using points that are colour banded based upon elevation. By scrolling through the time bar the evolution of the bathymetry can be observed on the map. Cross-sections can be drawn through the bathymetry with the option to display the data for all of the discrete periods returned, thereby enabling the change in the cross-section through time to be displayed in a simple plot of x versus z with a separate line for each period (Figure 4).

There is also bathymetry for 144 estuaries in England, Scotland and Wales. The bathymetry has been loaded with levels referenced to local

Chart Datum and the data is retrieved from the database in this format. The functionality of STEM has been developed further to enable the data to be translated between Chart Datum and Ordnance Datum in the map viewer with the click of a button.

To deliver this datum conversion functionality, chart datum to Ordnance Datum conversion points have been loaded in the database for Great Britain. Datum conversion surfaces have been generated which are used to calculate the magnitude of the conversion factor at all locations in the estuaries. The datum conversion surfaces are aligned normal to the main channel of the estuaries, so that the factor varies with distance up estuary whilst remaining constant across a given chainage. On conversion between chart datum and Ordnance Datum Newlyn, the contour data becomes redrawn as points due to the changing elevation properties with location in the estuary. Bathymetry data is exported with levels based to both Ordnance and chart datums.

Since STEM provides the ability to customise the axes of the plots that it generates, attributes can be analysed through time and depth and can be

plotted against other attributes. This again is of high value for estuarine science, since it facilitates investigations into the conservative/non-conservative nature of attributes with distance up-estuary along with analyses of depth/time variance and inter-comparison of attributes.

An issue which needed to be resolved prior to the input of data was the most appropriate means of consistently referencing the depth of water column measurements. Since the data came from a number of sources, different techniques of depth referencing were used. Data was received with depths measured from the bed, as a ratio of the water depth and depths measured from the surface. The tidal variation in the water surface made it difficult to retain all techniques, so a standard was adopted (depth from the mobile water surface) and all non-conforming data converted accordingly. As a result, when aggregating water column data into depth intervals, the measurements from a particular sensor may shift from one interval to another as the overall depth of water at the site changes over the tidal cycle.

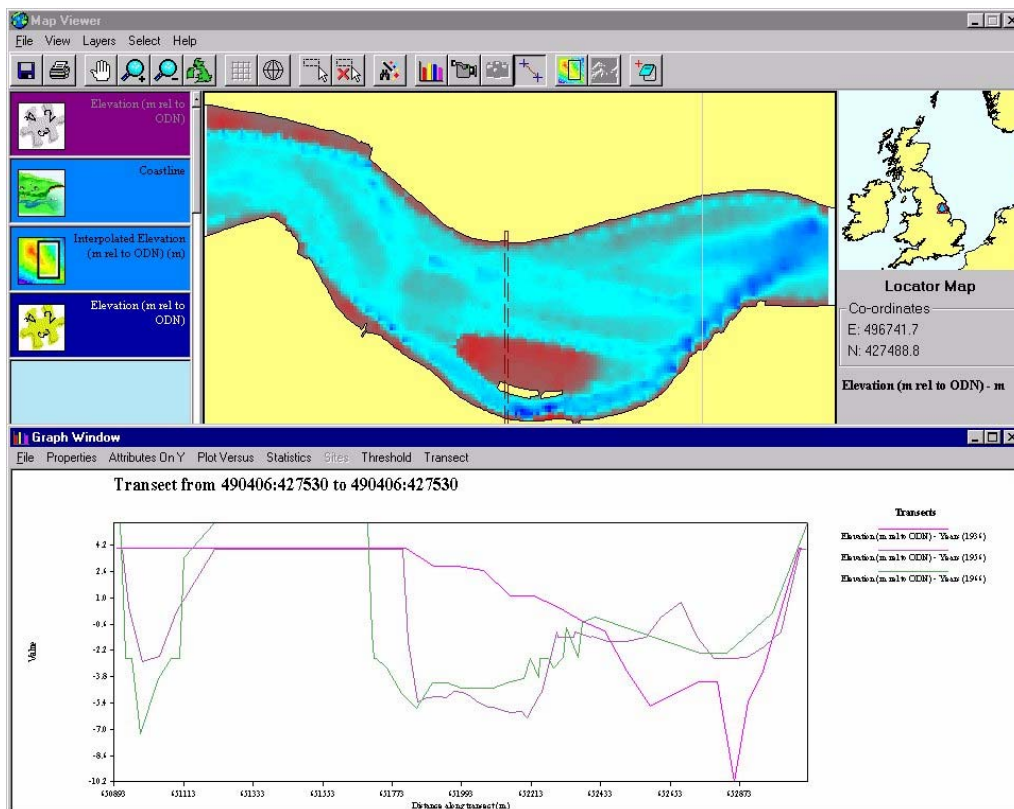


Figure 4 Bathymetric cross-section of the Humber Estuary at Read's Island between 1936 and 1956

The ability to customise all the terms and units and to expand the data model as required has enabled the database to evolve throughout the data acquisition phase while retaining the technical terminology appropriate to the data acquired. The dictionary of units has helped to maintain consistency throughout the database and data ownership facilities have ensured that all data stored is traceable to the data providers.

7. CONCLUSIONS

The Database Task of the Estuaries Research Programme Phase 1 has delivered 2 databases - an inventory of estuarine data sources and the EMPHASYS Database.

The inventory of data was used to help identify the most suitable estuaries with respect to data availability for predictive modelling.

A 4D GIS was used to store all of the estuary data that was acquired for input to the predictive models. STEM was chosen since it can exploit the full value of estuarine data enabling it to be stored and accessed seamlessly through the three dimensions and through time. The functionality of GIS is combined with the sophistication of a multidimensional data management system enabling the full evolution of data in the horizontal and vertical planes to be represented in a map interface. The system enables the generation of time series and profiles increasing its analytical capability making it an ideal platform for the Estuaries Research Programme.

The model testing during Phase 1 has however been restricted by the limited availability of key data sets. If our understanding of estuarine evolutionary processes is to advance, there is a clear need to improve future data collection and monitoring. This is required not only for future phases of the Estuaries Research Programme but also to provide adequate benchmarks against which the impacts of future environmental change, estuary management and compliance with legal requirements can be measured.

Such a monitoring programme should encompass strategic one-off coverage of a number of estuaries, more selective long-term programmes and the monitoring before and after developments take place to capture system response to specific events.

The case for the social, economic and environmental importance of estuaries has been made elsewhere (HR et al, 1996). One consequence is that estuaries are a vital link in delivering a number of European and international commitments signed up to by UK Government. Furthermore, the reporting requirements for a number of these commitments have overlapping data requirements (Collins & Ansell, 2000) and there is therefore a case for a much more co-ordinated approach to marine data collection. This has major implications for any estuary monitoring programme.

The database has been extensively used by the consortium during Phase 1 and would undoubtedly be a useful resource for subsequent phases and for the wider research community and other estuary user groups. Much of the data contained within the EMPHASYS Database is licensed for use during Phase 1 of the Estuaries Research Programme by members of the Consortium. Were the database to be made more widely available, new terms would need to be agreed with the providers of all non-public domain data. This ought not be allowed to become an obstacle for the wider use and further development of the EMPHASYS Database. A great deal of effort has gone into developing the database. It is an excellent platform upon which other estuary research programmes and monitoring programmes could be built. The database becomes exponentially more powerful and valuable as a resource, the more it is developed. Were the data derived from further research programmes or estuary monitoring programmes to be added to the data contained within the EMPHASYS Database, there is the potential to develop an exceptionally valuable asset to the UK marine research community.

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HUMBER ESTUARY SYNTHESIS PAPER

Paul Norton and Ian Townend,

email: pan@research.abports.co.uk

ABP Research & Consultancy Ltd, Pathfinder House, Maritime Way, Southampton SO14 3E, UK

1. INTRODUCTION

Phase 1 of the Estuaries Research Programme has involved the application of a wide range of modelling and analysis techniques for the assessment of long-term morphological evolution of estuaries. This synthesis aims to draw together the key findings of the various studies relevant to the Humber Estuary, as presented in the Phase 1 Interim Modelling Report.

2. THE ESTUARY

The Humber Estuary is located on the north-east coast of England and drains a catchment area of some 23,690km². Run-off from the catchment flows through the estuary through numerous rivers and tributaries, the largest of which are the Ouse, Don, Aire and Trent. At the seaward limit there is a large tidal range of approximately 6m (mean springs) resulting from the position of the mouth within the North Sea basin.

The estuary has a length of 147km to the tidal limit on the Trent and 122km on the Ouse with a confluence at Trent Falls, some 62km from the mouth. Tidal volume ranges from 1-2.5x10⁹m³ over a spring-neap cycle. The semi-diurnal tide exhibits marked asymmetry as the tidal wave propagates up-estuary and there is significant circulation due to density currents, particularly at times of high fresh water flows. This gives rise to seasonal changes, which is marked by the movement of the turbidity maximum.

3. HISTORICAL EVOLUTION

A potentially limiting factor when considering the historical development of the Humber Estuary is the available accommodation space for sediment to be deposited. Large differences in available accommodation space have been found for different estuaries. For the Humber, reclamations and the construction of flood defences have resulted in a 79% reduction in available accommodation space, assuming a 50cm rise in sea level. As a consequence the demand for sediment in the estuary is lower than it would be if the floodplains were active.

Based on the analysis of digital bathymetric data, compiled by ABP Research, a historical trend analysis was carried out, similar to that previously undertaken as part Stage 2 of the Humber Geomorphological Studies (Geo2). The analysis confirmed that there has been an overall gain in sediment in the Humber over the last 60 years although there has been a net loss of intertidal. An observed increase in intertidal area, over the same period in the inner estuary, supports the concept of stratigraphic 'rollover'.

4. GENERAL CHARACTERISTICS

An examination of the different shaped estuaries and sediment characteristics confirmed that on the east-coast there is a tendency for muddier sediments over the whole of the intertidal. A further trend of increasing sand fraction with higher tidal range was also identified. These observations appear to agree with sediment distributions within the Humber.

Analysis of measured tidal currents has shown that mean advection is out of the estuary for both spring and neap tides. This agrees with the general trend for the estuary based on previous modelling investigations (Geo2). Vertical gravitational circulation is considered important when considering transport of fine sediment during neap tides, suggesting that salinity effects need to be included in model simulations. Asymmetry of tidal conditions and sediment concentrations are important factors for sediment transport. Vertical profiles of flows and concentrations are also required for accurate predictions of transport processes suggesting that 3-dimensional modelling is required.

Some generic modelling was undertaken to investigate factors influencing the morphology of UK estuaries. The summary outputs from this investigation allow a rapid assessment of morphological 'drivers' for a chosen estuary to be made. The estuary properties which best describe the Humber are a shape factor, n=2 (exponential) and length of 100km. The associated width and depth at the mouth, estuary volume and freshwater discharge

applied in the model provide a good description of the Humber.

Based on the modelling, the following observations could be applicable to the Humber Estuary:

- A salinity flushing time of 16.9 days not sensitive to tidal range but very sensitive to river flow.
- Mean sediment concentrations along the estuary are only slightly influenced by river flow but highly sensitive to tidal range.
- Intrusion of marine sediments is highly dependent on river flow, particularly for fines.
- The concentration of fines in the water column is an order of magnitude greater than the concentration of coarse sediment.
- The time to fill the estuary by deposition of entire flood tide sedimentary load would be 900 years for coarse sediment and 9 years for fines.
- Of all the estuary geometries tested, only long, exponential estuaries show a significant influence of the time to fill the estuary with river flow.

In general, these observations agree well with previous experience in the Humber. In particular, the connection between river flows and deposition within the estuary has been recognised for some time. Recent investigations as part of the Geo2 studies found a direct link between freshwater flow records and changes in bed levels in the Sunk-dredged Channel. Further work on channel migrations in the inner estuary (University of Newcastle, ABP Research) have also been able to link high river flows combined with large tidal ranges to channel switching events.

5. MORPHOLOGY

Application of a rollover model to the Humber is complicated due to the sediment budget being in deficit. The transfer of sediment from the outer to inner estuary is therefore outweighed by a net export from the estuary as a whole. As a consequence, although the estuary is attempting to respond to sea level rise through rollover, the

process is inhibited by the limited supply of sediment from the North Sea.

Predictions from a rollover model, carried out as part of Geo2, suggest a landward migration of 11m at the mouth and 7m at the head of the estuary for a 6mm/yr increase in sea level. Based on a current rate of sea-level rise of 2mm/yr, estuary rollover will still be significant and place existing flood defences under increasing pressure.

Morphological modelling, using a bottom-up, process-based model, has shown that it was possible to reproduce some of the general features observed in measured bathymetric changes over time-scales of up to 11 years. However, field measurements of both hydraulic and sediment related parameters covering suitable spatial and temporal scales are required to set-up, calibrate and verify such models. Without such data, bottom-up morphological models are best suited to the investigation of local changes over shorter time-scales (<1 year) where the impact of a scheme is greater than the natural variability.

Long-term morphological predictions for the Humber Estuary were carried out using a hybrid modelling approach. The model was run with a constant rate of sea level rise of 20cm/century and predicted that the estuary would achieve a state of dynamic equilibrium after a period of 35 years. The predicted demand for sediment was $0.18 \times 10^6 \text{m}^3/\text{yr}$, which is slightly less than observed mean rates based on historical changes for a period when sea level rise was between 1-2mm/yr (Geo2 Synthesis Report). This sediment demand was found to be smaller than the volume increase resulting from the increase in tidal volume as a result of sea level rise. The increased tidal volume results from a combination of the additional storage area and increased tidal range.

Based on investigations using a hybrid, entropy-based model, the Humber Estuary was shown to be close to its 'most probable' state in terms of tidal energy flux. Comparison with different estuaries confirms that the macro-tidal conditions and exponential form of the estuary result in an approximately exponential decay in energy along the estuary. In the Humber, for the first 20km upstream from the mouth, the estuary appears to be close to its most probable state. A trend towards this state was found for the section 20-50km upstream of Spurn. Further upstream the total energy flux is lower than the most probable, possibly a result of the constraint caused by flood defences and training walls.

Although the energy in the rivers is below the most probable, there is a tendency towards this level. In terms of the future development of the estuary, this approach can be used to determine whether a scheme is likely to help or hinder the system in reaching its preferred state.

Although the importance of biotic effects on intertidal sediment transport has been appreciated for several years, models of these processes are still at an early stage of development. Such modelling on Spurn Bight in the Humber Estuary confirmed that bioturbating and stabilising biota have a significant effect on sediment re-suspension in intertidal areas.

The BIOTIDE model predicted much higher accretion rates than net accretion obtained from observations over longer periods. Assuming the model produces realistic results, this suggests that long-term erosion/accretion patterns are the result of large, short-period variations. This agrees with observations from other intertidal sites within the estuary and highlights the difficulties involved in long-term morphological modelling using bottom-up, process-based models. To help gain a better understanding of the overall significance of biotic processes in the Humber estuary, further observations of short-term bed changes and biota are required.

6. ECOLOGY

Modelling of ecological indicators, or physiotopes, has been used to identify homogeneous areas where a combination of physical parameters can be found. Based on two sea-level rise scenarios, a 20cm/century increase would result in little change in the distribution of physiotopes. However, a higher rate of 60cm/century would result in more severe changes to the predicted physiotopes. The actual distribution of benthic organisms will also depend on their ability to adapt to changing environmental conditions. A better understanding of the link between the predicted physiotopes and the distribution of benthic organisms will be required through continued modelling and monitoring.

The analysis of macrobenthic samples of core samples, obtained between 1984-1998, was carried out to identify trends in dominant assemblages. A good fit was obtained between the distribution of predicted physiotopes and the present day macrobenthic assemblages. Further

developments of this approach require continued analysis of available physical and biological data and modelling of processes, such as sediment transport, not previously included in the modelling.

A bird population model has been applied to the Humber Estuary and has proved useful in predicting survival rates as a result of changes in estuary morphology. Ultimately the combination of both physical and ecological models will be required to provide an integrated approach for the assessment of environmental impacts.

7. IMPACT OF DEVELOPMENTS

Managed setback of small areas of floodplain will provide additional accommodation space to the estuary and are likely to have a limited effect on the long-term sedimentary evolution of the estuary.

Application of the ESTMORF model to a large, hypothetical reclamation on Spurn Bight, showed an initial morphological reaction of deposition during the first 5 years followed by erosion over a much longer time scale. The model suggested that erosion of $10 \times 10^6 \text{m}^3$ would take place over a 50-year period.

8. KEY FINDINGS

- Flood defences and reclamations in the estuary have significantly reduced sediment demand due to the reduction in accommodation space.
- The demand for sediment is currently greater than the supply which inhibits stratigraphic rollover.
- Deposition within long, exponential-shaped estuaries, such as the Humber, is highly dependent on river flows.
- The hybrid modelling approach provides a useful method for predicting long-term estuary morphology.
- Process based, bottom-up morphological models can provide estimates of general trends in erosion/accretion but would require detailed knowledge of environmental conditions to provide better predictions.
- Bottom-up models are best suited to modelling local impacts of schemes where changes in bed levels are likely to be greater than natural variability.

- Biological activity has a significant effect on erosion and deposition in intertidal areas.
- Physiotope mapping has shown that this approach can be used to provide a means for predicting the presence of macrobenthic assemblages.

9. REFERENCES

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DATABASE FOR EMPHASYS PROJECT - MERSEY ESTUARY

David Prandle

email: dp@pol.ac.uk

Proudman Oceanographic Laboratory, Bidston Observatory, CH43 7RA UK

1. LOCATION/GEOLOGY

The Mersey Estuary comprises a trained approach channel through offshore sand banks; a narrow deep inerodible entrance channel and a wide, shallow inner basin of shifting banks and channels. The present coarse is likely the result of postglacial influences. BGS have extensive bore hole data.

2. KEY CHARACTERISTICS

At the mouth spring tidal ranges approach 10 m and currents through the Narrow exceed 3 m. Almost the whole of the inner estuary basin dries out at low water on spring tides.

3. BATHYMETRIC DEVELOPMENTS

During the 18th and 19th centuries much intertidal marsh was reclaimed with a likely subsequent reduction in tidal volume. Bathymetric surveys were made every 10 years from 1861 and every 5 years since 1881, the last detailed survey was in 1997. These surveys suggest a loss of tidal volume of about 10% between 1936 and 1956. More recent analyses suggest a stable volume but significant readjustments in the internal areas. Annual dredging activity has reduced from peaks levels of the order of 10 million tonnes in the first half of this century to about 1 million tonnes recently. Of this approximately 10% of the total has been deposited within the estuary system.

4. DYNAMICAL OBSERVATIONS

The Mersey has the longest recordings of tides and mean sea levels in the UK. Concurrent recordings at up to 4 gauges exist for the lower estuary. Currents have been observed during

many experiments and over extended periods from moored buoys. The 15 day towed ADCP cross-sectional survey of 1992 is the most extensive of its kind in the UK and is ideal for rigorous evaluation of 3D models.

River flows have been recorded daily for over 25 years.

5. TEMPERATURE, SALINITY, METALS, NUTRIENTS, (ORGANICS)

Monthly Axial profiles (at HW spring) over 30 years.

Metal Flux cross sectional surveys, 5 boats x 13 hours on 4 sites.

6. SEDIMENTS

Several short local studies including salt marsh cores. Continuous recordings at two levels over 3 months from moored buoy.

7. CONCLUSION

The Mersey has amongst the best available data sets for UK estuaries, ranging from many detailed short studies, to longer term moorings through to over a century of bathymetric surveys and over two centuries of tide and mean sea level recordings.

The unusual shape dictates a bottom-up approach in parallel with Top-down.

The large size and enclosed location of the estuary make it interesting for studies of interaction between estuaries and adjacent coastal regions.

INTER-COMPARISON BETWEEN ONE, TWO AND THREE-DIMENSIONAL NUMERICAL MODELS

Adrian Wright and Paul Norton

email: pan@research.abports.co.uk

ABP Research & Consultancy Ltd, Pathfinder House, Maritime Way, Southampton SO14 3E, UK

1. INTRODUCTION

The aim of this investigation was to identify the relative strengths and limitations of different numerical models and where possible quantify the predicted differences in terms of reasonable fit and satisfactory fit. To gain an understanding into the strengths and limitations of different numerical modelling schemes, a comparison of water levels predicted by 1, 2 and 3-dimensional models was undertaken.

A 1-dimensional (1D) hydrodynamic model of the Humber Estuary was set-up using the Mike11 software developed by the Danish Hydraulics Institute. This type of model is often used to examine flows in open channel systems (e.g. canals, rivers and estuaries).

The 2 and 3-dimensional (2D/3D) hydrodynamic models of the Humber Estuary were configured using the Delft3D software developed by Delft Hydraulics. These models are typically used to examine complex free surface flow regimes in estuaries and coastal areas.

2. METHODOLOGY

An existing 1D representation of the Humber Estuary and the major tributaries was set-up using Mike11. The full extent of the river-estuary system was represented by cross-sections in the model from Spurn Head to Trent Falls and included the rivers Ouse, Trent and Don to their tidal limits. The Delft3D model extends from approximately 30km seaward of Spurn Head as far upstream as Trent Falls including a short section of the river Ouse (Figure 1). Delft3D can operate in both 2D/3D modes by simply modifying the number of layers represented in the model.

In the 1D model 4 cross-sections were chosen along the length of the Humber where measured data was available for comparison. (Figure 2) shows an example of the Humber network used in the 1D Mike11 model along with the approximate positions of the cross-sections examined.

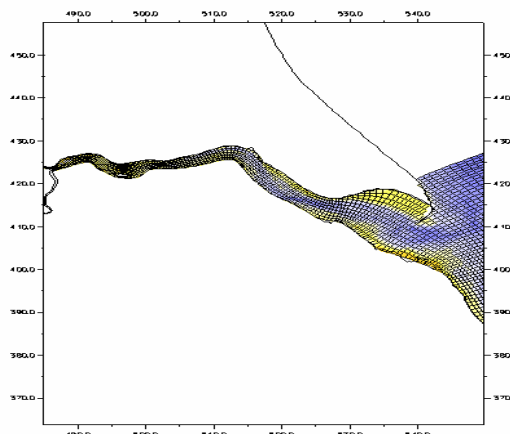


Figure 1 Curvilinear grid of the Humber Estuary used in Delft3D

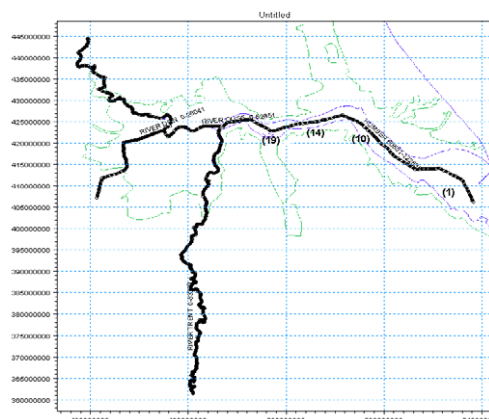


Figure 2 Network grid used in Mike11 showing the generalised positions of the cross-sections. The cross-sections chosen were, (1) Spurn Head; (10) Immingham; (14) King George Dock and (19) Hessle

The Delft3D model grid is curvilinear (Figure 1), which allows for a more accurate representation of the model domain in natural systems compared to a standard rectilinear grid. This enables the 2D/3D models to provide greater resolution in the areas requiring more detail such as river bends, for example. In order to compare model output with the 1D model (Figure 2), a series of grid points were selected to represent, as close as possible, the sections in the Mike11 model.

Mike11 is a 1D model and undertakes hydrodynamic calculations for each cross-section represented in the model. Generally, with more cross-sections represented, the better the model will perform but ultimately the model will be limited by its inability to simulate 2D and 3D processes, such as circulation patterns. In order to compare the 1D model results with output from Delft3D, data was extracted from the 2D/3D models at positions corresponding to each of the cross-sections chosen for comparison. Three points were extracted consisting of a point in the centre of the estuary and 2 points either side. The Mike11 values were then compared with an average of the 3 points from the 2D/3D model runs for each cross-section.

In the Mike11 model the sections were originally configured to be perpendicular to the main flow direction. Similarly, the curvilinear grid of the Delft3D model also provides sections across the estuary although the position and alignment is not necessarily the same as in the 1D model. This meant that a comparison of discharges between the models was not possible.

To allow direct comparisons to be made between the various models, the same initial and boundary conditions were applied in each case. The boundary condition for the seaward boundary was a series of water levels covering a 21-day period including both spring and neap tides. Each model included monthly mean freshwater flow inputs at the upstream limit of the model. The 2D/3D models also have a controlling water level boundary at Trent Falls, necessary because the river sections were not included in the model.

There were also differences between the model configurations as a result of the different approaches to model calibration, for example. The Mike11 model applied a variable Manning roughness coefficient whilst the Delft3D model used a constant Chezy bed resistance for the whole of the model area.

The simplified hydrodynamic equations used in the Mike11 model cannot represent density variations caused by salinity gradients, which can modify tidal flows in an estuary. When operating in 3D-mode, Delft3D can simulate both vertical and horizontal salinity gradients whilst in 2D model, only the horizontal gradient is accounted for. To allow for a fair comparison salinity effects were not included in 2D/3D models. Water temperature and density could be modified in

Delft3D but could not be specified in the Mike11 model.

3. RESULTS

Standard deviation values of the difference between the various model outputs were calculated in order to obtain a quantitative assessment of the agreement between each of the data sets. The standard deviation for each cross-section was calculated using:

$$Stdev = \sqrt{\frac{n \sum x^2 - (\sum x)^2}{n(n-1)}}$$

Where x = Water level at that point in time
 n = Number of time steps

Changes in the predicted water level brought about by the addition of salinity into the model equation are shown to have some effect. The difference in predicted water levels with salinity included and not included is between <1cm-6cm (Tables 1 and 2). Values for the 1D model with salinity included could not be calculated.

Table 1 Standard Deviation \pm values for numerical model comparison verses measured data – saline

Cross-sections	Neap tide			Spring tide		
	Field vs 1D (m)	Field vs 2D (m)	Field vs 3D (m)	Field vs 1D (m)	Field vs 2D (m)	Field vs 3D (m)
Spurn Head	N/A	0.114	0.156	N/A	0.004	0.005
Immingham	N/A	0.201	0.202	N/A	0.113	0.111
King George Dock	N/A	0.282	0.243	N/A	0.186	0.197
Hessle	N/A	0.259	0.297	N/A	0.278	0.268

Table 2 Standard Deviation \pm values for numerical model comparison verses measured data – fresh

Cross-sections	Neap tide			Spring tide		
	Field vs 1D (m)	Field vs 2D (m)	Field vs 3D (m)	Field vs 1D (m)	Field vs 2D (m)	Field vs 3D (m)
Spurn Head	0.056	0.121	0.160	0.004	0.007	0.007
Immingham	0.321	0.240	0.221	0.129	0.116	0.114
King George Dock	0.244	0.306	0.294	0.212	0.205	0.203
Hessle	0.254	0.299	0.321	0.245	0.301	0.285

3.1 Water Levels: Measured Data and 1D Comparison

Spring tide water level predictions at cross-section Spurn Head shows a slight deviation of $\pm 0.004\text{m}$ between the measured data and the 1D model. Spring tide water level prediction at Immingham shows the 1D model prediction to be approximately $\pm 0.13\text{m}$. Equally at King George Dock the 1D model predicted water level shows a deviation of approximately $\pm 0.2\text{m}$. A deviation of $\pm 0.25\text{m}$ was predicted at the cross-sectional area Hessele.

Water level predictions over the neap tide period for all cross-sections show higher deviations in the 1D model in comparison with the measured data. At Spurn Head the deviation between model and measured data was $\pm 0.06\text{m}$. The cross-section at Immingham showed the greatest deviation for all cross-sectional areas with a difference in predicted water level of $\pm 0.32\text{m}$ compared against the measured data. At King George Dock and Hessele the difference in observed and predicted water levels was $\pm 0.24\text{m}$ and $\pm 0.25\text{m}$ respectively.

3.2 Water Levels: Measured Data and 2D Comparison

At Spurn Head a slight deviation of $\pm 0.007\text{m}$ was predicted between the measured data and the 2D model for the spring tide. Spring tide water level prediction for the cross-section representing Immingham shows a deviation in the predicted high water and low water in the 2D model by $\pm 0.12\text{m}$ when compared against the measured data. At King George Dock in the 2D model the deviation in the predicted water level was $\pm 0.2\text{m}$ over the spring tide. At Hessele the deviation between measured and model data was $\pm 0.3\text{m}$ over the spring tide.

Neap tide water level predictions again show a higher deviation in the predicted high and low waters when compared against measured data, with the exception of Hessele. The 2D model predicted water levels at the cross-section Spurn Head shows a deviation of $\pm 0.12\text{m}$. At the cross-sections Immingham and King George Dock, a predicted water level deviation of $\pm 0.24\text{m}$ and $\pm 0.3\text{m}$ was recorded over the neap tide. At the cross-section Hessele the predicted deviation recorded was $\pm 0.3\text{m}$ over the neap tide.

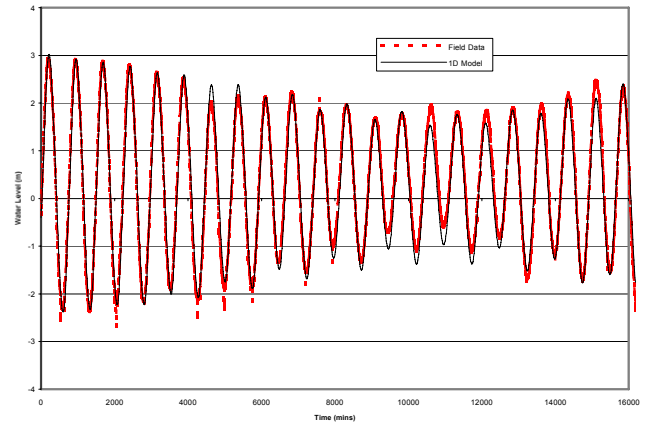


Figure 3 Predicted water levels in a 1-dimensional model in comparison with measured data at Immingham

3.3 Water Levels: Measured Data and 3D Comparison

Spring tide water level deviation between the measured data and the 3D model at Spurn Head show a small deviation compared with the measured data of $\pm 0.007\text{m}$. At the cross-section representing Immingham the deviation from the measured data is $\pm 0.1\text{m}$. At King George Dock there is an increase in the deviation with the 3D model predicting a deviation in water level of $\pm 0.2\text{m}$. At the cross-section Hessele the deviation measured is $\pm 0.29\text{m}$.

The neap tide water level prediction in the 3D model for the cross-section Spurn Head show a deviation from the measured data of $\pm 0.16\text{m}$. The cross-section at Immingham shows a deviation of $\pm 0.2\text{m}$ when compared against the measured data. At King George Dock the 3D model is predicting a slightly higher deviation of some $\pm 0.29\text{m}$ compared against the measured data. At Hessele the deviation from the measured data is $\pm 0.32\text{m}$.

4. DISCUSSION

Predicted spring and neap water levels in the 1D model are reasonably consistent with the 2D/3D models and on occasions show a better comparison with the measured data. Predicted neap cycle water levels in all models are fairly consistent in both the Mike11 model and Delft3D models, both predicting similar water levels. Deviation from the measured data increase along the length of the estuary during both the spring and neap tide for all models. The range in deviation from the measured data seen in all models is between $\pm < 0.01\text{m}$ at the start of the model run and $\pm 0.32\text{m}$ at the head of the estuary.

Differences in deviation between models is relatively low within the range of $\pm < 0.01\text{m}$ to $\pm 0.3\text{m}$.

The recorded deviations from the measured data may be accounted for by a variety of reasons. Initially, different calculations are used to derive the final water level prediction, the difference in computations could be in part an explanation for the observed values. However, possibly the major reason for the predicted water level deviation between Mike11 and Delft3D is because of the model set-up, a difference primarily in bed resistance. Also of note is the cross-sectional orientation.

Water level predictions over a spring tidal cycle show less of a deviation from the measured data than during a neap tidal cycle. An explanation for this observation may be accounted for by an increase in non-linear effects during the neap tidal cycle. The errors generated by differences in calculations of i.e. bed shear, bathymetry etc. make neap tide cycles more difficult to accurately predict. Other explanations include greater influence of bed resistance parameters during the neap tidal cycle and the reliability of the measured data over a neap tidal cycle.

Predicted water levels were with and without salinity included in the Delft3D model. The standard deviation from the measured data was seen to decrease in the 2D/3D model with salinity included. An estimation of the effects salinity has on water level prediction is of note and should be taken into account when constructing a hydrodynamic model. Here, this example shows the difference in predicted water level introduced by not including salinity is in the order of some $\pm < 1\text{-}6\text{cm}$.

There is only a reasonable variation in water level along the estuary between the Mike11 and Delft3D models. The difference in predicted water level is no greater at positions around bends than it is at straight sections, in fact the greatest difference between predicted and measured data typically was at Immingham. Therefore, in this study the 1D model has provided a good representation of water level variations along the estuary, which includes bends that compare favourably with the 2D/3D model results. This can partly be attributed to the detailed calibration procedure used when setting-up the 1D model.

An inter-comparison of the 2D and 3D model predicted water levels show a close comparison with a standard deviation from the measured data in the range of $< 0.1\text{-}0.4\text{m}$ over a neap tide and $\pm < 0.1\text{-}0.2\text{m}$ over a spring tide. Considering that both models were run using the same parameters and computational calculations, it is not surprising that the results obtained show very similar water level predictions. A 3D model with 3 layers can be expected to produce results similar to a 2D model whilst with 10 layers the results might be quite different. The difference in the results would be highly dependent on the importance of 3D flow effects. In this case 5 layers were used to represent variations through the water column. Another explanation may be that the estuary has little change in structure through the vertical, which would account for the high level of agreement between the 2D/3D models.

5. CONCLUSION

The point of this exercise was to compare one, two and three-dimensional models and if possible quantify in terms of reasonable and satisfactory fit. The guidelines used to quantify the terms satisfactory and reasonable fit are those suggested by J. Bartlett (1998), the author suggests a degree of accuracy of $\pm 0.1\text{m}$ at the mouth and $\pm 0.3\text{m}$ at the head of the estuary as guidelines of validation for the hydrodynamic model.

At Spurn Head the water level deviation seen in the Delft3D and Mike11 models over a spring tide was $< \pm 0.1\text{m}$ and can be considered a satisfactory fit. The 2D and 3D models showed a slightly higher deviation than the $\pm 0.1\text{m}$, and show only a reasonable fit. The 1D model showed a satisfactory fit over the neap tide at Spurn. The 2D and 3D models predicted water levels seen at Immingham for both spring and neap cycles can also be considered a satisfactory fit. The 1D model showed a reasonable fit over the neap tide but a satisfactory fit during the spring tidal cycle. At King George Dock in all models over the spring tide the standard deviation is within the $\pm 0.3\text{m}$ and can be considered a satisfactory fit. Over the neap tide the 2D model predicted water level is greater than the ± 0.3 and can only be considered a reasonable fit. In the 1D and 3D models a satisfactory fit was predicted over the neap tidal cycle. Predicted neap water levels at Hessle for the 3D model shows only a reasonable fit were as in the 1D and 2D models a satisfactory

fit was predicted. Over the spring tide a satisfactory fit was seen in all models.

In this investigation the 1D model has shown similar deviations from the measured data as the 2D and 3D models, and in some examples a better comparison was recorded. This is probably due to a more detailed cross-sectional area than was set-up in the Delft3D model. Similarly, a criticism of the 1D model is its poor ability to accurately predict hydrodynamic actions around bends or obstacles. In terms of water levels, since a higher deviation was not predicted at Kings Dock this criticism may not be applicable. Water level predictions are very similar when 2D/3D effects are included, a comparison of water velocities might have shown a better indication of the effects not modelled by Mike11.

The strengths of a 1D model include its relative simplicity and its computational speed. In comparison, Delft3D requires much longer run-times of several hours compared with a few minutes for Mike11 simulations. Delft3D is not as simple to set-up and requires more time to configure and is therefore, more costly to operate. However, Delft3D has the advantage of being able to predict small-scale hydrodynamic changes at both coarse and fine scales.

An inter-comparison of models in this investigation has shown that generally a satisfactory fit in water level prediction could be achieved in a 1, 2 and 3-dimensional model over spring and neap tidal cycles. Figure 3, illustrates the close similarity between the measured data and the 1D model data. Only a reasonable fit in comparison to the measured data was seen on one occasion in each of the models, this was probably due to an artefact of the model set-up with the deviation generally being no greater than 2cm.

Overall, in this investigation the 3D model has generally shown to be the most accurate and reliable, predicting water levels closer to the measured data than the 2D and 1D models, this is true both during the neap and spring tidal cycles. The 2D model predicted water levels are generally more accurately than the 1D model. However, the 1D model has shown comparable accuracy to the Delft3D model and in some examples a better water level prediction.

6. REFERENCES

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TWO AND THREE DIMENSIONAL MODELLING OF SEDIMENT TRANSPORT MECHANISMS IN THE MERSEY ESTUARY

Jeremy Spearman*, Michael Turnbull*, Christopher Thomas† and Alan Cooper*

email: jez@hrwallingford.co.uk

*H R Wallingford, Howbery Park, Wallingford, Oxon, OX10 8BA UK

†Oxford Brookes University, UK.

1. INTRODUCTION

As part of the EMPHASYS project 2D and 3D hydrodynamic and sediment transport models were used to investigate the historic sediment transport processes that have occurred in the Mersey Estuary, UK. The bathymetric changes in this estuary have been well documented over the last century by a series of cross-sectional surveys that have taken place at the same locations, at a spacing of 200-500m throughout the estuary. Over this period the Mersey Estuary has experienced significant estuary wide changes in bathymetry. Between the turn of the century and 1977 a significant volume of accretion occurred, and the volume capacity of the estuary reduced by approximately 10% (Price and Kendrick, 1963). Since this time the estuary has more-or-less stabilised, even showing signs of a small increase in volume capacity (HR Wallingford, 1983, Thomas, 1999).

The onset of the morphological evolution described above coincides with the construction of training walls in the Outer Estuary in Liverpool Bay, which took place over the period 1906-1936 (Figure 1). The walls were built to stabilise the main navigation channel into the Estuary. The coincidental timing of both events has been identified as the most probable cause of the estuary wide accretion, although dredging practice has also been pointed to as an additional, but less important, contributory cause (Price and Kendrick, 1963). The suggestion of these authors is that the primary mechanism for sedimentation in the Mersey was the creation of a sediment pathway from a source of sediment in Liverpool Bay to the mouth of the estuary which experiences a net landward residual current (caused by gravitational circulation) resulting in landward movement of sediment near the bed.

The primary objective of this study was to examine the validity of the Price and Kendrick hypothesis using 2D and 3D models and to compare the types of results that are gained from these different modelling tools. The secondary objective was to demonstrate the importance of sediment exchange at the mouth of an estuary when considering long term estuary evolution.

2. METHODOLOGY

2.1 Hydrodynamic models

The 2D and 3D hydrodynamic models used in this study were part of the TELEMAC suite, a finite element model system developed by LNH, Paris, which uses an unstructured grid. Both models were set up identically using the same grid and boundary conditions. The model area covered an area from Fleetwood in the north to Llandudno in the west and includes the Mersey and Dee Estuaries (Figure 2). The model resolution was 100-300m in the Mersey Estuary and 200-400m in Liverpool Bay, increasing to 6km at the offshore boundaries. The 3D model incorporated 5 vertical layers which were equally spaced throughout the water column. The offshore water level boundary condition was taken from a previous HR Wallingford model of Liverpool Bay (HR Wallingford, 1989).

The 2D model was run without salinity effects whereas the 3D model was run with varying density. For this an initial salinity distribution was derived from a previous study (HR Wallingford, 1985) which was slightly redistributed by the model during the simulation. Calibration was undertaken using the 1977 bathymetry by comparing model predictions of current patterns in Liverpool Bay with Admiralty Tidal Diamond Data and by comparing model predictions of water levels within the Mersey with measurements taken from West (1980). The models reproduced these observations well. The

hydrodynamic models were used to derive the residual tidal movements in Liverpool Bay, and to produce the necessary input to sand transport and particle tracking models.

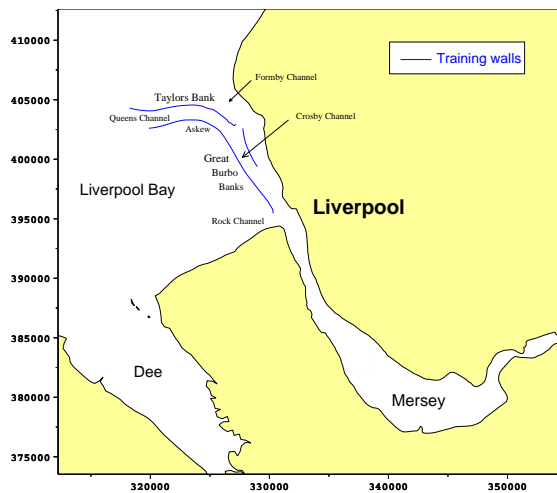


Figure 1 Mersey Estuary and Training Walls

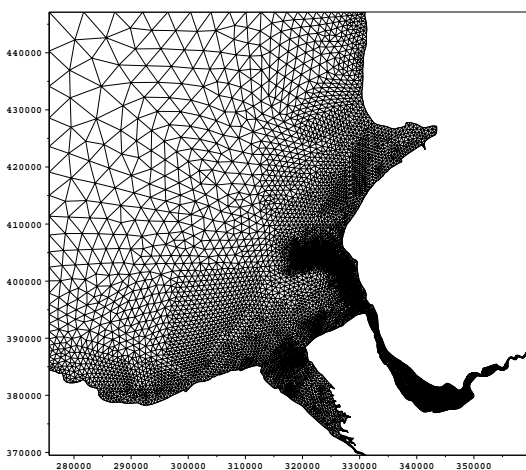


Figure 2 Modelled area and grid

The 2D model was run without salinity effects whereas the 3D model was run with varying density. For this an initial salinity distribution was derived from a previous study (HR Wallingford, 1985) which was slightly redistributed by the model during the simulation. Calibration was undertaken using the 1977 bathymetry by comparing model predictions of current patterns in Liverpool Bay with Admiralty Tidal Diamond Data and by comparing model predictions of water levels within the Mersey with measurements taken from West (1980). The models reproduced these observations well. The hydrodynamic models were used to derive the residual tidal movements in Liverpool Bay,

and to produce the necessary input to sand transport and particle tracking models.

2.2 Particle tracking model

The particle tracking model used in this study was SEDPLUME-3D, which uses 3D hydrodynamic data and a random walk approach to reproduce the advection, diffusion, settling and erosion of sediment particles under the action of tidal currents. In this study the model was used primarily to investigate the advection of particles under the different tidal current fields corresponding to three different historic bathymetries. The particle tracking model was used to track the movement of discrete particles from different locations in Liverpool Bay and to identify the source of sediment that could enter the estuary under different historical conditions.

The evidence from bed sampling is that the sedimentation occurring in the Mersey Estuary over the last century is predominantly sand (Kendrick, pers.comm.). For this reason the particle transport was modelled as sand particles moving near the bed.

2.3 Historic bathymetries

The 2D, 3D and particle tracking models were run for the years 1906, 1936 and 1977. These three years correspond to times just before training wall construction when the Mersey appeared to be roughly in equilibrium, after training wall construction when the estuary appeared to have been evolving and when the estuary appeared to have re-attained a degree of equilibrium. The Liverpool Bay and Mersey bathymetries were taken from Mersey Harbour Authority Charts and supplemented by Admiralty charts for offshore areas. The crest of the training walls was set to 2.8mCD in Crosby Channel and 1.6mCD further offshore.

Although the training wall was not fully completed in 1936, the last 1-2km of the training wall being completed in 1948, the entire training wall was modelled with the 1936 bathymetry.

3. RESIDUAL CURRENT PATTERNS

Using the 2D and 3D hydrodynamic output, the residual current velocities throughout the model area were identified. The (depth averaged) 2D results for the years 1906 and 1977 are presented in Figure 3 and show the following:

- All sets of results indicate a net seaward residual within the Mersey and the outer navigation channel.
- Within the estuary the 1906 and 1936 results show a weaker seaward residual at the estuary mouth.
- There is no clear pathway of sediment movement to wards the mouth of the Mersey from the west of Liverpool Bay.

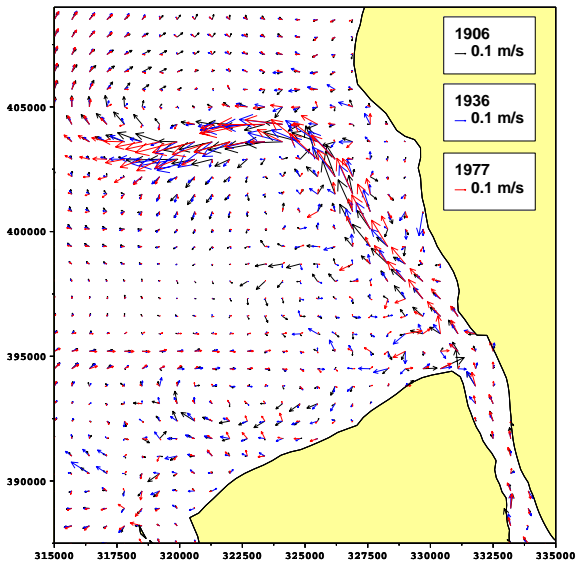


Figure 3 Residual spring tide depth-averaged current patterns, 1906, 1936 and 1977 scenarios

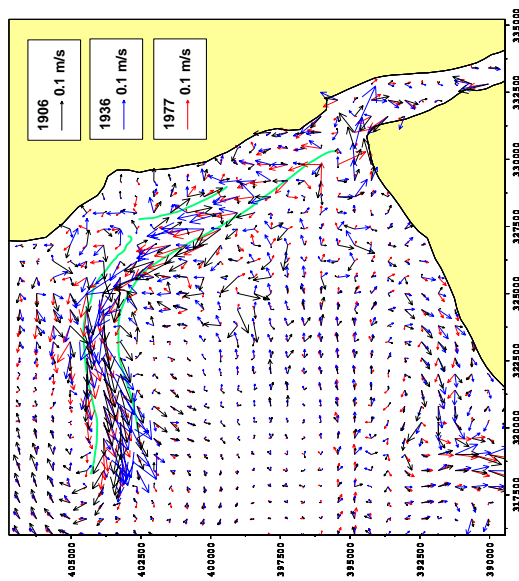


Figure 4 Residual spring tide near bed current patterns, 1906, 1936 and 1977 scenarios

The results for current patterns at the bed for the 3D model for the years 1906, 1936 and 1977 are shown in Figure 4. The 3D results show the following:

- All sets of results indicate a net landward residual on the east side of the estuary mouth and a seaward residual on the west side.
- The results suggest the presence of a transport route from the west to the estuary mouth, with a generally stronger transport flux in 1936 compared to 1906 and 1977.

The following points can be made:

- The 2D results are unable to reproduce the landward residual current velocity within the Mersey that is caused by gravitational circulation.
- The 2D results are unable to reproduce the eastward transport route in the Bay.

4. RESIDUAL SAND TRANSPORT PATTERNS

Sand moves both a suspended load and as bedload. In this paper it is bedload that is primarily considered, the underlying assumption being that the historical patterns of suspended load will follow the same trends as those for bedload. In reality there will be some differences due to the lagrangian nature of suspended load.

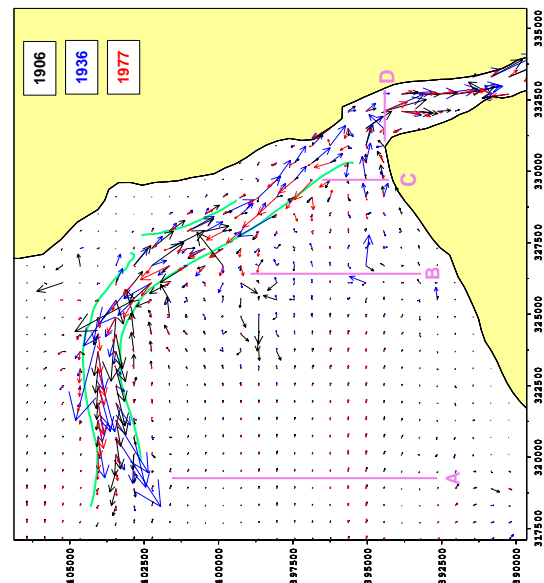


Figure 5 Residual (potential) bedload transport, 1906, 1936 and 1977 scenarios

From the 3D model output the residual bedload sand transport was calculated for the years 1906, 1936 and 1977 are shown in Figure 5. The vectors shown represent the residual transport flux per spring tide for medium sand ($D_{50} = 0.4\text{mm}$). The main features of the results are as follows:

- Analysis showed that the flux of material through Liverpool Bay (the integrated flux through sections B and C on Figure 5) increases up to 1936 and reduces again after the next 40 years. Furthermore the ability of the currents at the mouth of the Mersey (the integrated flux through section D on Figure 5) to transport material in a landward direction is broadly the same in 1906 and 1936 but reduces dramatically in 1977.
- There is a net eastward flux of sediment towards Liverpool Bay. This agrees with the direction of sediment transport published in (MAFF, 1981).
- The flux eastwards through the Bay is larger in 1936 and 1977 compared with 1906
- The flux outward along the Crosby channel becomes more strongly landward in 1936 compared with 1906 and then more strongly seaward in 1977.
- There is net influx everywhere along the entrance to the mouth and this net influx is smaller in 1977 compared with 1906 and 1936.

It is important to note that the sand transport patterns show significant differences when compared with the near bed residual current directions shown in Figure 4. This is because the direction of sand transport, especially bedload, is dominated by the direction of peak current speed. This phenomenon causes the net landward movement of sediment within the Mersey to be more significant since the Mersey experiences bigger current speeds on the flood tide. These effects also explain why the overall pattern of bedload sediment movement in Liverpool Bay is different from both the depth-averaged and near bed residual current patterns.

5. HISTORICAL CHANGES TO SEDIMENT TRANSPORT PATTERNS IN LIVERPOOL BAY

Using different historical sources (Price and Kendrick, 1963, Cashin, 1949, Water Pollution Research, 1938, HR Wallingford, 1958, Mersey Conservator Annual Reports to Secretary of State, 1950-77) and by comparing digitised bathymetric charts an attempt was made to summarise the changes occurring in Liverpool Bay and the Inner Mersey over different historical periods, and to estimate the annual flux of *sandy* material entering the Liverpool Bay/Mersey system. The results are shown in Table 1.

Table 1 Historical volumetric changes, dredging and disposal in Liverpool Bay and the Mersey

Period	Net volume change Mersey change		Dredging in outer channel	Dredging in Inner Mersey (channels only)	Disposal within system
	Liverpool Bay	Inner Mersey			
1833-	71 Mm ³	-16 Mm ³	0 Mm ³	0 Mm ³	0 Mm ³
1871-1906	65 Mm ³	5 Mm ³	<i>After 1890</i> 60 Mm ³	<i>After 1890</i> 15 Mm ³	<i>Not known but small</i>
1906-1936	-22 Mm ³	33 Mm ³	180 Mm ³	65 Mm ³	30 Mm ³
1936-1977	130 Mm ³	40Mm ³	135 Mm ³	75 Mm ³	25 Mm ³

The numbers shown are relatively crude as there is always some uncertainty in historical records especially when comparing numbers from different sources. However, the accuracy is certainly enough to identify the main trends of the historical changes. The main features are as follows:

- The dominant contribution of dredging, particularly in the outer channel, to the sediment budget
- The accretion in Liverpool Bay before the construction of the training walls
- The net erosion that took place during the thirty year period of training wall construction
- The significant accretion in Liverpool Bay over the period 1936-1977.

Figure 6 shows the changes that occurred in Liverpool Bay between 1906 and 1936. Notice the area of erosion on the Great Burbo Banks, which particle tracking confirmed as a principle source of sand moving into the estuary.

The results of this analysis indicate that before the construction of the training wall there was net deposition in Liverpool Bay (but not necessarily the inner Mersey itself). This deposition is probably a reason for to the deterioration of the Formby and Rock channels which were, before the mid-1800's, the principal entrances to the Port of Liverpool. The principal impact of the training walls therefore seems not to have increased the rate of transport of material *into* Liverpool Bay but rather to increase the rate of transport of material *from* Liverpool Bay into the inner Mersey. Over the 70 year period after the start of the Training Wall construction the morphological changes in the Mersey Estuary eventually resulted in a reduced residual landward transport of material through Liverpool Bay and into the mouth and reversed the direction of transport in the Crosby Channel, thus reducing the overall influx of material into the inner Mersey. The influx of sand into the inner Mersey caused the area of intertidal flats to increase (Water pollution research, 1938). This had the morphological feedback effect of reducing the period of the ebb tide with respect to the flood tide, thus enhancing ebb currents speeds with respect to flood current speeds (Dronkers, 1996, Friedrichs and Aubrey, 1988) with a corresponding reduction of landward sand transport. This reduction in landward transport slowed down the loss of estuary capacity

to the point where the net influx of sand reduced to near zero.

For a more complete assessment of the sediment transport budget in the Bay it is necessary to consider the flux of sand into Liverpool Bay – necessitating the consideration of suspended load as well as bedload. In this analysis the role of wave action in enhancing sand transport should also be included. Furthermore, since the dredging volumes dominate the sediment budget, and a significant proportion of dredge material results from mud infill it is necessary also to consider the transport and settling of muddy sediment into the outer channel and inner Mersey.

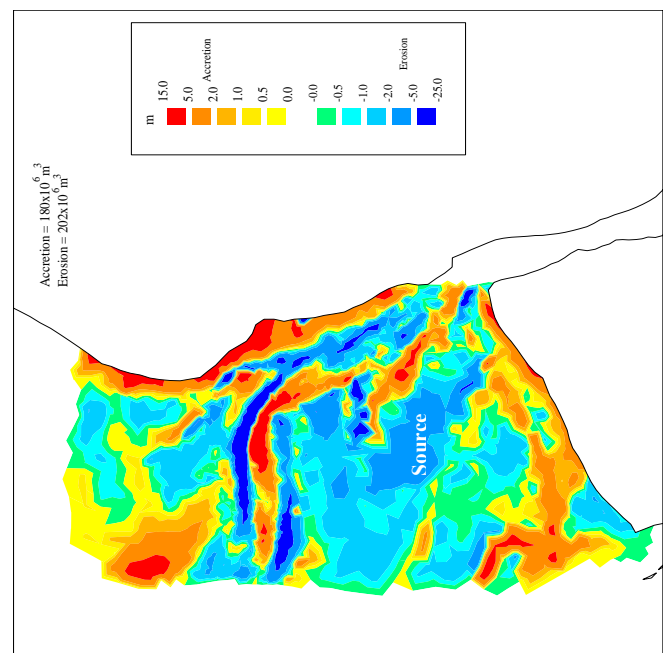


Figure 6 Bathymetric changes, 1906-1936

6. CONCLUSIONS

This study shows some of the potential benefits and related problems of using available 2D and 3D modelling tools to understand sediment transport mechanisms. It has been demonstrated that the consideration of 3D hydrodynamic processes can be very important for understanding transport mechanisms and that consideration of sediment transport mechanisms, rather than residual currents alone, can also be crucial for understanding the pattern of sediment movement. Thirdly the use of historical bathymetric, dredging and disposal data to form a pattern for historical trends is invaluable, although due consideration should be given to the accuracy of such data sources.

The results also clearly demonstrate the importance of considering what is happening in the outer estuary or offshore area as well as what is happening within the estuary itself. The evidence suggests that the driving force for the observed morphological evolution of the Mersey Estuary, caused by the formation of a new sediment transport path, itself produced by a change in current patterns, is located outside of the Estuary, in Liverpool Bay. Therefore, in order to reproduce the correct sediment transport mechanisms it is essential to include the Bay in the investigation. This principle may be more obvious in the case of the Mersey, where major works have taken place in the outer estuary, but is a general principle that should be considered for every study of estuary-wide sediment transport. With a few notable exceptions, the sediment transport within UK estuaries is a function of the exchange at the estuary mouth, itself a function of current patterns and sediment availability in the offshore area.

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MODELLING TIDE AND MARINE SEDIMENTS IN THE MERSEY WITH 1-D, 2-D AND 3-D MODELS – A CRITIQUE OF THEIR RESPECTIVE CAPABILITIES AND LIMITATIONS

David Prandle and Andrew Lane

email: dp@pol.ac.uk

Proudman Oceanographic Laboratory, Bidston Observatory, CH43 7RA, UK

ABSTRACT

Results are shown for simulation of tidal propagation and SPM (suspended particulate matter) transport in the Mersey estuary using 1-D (cross-sectionally averaged), 2-D (vertically averaged) and 3-D models. These results are compared with observational data from two earlier studies. The applicability of each model is summarised together with limiting constraints. The success in simulation of tidal propagation is contrasted with the wide range of sensitivities involved in simulating SPM. Future opportunities to develop robust, portable 3-D model are highlighted together with suggested related observational and process study requirement for Phase 2 of this programme.

1. OBJECTIVES

The objectives of the study were: (i) to provide a critique of 1-, 2- and 3-D estuarine models, indicating their capabilities and limitations for predicting tidal propagation, salinity and sediment intrusion, (ii) to link this assessment of performance to the availability of observational data and to the accuracy and robustness of related process algorithms.

Related tasks were:

- (i) To formulate 1-, 2- and 3-D models of the Mersey to examine tidal, salinity and SPM distributions.
- (ii) To identify respective applicability's in relation to studies of suspended sediment concentrations.
- (iii) To indicate observational and process-study requirements for Phase 2 of this programme.

2. INTRODUCTION

Latest bathymetric data (1997) was made available by E.A. Warrington and used jointly with parallel HR studies.

The 1-D model adopted a triangular cross section, the 2- and 3-D models both used the same 120 m rectangular grid. All three models used finite-difference solutions, explicit for

horizontal integration and implicit for vertical (current profile) integration.

Simulation of SPM involved 'random-walk' particles in the 2-D and 3-D models and sectionally-averaged concentrations in the 1-D model. The 1-D model formulation follows the description provided in the accompanying EMPHASYS report on the top-down modelling. The 2-D model follows conventional explicit finite-difference techniques (e.g. Prandle 1984). The 3-D model is a simplified version of POLCOMS with vertical eddy viscosity and diffusivity prescribed in a time and depth-averaged form $0.5\hat{U}D$ where \hat{U} is the M_2 tidal velocity amplitude. This expedient was used to minimise simulation times (spring-neap cycles are essential for SPM studies), and considered acceptable considering the flow ratio of 0.01 (Section 3), however more stratified estuaries would necessitate the direct computation of the turbulence profile – including the influence of both temperature and salinity density variations.

As in the accompanying EMPHASYS top-down study, only the influence of marine sediments is considered here.

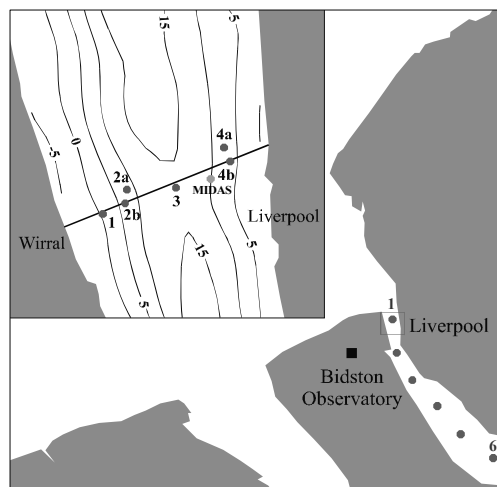


Figure 1 The Mersey Estuary with the location of the monitoring transect, and model output positions 1 to 6

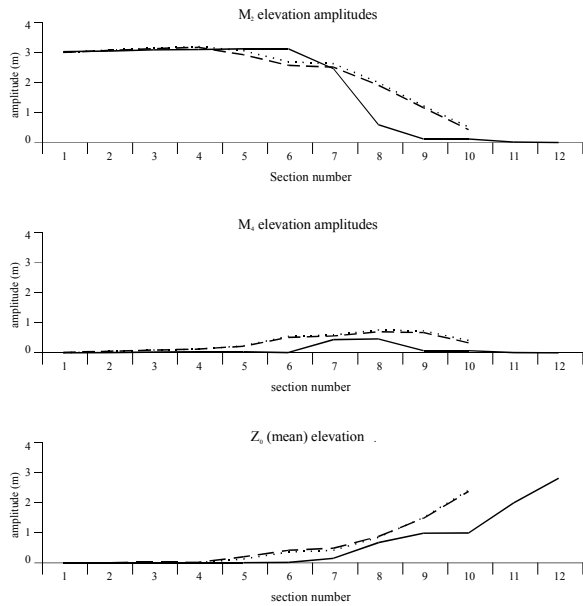


Figure 2 M_2 , M_4 and Z_0 (mean) elevation amplitudes from 1-D (solid), 2-D (dash) and 3-D (dot) models

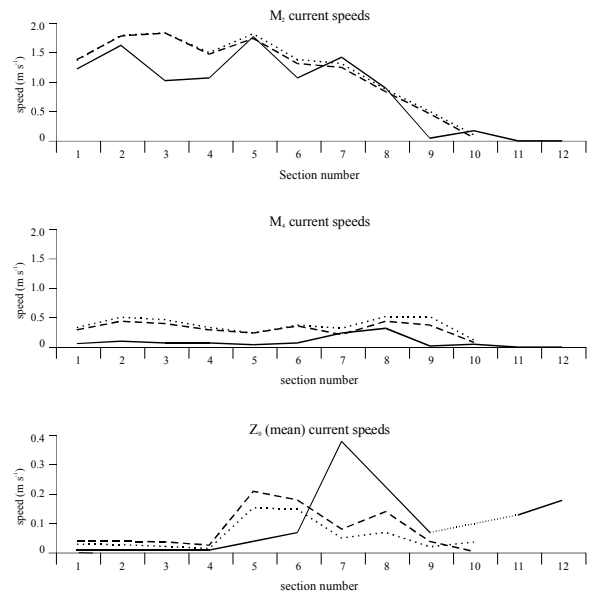


Figure 3 M_2 , M_4 and Z_0 (residual) current speeds from 1-D (solid), 2-D (dash) and 3-D (dot) models

Table 1 Results of tidal analysis of elevations recorded by the Liverpool tide gauge during July 1992

Constituent	Amplitude (m)	Phase (°)
Z_0	5.18	—
MSf	0.04	279
N_2	0.59	301
M_2	3.07	325
S_2	1.00	11
M_4	0.24	210

The Z_0 values are measured with respect to chart datum.

3. THE MERSEY ESTUARY

The Mersey is a macrotidal estuary with tidal ranges at the mouth varying from 4 to 10 m over the extremes of the spring-neap cycle (Figure 1). The Narrows is approximately 1.5 km wide with a mean depth of 15 m, and tidal currents through this section can exceed 2 m s^{-1} . Freshwater flow into the Mersey Estuary, Q_f , varies from 25 to $200 \text{ m}^3 \text{ s}^{-1}$ with a mean flow ratio ($Q_f \times 12.42 \text{ hr/volume}$ between high and low water) of approximately 0.01. Low ratios of less than 0.1 usually indicate well-mixed conditions, though in certain sections during part of the tidal cycle, the Mersey is only partially mixed. Additional freshwater enters via the Manchester Ship Canal.

Historically, the Mersey has been seriously polluted by industrial discharges and adjacent sea dumping. A comprehensive programme is presently being undertaken to improve water quality in the river (National Rivers Authority, 1995).

3.1. Surges: correlation of wind, residual elevations and residual currents

The residual ('surge') time series was extracted from the tide gauge data for July 1992 recorded at Liverpool (Gladstone Dock), a maximum correlation coefficient between wind and residual elevation of 0.54 was calculated for a time lag of 5 hours. This is improved when the hourly residuals are first filtered using a 13-hour running-average (to remove extraneous semi-diurnal variations), giving a correlation of 0.66 for a time lag of 8 hours. There is no significant linear correlation between the month-long time series for residual currents and residual elevations. The low correlation with the wind record suggests that, away from the immediate surface, the wind did not have a direct influence on currents in the Mersey during this survey (calm weather conditions were sought to minimize non-tidal effects). However, the wind has a significant correlation with residual elevation – possibly due to processes external to the estuary.

3.2. Tidal currents

Prandle et al. (1990) described earlier attempts at monitoring currents in this estuary using electromagnetic current meters mounted on a floating buoy. In a subsequent exercise in 1992, the ADCP, electromagnetic and mechanical current meters were mounted on PMPs (POL monitoring platform) across a section of the estuary. In addition, the Environment Agency's

vessel *Coastal Guardian* was used for continuous ADCP transects across the Mersey Narrows over a complete 15-day spring-neap tidal cycle. These towed data provided detailed 3-D spatial patterns of current ellipse distributions for the major constituents. Analyses of towed ADCP data present difficulties in their transformation onto a geographic reference frame, relative to which there is also an irregular sampling frequency.

3.3. Suspended particulate matter

SPM observations at the MIDAS buoy location were made by the E.A., Warrington, analyses of these data are described by Prandle et al. (1990).

4. MODEL RESULTS

Numerical modelling of tidal and surge elevations in estuaries is well developed, and generally requires only a limited number of elevation measurements for validation. However, tidal currents vary over much shorter spatial scales with localised changes in bathymetry, creating small-scale variability in both the vertical and horizontal dimensions. These changes in velocity produce even more localised variability in erosion, deposition and transport of suspended material. Thus, numerical modelling of contaminant fluxes is less well developed and requires more detailed spatial resolution, with a corresponding increase in the resolution of observational surveys used for validation.

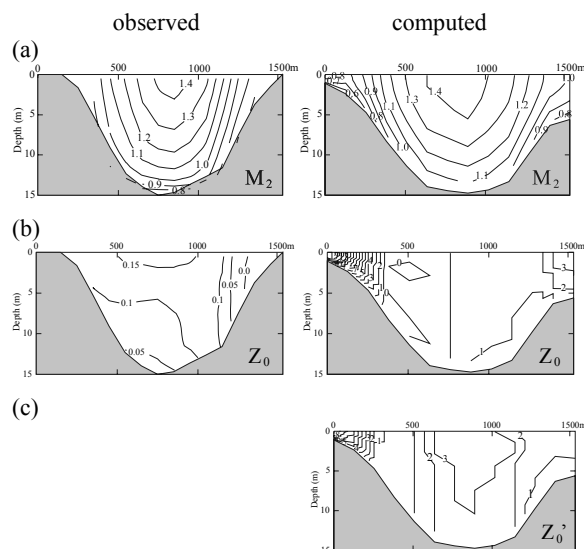


Figure 4 Observed and computed cross-sectional (see Figure 1) current distributions M_2 and Z_0 (residual). (a) M_2 observed vs computed, (b) Z_0 observed vs computed, tidal mean of currents at fractional (coordinate) heights, (c) Z_0 computed, tidal mean of 'transports' at fractional heights (i.e., $u_o(t)$)

4.1. Tidal elevations and currents

Axial distributions: Figures 2 and 3 show M_2 , M_4 , and Z_0 (residual) tidal elevation and current amplitudes, respectively, for locations along the river as calculated by 1-, 2-, and 3-D models. There is generally good agreement for the principal M_2 constituent and likewise for its 'first harmonic' M_4 (generated via various non-linear interactions of M_2). However, the residual currents yield significantly different results, this is partly attributable to the manner in which 'residual' currents are defined.

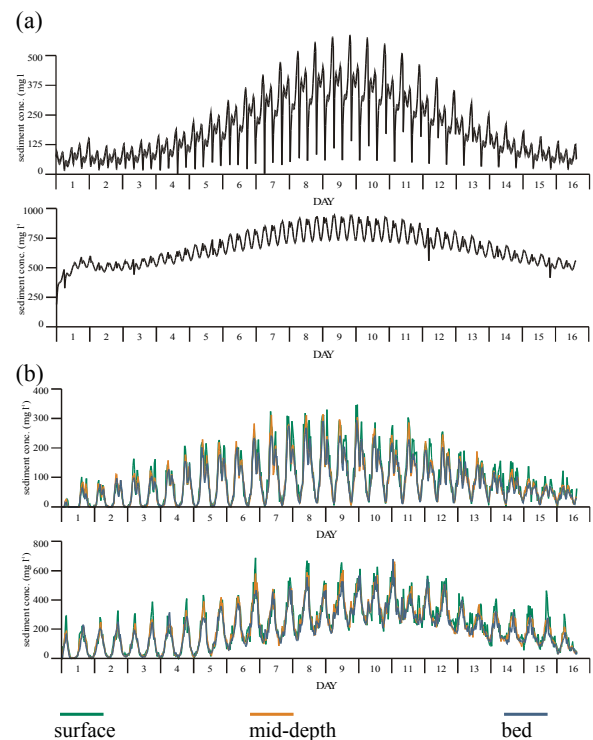


Figure 6 Suspended sediment concentrations from the (a) 1-D, and (b) 3-D models for $w_s = 0.005 \text{ m s}^{-1}$ (above) and $w_s = 0.0005 \text{ m s}^{-1}$ (below)

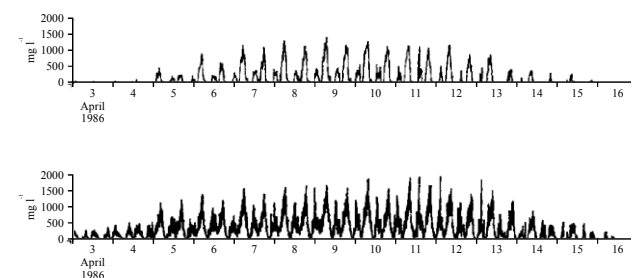


Figure 7 Observed suspended sediment concentrations at surface (above), and mid-depth (below)

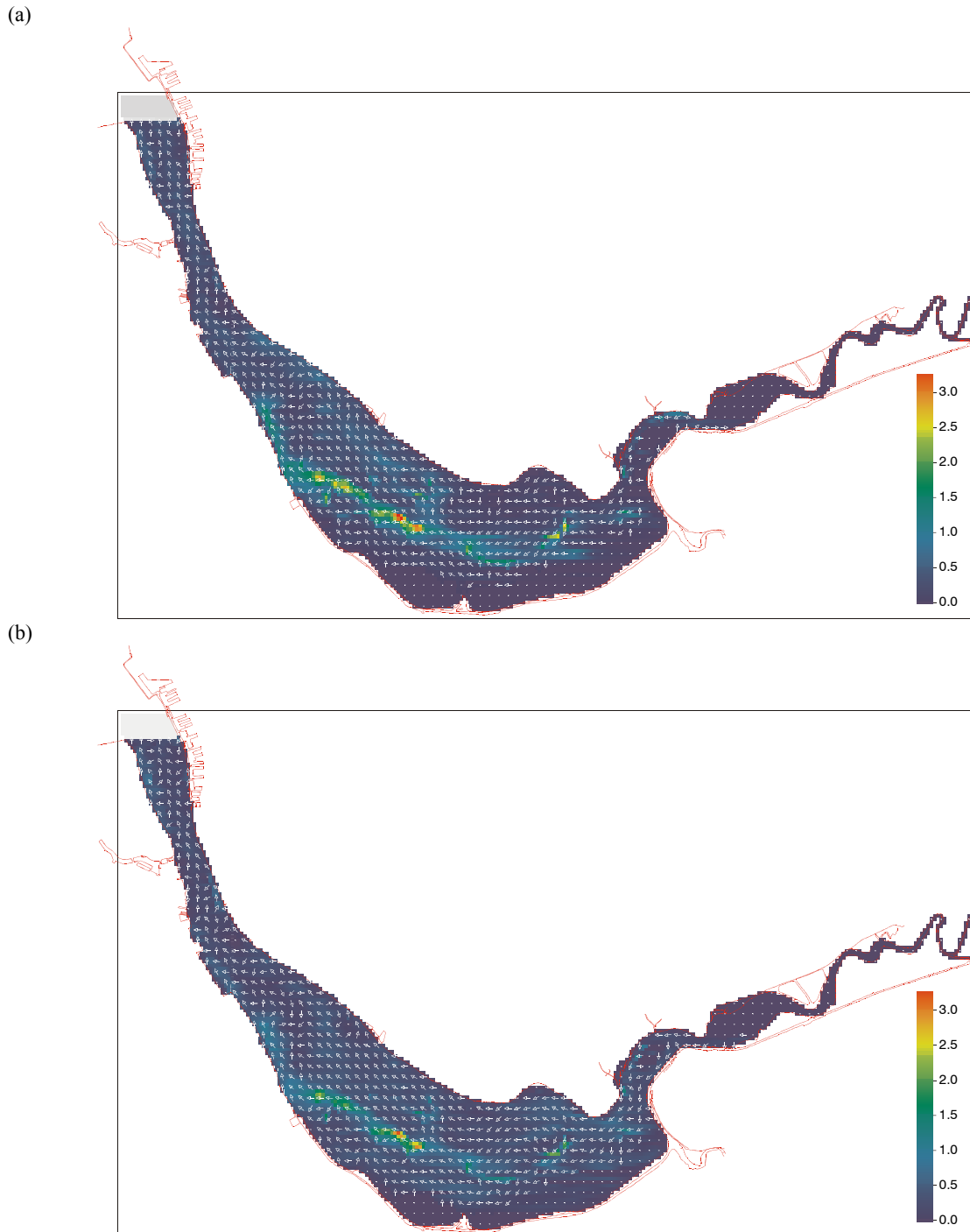


Figure 5 Residual currents at sea bed in cm s^{-1} , (a) 2-D depth averaged model (b) 3-D ($\sigma = 0.05$) model

Cross-sectional distribution: (Midas section, Figure 1) (3-D model results and observations). The M_2 constituent dominates the time series at the Midas section, having a maximum amplitude of 1.5 m s^{-1} , and is almost rectilinear (with a depth-mean eccentricity of -0.03). The N_2 constituent has approximately half the amplitude of the S_2 constituent which, in turn, is about one-

third of the magnitude of the M_2 amplitude. Vertical profiles of the axial component of the above current ellipses along the transect line are shown in Figure 4 for M_2 and the residual Z_0 . For M_2 , the largest currents occur at the surface in the centre of the channel, decreasing with distance towards the solid boundaries. A simplified model based on a theory by Prandle (1982) is able to reproduce the salient

characteristics indicating that most of the vertical and transverse variability in the tidal current distribution represents a localised response to depth variations.

Residual currents In analysing the towed ADCP data and in the 3-D model a modified sigma coordinate framework was adopted combining a product of current at a fractional height ($\sigma = 0$ at the bed, $\sigma = 1$ at the surface) with the tidally varying parameter $(D + \zeta)/D$, where D is the depth of water below chart datum, and ζ is the elevation.

By contrast with the good agreement between observations and models evident from the M_2 , the lack of agreement for Z_0 can be variously attributed to: (i) salinity effects, (ii) inherent inaccuracy of observations for Z_0 and (iii) the complexity of precise definition of Z_0 in an estuary with large amplitude:depth ratio. The latter point is discussed by Lane et al. (1997) and illustrated by the difference in Z_0 as shown in the model results Figures 4b and 4c.

Sea-bed residual currents (2-D and 3-D model results)

Figure 5 shows estuarine-wide residual currents calculated from the 2-D model (i.e. depth-averaged Eulerian) and at the sea-bed in the 3-D model. These differences indicate how differing residual pathways can be expected for coarser ('bed-load') sediments as opposed to finer sediments which extend higher through the water column.

4.2 Suspended particulate material (SPM)

Figure 6 shows SPM time series from the 1-D and 3-D models at the MIDAS (Mersey Inshore Data Acquisition Station) position in the Narrows for which corresponding observations were available (Figure 7). (Results for the 2-D model are essentially similar in character to those of the 3-D model and, hence, are omitted here.) The model simulations correspond to particles with fall velocities, w_s , of 0.005 m s^{-1} (fine sand) and silt 0.0005 m s^{-1} . Recent studies (Hill, personal communication) suggest that the median fall velocity $w_s = 0.003 \text{ m s}^{-1}$. These model results assume unlimited supplies originating exclusively from the mouth of the estuary.

As discussed in detail in the accompanying EMPHASYS report on 'top-down' modelling, the main (tidal) features of these observed and

modelled time-series can be explained from existing theories. No attempt is made here to 'tune' the model results to 'fit' the observations but the following sensitivities may be noted (see Prandle, 1997 for details).

Fine and coarse sediments: concentrations proportional to γ and n in erosional formula $\gamma k \hat{U}^n$

Fine sediment: concentration proportional to: \hat{U} via combined influence of erosion and deposition

Coarse sediment: Concentration proportion to: $\hat{U}^3 k^2$, and $1/w_s^2$ via combined influence of erosion and deposition.

Add to the above complexities the complications of: supply (marine only here), consolidation, flocculation, bioturbation, a wide spectrum of w_s (i.e., particle types) together with the dynamical feed-back between sediment motion, bed forms and overlying dynamics. It can be seen that, whilst such a wide range of parameters may allow seemingly close reproduction of specific concentration time series, the likelihood of broader scale, longer term accurate reproduction of SPM is much less certain. Moreover, SPM concentrations depend on recent chronology providing erodible surficial sediments. Thus the uncertainties in simulating bathymetric evolution – dependent on the long term temporal integration of spatial gradients in relative erosion-deposition budgets, is evident. Nonetheless, bottom-up models can indicate areas and conditions (e.g., spring tides, flood flow, surge events) where regions within any estuary are likely to be subjected to greater or lesser erosion or deposition of fine or coarse sediments. Figure 8 provides indications of such budgets to illustrate how detailed processes within these models can be examined. Although not discussed here, the net quantities of SPM entering the Mersey and the rate and spatial patterns of deposition (for $w_s = 0.005 \text{ m s}^{-1}$) are consistent with observations.

5. CONCLUSIONS

Observational data relating to tidal elevations, current ellipses and SPM time series were extracted from Prandle et al. (1990) and Lane et al. (1997). Tidal propagation in the upper reaches was shown to be highly sensitive to the bathymetry, given the mobility of the bathymetry

in this section combined with a paucity of observational data on tidal constituents, the study focused on the wider lower estuary. Intercomparisons between theory and observations of detailed cross-sectional variability in the current distribution for the predominant semi-diurnal constituents show this variability to be dependent on local changes in bathymetry. Corresponding intercomparisons for the residual component are complicated by questions of definition and accuracy of observations.

Whilst the essential characteristics of SPM distributions can be reproduced by all three models, the large sensitivity to a range of parameters indicates the difficulty in simulating bathymetric evolution.

6. CRITIQUE OF 1-D, 2-D AND 3-D MODELS

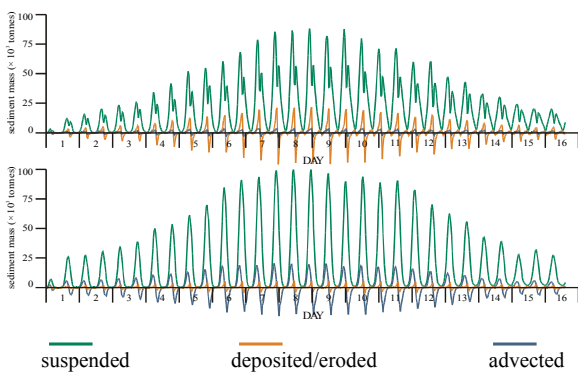


Figure 8 Suspended sediment fluxes within an axial section (1 to 2 in Figure 1) of the Mersey for $w_s = 0.005 \text{ m s}^{-1}$ (above) and $w_s = 0.0005 \text{ m s}^{-1}$ (below)

The 1-D (cross-sectionally averaged) model provides accurate simulation of tidal elevation amplitudes and cross-sectionally averaged currents for the primary tidal constituents. This hydrodynamic framework may, likewise, be adequate for simulating the transport of finer particles which stay in suspension much longer (see POL's top-down study) and are effectively mixed vertically and laterally in high current regimes. However, such models are less well suited for simulation of coarser sediments (more sensitive to near-bed current profiles) or to wider estuaries where lateral circulation is often significant and lateral variability in ebb-flow dominance occurs.

The 2-D (vertically-averaged) models afford significant advantages over the 1-D, by resolving the pronounced lateral depth variations. The associated (depth-dependent) non-linear processes involved in tidal propagation are now resolved together with rotational (Coriolis) and spatial accelerations (advection) in accurate simulation of higher harmonics and (especially) fine-scaled residual current circulations. This enhancement in resolution of currents greatly improves the simulation of pathways of sediments – both fine and coarse.

The 3-D models introduce both vertical current structure and some description of turbulence intensity. Whilst depth-averaged currents are often relatively insensitive to these additional features (and hence simulation of tidal dynamics is relatively little improved), the magnitude of the related bed stress is especially sensitive and, hence the erosion and deposition processes. (This sensitivity is especially marked for estuaries where tidal constituents are close to their inertial latitudes, Prandle, 1997). Although 3-D models introduce significantly more complicated processes (turbulence profiles) they do offer the only realistic possibility of robust sediment erosion, transport and deposition algorithms able to reflect temporal and spatial variations in turbulent intensity and associated stratification (at the seabed or fresh-salt water interface). Such 3-D models presently involve not inconsiderable computational requirements. However, the progressive growth in the power and decrease in cost of this resource is continuously removing this obstacle to progress, i.e., is providing new opportunities for wider utilisation of 3-D models.

Whilst such 3-D models significantly enhance the accuracy and resolution of simulation of tidal dynamics, many of the fundamental problems concerned with simulation of SPM (described in Section 4) remain.

7. RECOMMENDATIONS REQUIRED ON OBSERVATIONAL DATA AND PROCESS-STUDY RESEARCH

- (i) The fundamental limiting data for almost all estuarine models is inaccuracy and inadequate resolution of existing bathymetry.
- (ii) Essential observational data for evaluation of computed suspended sediment concentrations includes representative monitoring, typically over not less than 15 days, at intervals of say 15 minutes of suspended sediment

- concentrations at the mouth and axial distributions (at three or more locations).
- (iii) Description of surficial sediment distributions (possibly inversely by frequent (hourly) CASI aircraft surveys over a tidal cycle at 7 day intervals).
 - (iv) Observational data for evaluation of bathymetric evolution LIDAR (+ calibration and assessment via in-situ surveying techniques) surveys at LLW springs monthly for 1 year or more (in estuaries with pronounced dynamic bathymetry). Seasonal marine surveys of deep water regions.
 - (v) Process studies: concentrated (in limited number of estuaries) programmes to link existing capabilities in small scale (micro) measurements (and modelling) of erosion, suspension and deposition to longer (macro) scale algorithms employed in numerical models. (To include measurements of currents, turbulence, bed features, sedimentary, botanical, biological and chemical constituents.)

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ESTBED MODEL

Darren Price and Paul Norton

email: dmp@research.abports.co.uk

ABP Research & Consultancy Ltd, Pathfinder House, Maritime Way, Southampton SO14 3E, UK

1. THE ESTBED MODEL

EstBed is a bottom-up model, which has been developed at ABP Research to enable predictions of short to medium term bed evolution to be made for a two-dimensional area over a prescribed period of time. EstBed is based around MIKE21 hydrodynamic, sediment transport and wave modules (waves not included in this study) developed by the Danish Hydraulic Institute (DHI). EstBed works by running the modules in turn and then based upon the sediment transport predictions changes the model bathymetry accordingly. This new bathymetry then influences the hydrodynamic regime and hence that of the sediment transport, enabling feedback between the different modules and bed evolution to take place.

For the work undertaken under EMPHASYS, EstBed has been applied to the upper Humber Estuary to try to simulate the effects that the training walls at Trent Falls had following their construction.

2. EXAMPLE OF MODEL PREDICTIONS - THEORETICAL ESTUARY INFILLING

It is important to understand how estuaries evolve over time in order to understand how they may change in the future. During the creation of the EstBed model, a number of tests were performed to see whether the model was performing in a realistic manner. One such test looked at how the model would predict the infill of an empty basin to create an estuary.

It should be noted that the purpose of this exercise was to see whether the model predicted anything believable and therefore arbitrary, but not unrealistic, model parameters were chosen. The model domain (estuary dimensions) chosen, were 2700m long by 500m wide, thus representing quite a small estuary basin. A constant freshwater discharge (no suspended sediment) of 50 cumecs was applied at the head of the estuary basin and a large tide with a range of 8m applied at the mouth of the estuary. The water entering the estuary via the mouth had a

suspended concentration of 300mg/l. Parameters relating to sediment properties were idealised and related to a muddy environment, but were also chosen so that the accretive process would be speeded up and hence the simulation time to steady state would be reduced.

The model was run for a period of one year until the estuary reached a steady-state. Figure 1 shows the estuary bathymetry at this time after it has filled up with mud.

It can be seen in Figure 1 that a channel has formed within the estuary extending from the head to the mouth. The channel near to the head of the estuary is seen to have formed at the south bank, whilst the channel which also started to form to the north eventually filled in. The way in which the model evolved the bed was altered to include a random component to see if this would alter the two channels and the dominance of one over the other but did not seem to have a significant effect. However, changes to the latitude of the model (i.e. changes to the coriolis forcing) between being in the northern hemisphere (as shown in Figure 1) and the southern hemisphere, caused the dominant channel to be on the northern side of the estuary.

Also evident in Figure 1, is the formation of what looks like flood and ebb channels and some siltation which could be compared to an ebb delta.

The main findings from this work were that the model could be used to look at relatively long periods of time (greater than a year) and assessments of different forcings could be assessed (water levels, fluvial flow etc.) It was found that a single solution was found if uniform boundary conditions were applied.

However to progress this work to enable the simulation of more realistic situations, the following hypothesis for testing was put forward.

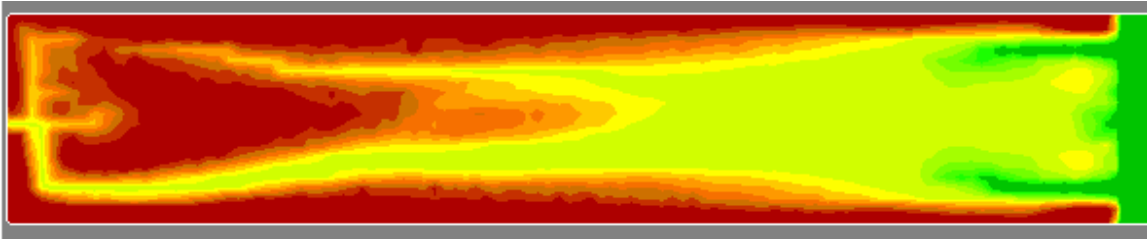


Figure 1 Predicted estuary bathymetry after one year

3. HYPOTHESIS

To test the EstBed morphological model it was necessary consider a site where significant bathymetric changes have taken place. To determine the limits of application for the model, the chosen site should ideally include complex channel formations. An adequate set of bathymetric data sets to enable the performance of the model to be assessed was also required. The Trent Falls area in the Humber Estuary, at the confluence of the Rivers Trent and Ouse, was chosen as the most suitable site.

Detailed bathymetric records are already available in digital form covering the period from 1900 to the present. In an attempt to control the migration of the channels in the upper reaches of the Humber, training walls were introduced at Trent Falls over a period of years between 1929 and 1935. An investigation of the morphological changes during and after the introduction of these training walls was therefore chosen as a basis for testing the morphological bottom-up model, EstBed.

4. INTRODUCTION

Model bathymetries for the following years were considered whilst investigating morphological developments: 1925, 1936, 1940, 1950, 1956. These bathymetries illustrate the considerable variability in the channel positions within the upper reaches of the estuary. Previous studies on channel migration by University of Newcastle and ABP Research (University of Newcastle,

1998, Binnie, Black and Veatch, 1999, ANNEX 5) have linked channel 'switching' to extreme water levels in combination with high freshwater flows. Channel 'switching' occurred in 1930, 1935, 1947, 1977 and more recently in 1994 when the channel moved from the Ancholme reach to the Redcliff reach (i.e. from south of Read's Island to the north).

5. TIDAL MODELLING

A hydrodynamic model of the upper reaches of the Humber Estuary was configured using the MIKE21 modelling system. The downstream model boundary was located near Hessle, the site of the Humber Bridge crossing. The upstream limits of the model were included as separate labyrinth networks for both the Trent and the Ouse rivers, see Figure 2. These labyrinths were designed to provide an adequate representation of tidal storage and discharge characteristics. Constant river discharges of 100 cumecs were applied to both the Rivers Trent and Ouse. A constant grid-spacing of 50m was chosen to provide sufficient resolution of the narrow, sub-tidal channels and to allow a realistic representation of the river sections as far upstream as possible.

6. SEDIMENT MODELLING

The sediment transport model was also based on the MIKE21 system and used the 'multi-layered mud-transport' model. This model allows layers of cohesive sediment to be defined with different sediment properties such as erosion threshold and density. Since there have not been any specific measurements on the erodibility of sediment in this area, an assessment of appropriate values was based on recent measurements carried out at other locations within the estuary. Additional inputs to the sediment model include suspended sediment concentrations at the boundaries. At the downstream limit of the model a constant input of 600mg/l was specified whilst in the rivers a constant supply of 50mg/l was assumed. In reality it is appreciated that there is considerable variability in sediment supply which varies through the tide as well as with tidal range and the volume of freshwater flow.

Sediment properties used within the model were derived from those used in existing models and available fieldwork, however sensitivity testing described later enabled the final values to be chosen.

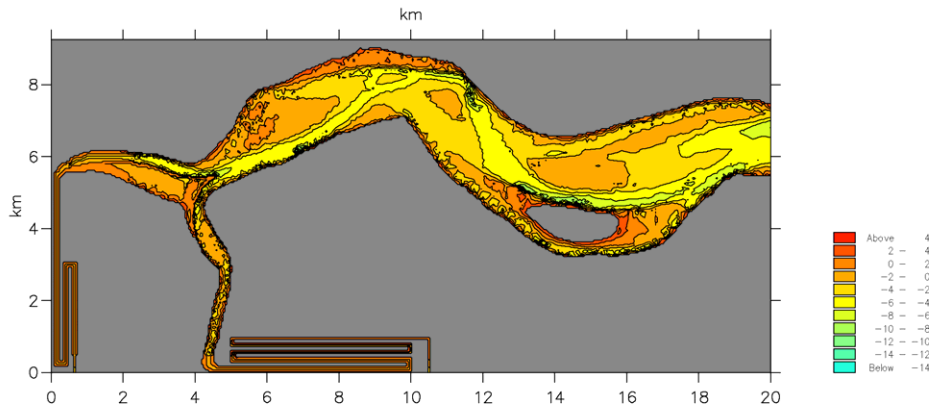


Figure 2 Model domain

7. CALIBRATION

The hydrodynamic model was calibrated using tidal level data based on harmonic constituents. Constituents for Blacktoft in the River Ouse were obtained from the analysis of 1-year of water levels measured in 1992. Constituents for Burton Stather in the River Trent were also available based on analysis of a 31-day record measured in 1983. Since these measurements were obtained in recent years, after the construction of the training walls, the calibration period was chosen as a sequence of spring and neap tides in 1956, the model also used bathymetric data from 1956.

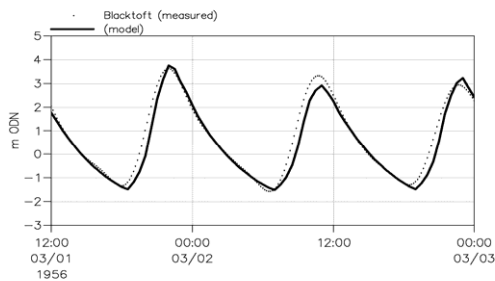


Figure 3a Predicted versus observed water levels

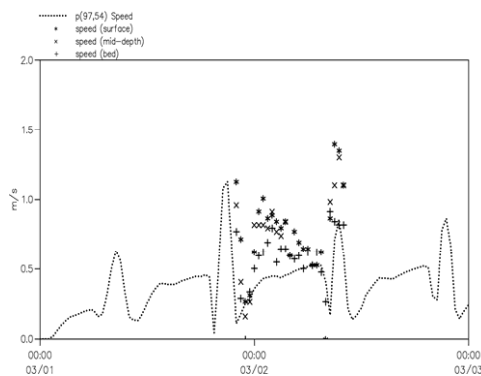


Figure 3b Predicted versus observed current speeds at Keadby

This period is also suitable for the morphological predictions described later as it was a period without extreme high freshwater discharges. Comparisons between the observed water levels at Blacktoft in 1956 and those predicted by the model are shown in Figure 3a. Comparisons between observed current speeds (recorded in 1966) at Keadby and those predicted by the model are presented in Figure 3b. Parameters such as friction and eddy viscosity were chosen to be the same as values used for more recent calibrated models in the Humber.

Calibration of the sediment transport model was not as straightforward due to the limited amount of detailed survey data available within the model domain.

A series of sensitivity tests were carried out to assess the variability in predicted sediment patterns over a spring-neap cycle whilst varying the main input parameters to the sediment transport model. These parameters included erosion thresholds and rates, settling velocity, dispersion coefficients and boundary concentrations. The initial values were based upon values used in a number of other modelling studies in the Humber Estuary. It was necessary to assess the level of calibration by using EstBed to predict bathymetric changes over a period of several years. Experience from the short term sensitivity testing was used to look at sensitivity of some of these parameters for longer term morphological predictions.

8. MORPHOLOGICAL CALIBRATION AND SENSITIVITY ANALYSIS

The hydrodynamic and sediment transport model took approximately twenty minutes to run a simulation of one tide. This therefore had implications on the time it would take to run morphological simulations of the order of years if every tide were to be simulated (approximately 10 days real time per year of simulation). Therefore a method of accelerating the speed at which the simulations took place was introduced.

This highlights one drawback of bottom-up models: to simulate long periods of time, assumptions need to be made for some of the forcing factors acting on an estuary. Not all of the morphological influences can be taken into account, for example to predict future change how important is it to know the magnitude and duration of surge tides, winds and freshwater flows?

The method used to accelerate through time was based upon the relative amount of sediment deposited on a mean spring tide compared with a spring-neap cycle. It was found that on average at a number of sites, one mean spring tide provided 0.115 times the sedimentation of a spring-neap cycle. Therefore one spring tide provides 1.6 days worth of the mean deposition experienced over a spring-neap cycle.

An acceleration factor was used for all of the morphological simulations described in this paper. This factor was chosen to have a value of 30. The morphological simulations work by running the flow and sediment transport models for one spring tide, then multiplying the accretion and erosion by this acceleration factor (30), updating the bathymetry and so on for the full duration required. If a mean spring tide is equivalent to approximately 1.6 days of mean sedimentation, then multiplying by 30 gives a morphological timestep of 48.3 days. Therefore for each tide run by EstBed, the bathymetric update is equivalent to 48.3 days.

This methodology has an obvious advantage in the reduction of the simulation times but also a disadvantage in the assumption that the results from a spring tide are related directly to the sedimentation of a spring-neap cycle.

The period used to calibrate EstBed was between 1950 and 1956, a period when the main channels did not switch. It is important to note that the

upper Humber estuary which has been modelled, is a very dynamic area with channels moving around significantly under extreme conditions. Therefore such a period is a good choice, although even without the extreme events the channels were not stationary.

A mean spring tide was applied at the downstream boundary, and constant discharges of 100 cumecs were applied to each of the Rivers Ouse and Trent.

Sediment concentrations at the downstream boundaries were set at a constant 600mg/l and at 50mg/l for the Rivers Trent and Ouse. It is acknowledged that concentrations can vary above and below these values, but in order to simulate a long period of time, some simplifications were needed. This highlights a further limitation; a detailed bottom-up model has been used which can represent detailed processes, but in order to run for a long period of time, simplifying assumptions are required.

The erosion thresholds chosen, after a number of sensitivity tests, were 0.45 N/m² for the surface (first) layer, 0.8 N/m² for the second layer and 0.9 N/m² for the bottom (third) layer. There was also a transition rate applied between the first/second mud layers (0.005 g/m²/s) and second/third layers (0.001 g/m²/s). This represented consolidation by passing sediment from one layer to the next and thus making the sediment harder to re-erode the longer it had been on the bed.

Another main parameter used within the mud transport model is the sediment settling velocity. A number of sensitivity test were also undertaken with this parameter. For the simulation of the period 1950 to 1956, constant settling velocities of 0.0002m/s (referred to as low settling velocity) and 0.0005m/s (referred to as high settling velocity in this paper) were examined. It was found that the high settling velocity produced more deposition as would be expected. It did however produce too much deposition to the South of Read's Island and was rejected in favour of the results produced with the lower settling velocity.

It is noted that settling velocity of mud is concentration dependent, a simulation with a high settling velocity and concentration dependence produced too much siltation. It was therefore decided to use the lower value of 0.0002m/s as a constant value.

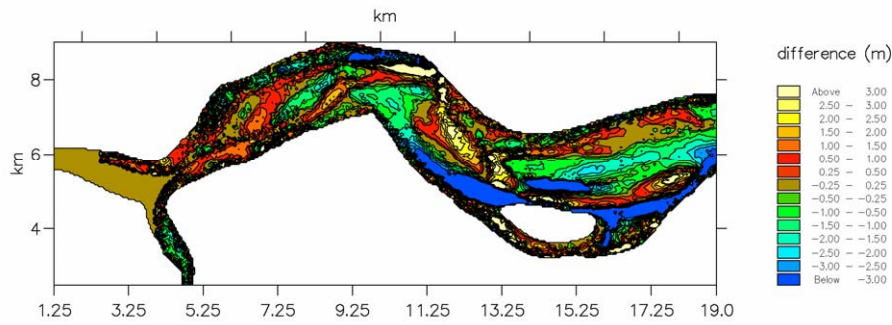


Figure 4a Observed bed changes between 1950 and 1956

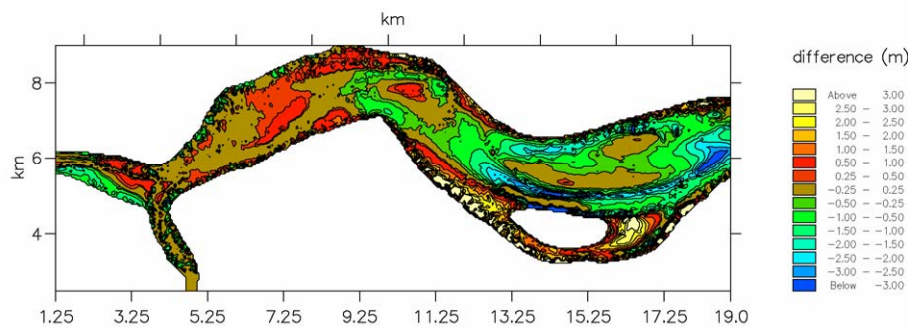


Figure 4b Predicted bed changes between 1950 and 1956

The observed bed changes and those predicted by the EstBed simulation for 1950 to 1956 are presented in Figures 4a and b respectively. In these Figures, positive values represent accretion has taken place, and negative values represent erosion. It was found that it was easier to examine change in this way and judge how well the model performed in different areas and whether the magnitude of deposition/erosion was of the right order.

It can be seen from these two figures that predictions are by no means exact. However EstBed does predict changes which are of a similar order of magnitude to that observed, as well as being in similar locations. What is evident from the model results, when compared with the historic data is that it is unable to predict movement of the channels.

Another method of comparison was to examine the volume of water (wet volume) that would be present if a 'flat lid' of water was imposed on the bathymetry maps at a level of mean spring high water. For the observed (historic) bathymetries the wet volume was found to be $0.25 \times 10^9 \text{ m}^3$ for 1950 and $0.267 \times 10^9 \text{ m}^3$ for 1956, an increase in volume of $1.7 \times 10^7 \text{ m}^3$, indicating there was a net loss of sediment from the upper part of the

estuary during this time. The volume predicted by EstBed in 1956 was $0.258 \times 10^9 \text{ m}^3$ an increase in volume of $0.8 \times 10^7 \text{ m}^3$. Thus EstBed has also predicted a net loss of sediment during this time although approximately half the actual amount. It may be that there had been a period of increased accretion prior to 1950 and the estuary was in a form which was conducive for erosion to take place. The simulation was also carried out using the higher settling velocity and this produced a net loss of wet volume over the same period showing the sensitivity of the long term predictions to such parameters.

It is obvious that the predicted erosion and accretion patterns at the end of the six year simulation are by no means exact and do not simulate the dynamic movement of channels that took place over the same period. However, it was felt that the magnitudes and areas of accretion and erosion did show similarities and the change in volume predicted was of a similar magnitude and in the correct direction (net increase).

9. IMPACT OF TRENT FALLS TRAINING WORKS

The hypothesis for testing is described above in Section 3. All the parameters used for the flow model and the sediment transport model were the same as described above with the low settling

velocity (0.0002m/s). The period chosen for model simulations was 1925 to 1936 for the construction of the training walls and beyond to 1941. Figure 5 shows the bathymetry for 1925.

Initially the simulation was undertaken without the training walls in place so that the likely effect that these walls had upon the estuary could be judged. In effect this is the approach that most modelling studies take, i.e. perform a with and a without scenario.

The simulation with the Trent Falls training walls in place was performed over the same period of time, namely 1925 to 1941. At the start of the simulation the walls were not in place, however as time progressed, the walls were incorporated into the model bathymetry in stages, representing the actual extent of the walls in any one year, as derived from historical charts.

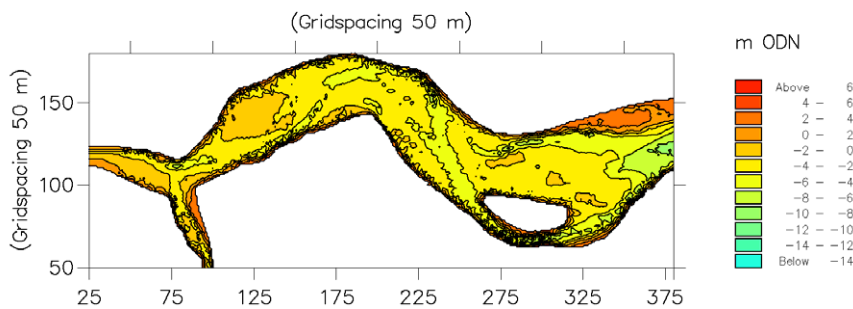


Figure 5 1925 bathymetry

It is also evident when comparing Figures 5 and 6, that there was an increase in deposition between these two periods. This equates to a decrease in water volume of $3.4 \times 10^7 \text{m}^3$. This change in volume has been used as a means of determining how the EstBed model performed and what the potential consequences of the training walls had upon estuary volume for these upper reaches.

Figure 7 presents the predicted bathymetry without the training walls in place. It is evident that the model has not predicted the exact changes observed in 1936. The Trent Ness is also in place and therefore the model is not predicting this area to be eroding.

Figure 8 however, presents the results from the EstBed simulation with the gradual construction of the training incorporated. It can be seen that the channel in the River Trent has been predicted to move from the west to the east bank. It has also eroded the Trent Ness significantly, in a very

Figure 6 presents the surveyed bathymetry in 1936. Figures 7 and 8 respectively present the predicted bathymetry in 1936 without and with the training walls included in the simulations.

It is evident when comparing Figures 5 and 6, that the main changes that occurred in the locality of the Trent Falls was the movement of the channel at the end of the River Trent which was pushed sideways by the training walls towards the eastern bank. This caused significant erosion of the intertidal mudflats known as Trent Ness.

Further afield there are other changes which occurred during the period 1925 to 1936, which included the main channel switching sides, the main flow being to the south of Read's Island in 1925 and to the north of Read's Island in 1936.

similar manner to that which was observed in 1936. There was also siltation predicted within the training walls where the old River Trent channel was before, however the level of siltation is under-predicted. This may be partly due to the relatively crude way in which the model simulated construction of the training walls, incrementing changes at the beginning of a year only and not gradually.

Table 1

Year	Observed volume (m3)	Predicted volumes (m3)		
		Without training wall	Training wall	Training wall and annual peak river discharges
1925	2.73×10^8	2.73×10^8	2.73×10^8	2.73×10^8
1936	2.387×10^8	2.64×10^8	2.609×10^8	2.61×10^8
Difference	3.4×10^7	0.9×10^7	1.21×10^7	1.2×10^7

The migration of the main channel is not predicted by EstBed. Table 1 presents the volume (calculated as wet volume below mean high water springs) and volume change predicted by EstBed, compared with the observed data.

It can be seen that the estuary underwent a considerable period of deposition (reduction in wet volume) between 1925 and 1936 ($3.4 \times 10^7 \text{ m}^3$ or 12%), although the exact timing is not known. The predictions with the training wall suggest this part of the estuary has infilled by $1.21 \times 10^7 \text{ m}^3$. Which compared with the volume change observed is only 36%. Therefore EstBed is under-predicting siltation in the upper part of the estuary by approximately 64% over an 11 year period. At first glance this seems widely off mark, but when one considers that predictions by sediment transport models can vary by an order of magnitude but still be deemed acceptable, then the model has not performed too badly in predicting volume change over such a long period of time. Where it does not perform well is with the predictions of actual change to the tidal channels away from the training walls and the way in which they can migrate.

The simulation without the training wall in place predicts a decrease in wet volume of $0.9 \times 10^7 \text{ m}^3$, or 3.3%. The simulation with the training wall predicts a decrease in wet volume of 4.4%. Although these figures are not definitive, they do allow an estimate of the potential effect that the training works had upon the amount of siltation experienced within the upper estuary. The percentage changes of volume suggest that the training walls could have increased siltation by up to 25%.

10. INFLUENCE OF FRESHWATER FLOW

As a sensitivity test to the effects of freshwater flow, the model was run with higher flow conditions occurring for a specified period every year. The simulation with the training walls was run with a constant 100 cumec river discharge in the Trent and Ouse for most of the time (as previously run), except once per year (equivalent to a period of 1.5 months) the discharge in each river was increased to 250 cumecs. Table 1 present the changes in volume experienced between 1925 and 1936. The difference between the volume predicted with the constant freshwater flow and that predicted with the intermittent higher flow was an increase in wet volume of 525400 m^3 . Therefore the freshwater flow is reducing the amount of sedimentation experienced in the upper estuary. There was no channel switching predicted under the conditions applied. It may be that high flows along with larger tides are required for this to occur.

11. CONCLUSIONS

One of the main processes to be undergone in a study of this nature is the calibration of the models. The sediment transport model can be very difficult to calibrate (even if there is sufficient data to calibrate it with) because of the large number of parameters it uses (erosion thresholds, density, consolidation, settling velocity etc). Small changes to parameters such as settling velocity can have large effects upon bed levels if modelling changes over a period of years. Due to the simulation time (3 days to run an 11 year simulation in this case) it also becomes difficult to run a large number of sensitivity tests.

In order to define many of the aforementioned parameters, adequate field work is essential to define the hydrodynamics and sediment properties. Not only with suitable spatial resolutions but also with temporal variations if this is important, for example erosion thresholds may vary seasonally due to the activities of various benthic communities. Occurrences such as freezing or drying of mudflats will obviously play a part in the evolution of the estuary, however this is not taken into account in this model. Fieldwork required should entail data collection for the following parameters; settling velocity, erosion threshold of sediment through depth, density of sediment, particle size distribution, consolidation rates.

Waves or salinity were not included in the simulations either, although these may have an effect on estuary evolution. One problem with including such forcing factors, similarly for variations in freshwater flow and meteorological induced variation in water level, is defining the chronology of such events. If the order in which such events occur is not known, then exact predictions as they occur through time will be difficult, although the overall change might be within acceptable limits.

The results show that EstBed is able to reproduce some of the general patterns which can be identified in actual bathymetry changes such as accretion on the upper intertidal. In some areas even the magnitudes of change are also reasonably well predicted. However, the model was not able to reproduce the sudden changes in channel alignment which are known to have occurred in this dynamic part of the estuary. For this reason, EstBed would be best applied to problems of progressive change, when using long-term forcing of the model. Rapid changes are likely to be a consequence of episodic

events and they probably need to be faithfully reproduced if the model is to simulate changes such as channel switching.

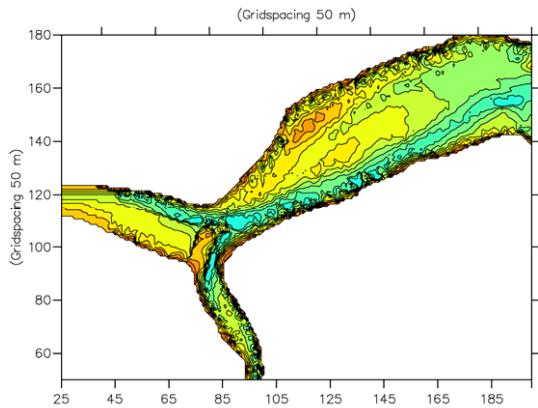


Figure 6 1936 bathymetry

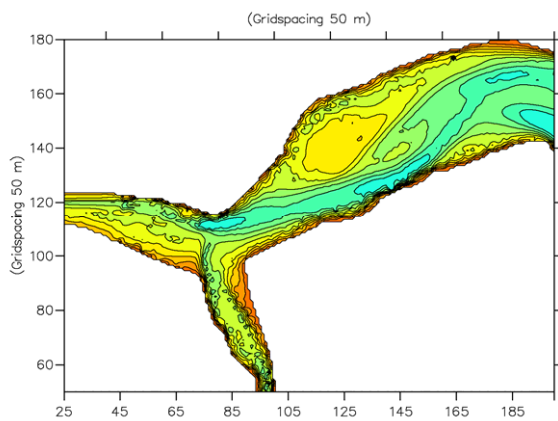


Figure 7 Predicted 1936 bathymetry without training walls

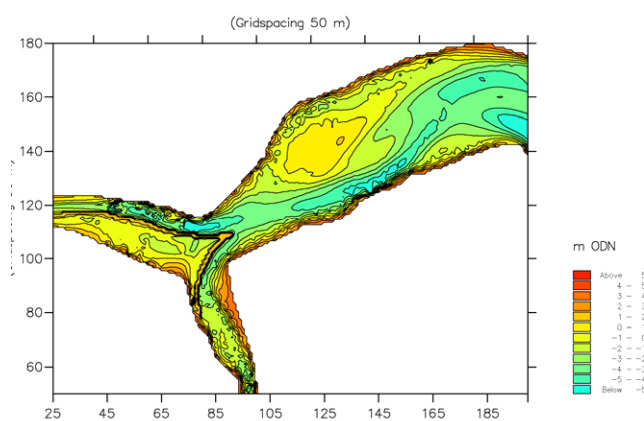


Figure 8 Predicted 1936 bathymetry with training walls

However, EstBed can be used to show the direction and order of change. For example for the period 1925 to 1936 the model predicted accretion in the upper estuary, but only 36% of

that which occurred. The case that was run without the training walls allowed relative change to be assessed such that the training walls could have increased siltation by 25%.

Where EstBed is well suited, is for the predictions of bed change around structures which create changes in the hydrodynamics greater than the natural variations. For example, the construction of the training walls significantly altered the flow in the adjacent water at the mouth of the Trent and caused the erosion of Trent Ness, which EstBed was able to predict.

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A MODEL OF BIOTICALLY-INFLUENCED SEDIMENT TRANSPORT OVER AN INTERTIDAL TRANSECT

Rose Wood

email: r.wood@pml.ac.uk

Plymouth Marine Laboratory, Prospect Place, West Hoe, Plymouth PL1 3DH, UK

ABSTRACT

A one-dimensional model of an intertidal transect (BIOTIDE) is constructed. The model is aligned cross-shore, and includes movement of water and suspended sediment. Tidal currents can erode sediment, in a form which allows bioturbation to alter the erodability of the bed sediment. The concentration of chlorophyll in the surface sediment (as an indicator of microphytobenthos) alters the erosion threshold according to a linear function. External sediment supply is specified as an offshore suspended matter concentration. The model is applied within Spurn Bight and within the Mersey. The effects of various tide heights, biota densities and external sediment levels are investigated. Offshore sediment supply dominates the net deposition below mean sea level, but intertidal sediment movement becomes important at higher bed levels.

1. INTRODUCTION

Sheltered estuaries often have extensive intertidal areas. These are important both as sources and sinks for fine sediment within the estuary. As such, they have a major role in the storage and cycling of those pollutants which preferentially bind to small particles. Mudflats and saltmarshes in the U.K. are an important habitat for wintering birds and the fauna which support their food chain. Extensive vegetated intertidal areas can form a barrier to tidal surges and absorb some of the energy from storm waves. Accretion of mudflats and saltmarshes may be a valuable natural coastal defence in a regime of rising sea-level.

The shallow coverage of water on the intertidal zones allows wave energy to penetrate to the bed, increasing the effect of small waves on sediment erosion. Rapid flooding and drying of large, low gradient areas can also cause erosion by raising current speeds above the critical value. Turbid water is

advected across the flats as the tide rises, and is deposited during the long period of low current speeds near high water. Populations of benthic animals can actively and passively affect erosion and deposition of particles. Algal mats and macroalgae can also influence sediment exposure and velocity profiles.

This paper addresses the question of ‘how important are biotic effects on sediment transport over a whole tidal cycle, compared to the importance of tidal forcing and external sediment supply?’. The answer is expected to vary with the bathymetry of the transect (wide flat intertidal areas having very different currents and biota distributions from narrow steep areas), tidal parameters, exposure to wave effects, and season and year (giving changes in biota).

The method chosen to approach this question was to construct a model of an intertidal transect, including the minimum set of processes needed for the comparison to be made. Model conditions can then be varied to compare responses under various biotic and physical forcings. The model uses sediment erosion functions, which incorporate bioturbation effects, within an advective model of sediment transport. Net deposition for a tidal cycle is then predicted over a 1D shore-normal transect. The relative importance of biotic and physical forcing to the longer-scale evolution of the bed can only be assessed when you integrate erosion under realistic tidal velocities. Previous models have not directly compared biotic effects to abiotic effects on intertidal sediment transport.

Intertidal areas have frequently been modelled as part of 2D or 3D models of whole estuaries (Cheng et al, 1993, and Roberts and Whitehouse, 2000). These models are larger and more complex than is needed for our

purpose here, which is more an experimental investigation into combining processes rather than a predictive model for a particular area. One-dimensional models of cross-shore transects have been used by Woolnough et al (1995) for studying morphological evolution of saltmarshes. Goodwin et al (1992) used methods of characteristics to model propagation of the tidal surface wave across the intertidal zone. Wood et al (1998) modelled a 1D transect across Spurn Bight using simplified equations and the results compared favourably with current meter observations at about mid-water level. Friedrichs and Aubrey (1996) examined the velocities over a uniformly sloping bed due to volume conservation of a flooding and drying tidal flow. Recently, Le Hir et al (2000) re-affirmed the suitability of using volume conservation equations assuming a horizontal water surface for flow over tidal flats in most circumstances.

Many experiments and observations have confirmed that benthic animals can affect sediment erosion and deposition. Graf and Rosenberg (1997) review the direct (e.g. sediment disturbance by siphon feeding, production of large pseudo-faeces) and indirect (e.g. effects on flow speed and effects of mucus on particle cohesiveness) mechanisms of bioresuspension and biodeposition. They conclude that erosional or depositional fluxes can be more than doubled by benthic biota. Biopolymers exuded by microphytobenthos have been observed to increase sediment stability (de Brouwer et al, 2000) and increase erosion thresholds (Widdows et al. 2000b, Amos et al. 1998). Bioturbation by *Macoma* has been studied by Widdows et al. (1998a) in flume experiments within the laboratory and in the field. Willows et al. (1998) used flume data to form a semi-empirical model formulation for behaviour of suspended sediment within the flume, dependent on water velocity and *Macoma* density. When exposed to a constant velocity, exceeding the critical threshold, increasing the density of *Macoma* leads to larger amounts of sediment being eroded. Increasing *Macoma* density further has a progressively smaller effect, until an asymptote is approached, which corresponds to the whole surface of the sediment being within siphoning range of at least one *Macoma* individual. Fieldwork has

confirmed the nature of this relationship at the experimental site.

2. MODEL DESCRIPTION

The model combines a simple 1D onshore-offshore model of water movement with a semi-empirical model of cohesive sediment erosion and deposition. It is applied to transects within Spurn Bight and the Mersey. Each transect is taken as representative of a section of estuarine shore which is uniform in the longshore direction. Sea surface elevation is supplied to the model, and volume conservation is used to calculate depth-averaged velocities. These cross-shore velocities are used to advect water and suspended sediment. Erosional velocities can either be taken as equal to the advection speeds (as in Spurn Bight), or defined separately. For the Mersey, they are taken as functions of time, based on observations of predominantly long-shore velocity. A near-bed wave orbital velocity could be added, or velocity could be modified to take account of wave-current interaction, but this is not performed for the calculations described in this paper.

Erosion rate is calculated as a function of velocity and the density of *Macoma balthica* (a small bioturbating clam). This is based on flume experiments with varying *Macoma* numbers in the laboratory (Widdows et al 1998a and Willows et al 1998). Comparison with field data from the Skeffling transect in the Humber show that the same functional form fits field data with similar parameter values (Willows et al, 1998). Field data also show that critical erosion stress is significantly affected by colloidal carbohydrate, which is produced by diatoms within the surface sediment. Erosion threshold is taken as a linear function of surface chlorophyll concentration (based on observations in the Westerschelde, Widdows et al. 2000a). The population density of *Macoma*, and microphytobenthos are specified along the transect. External suspended sediment can be imported to the transect with the flood tide water.

The model runs for single tidal cycles. At the end of a tidal cycle, the model produces a profile of net deposition of sediment (mass per unit area). Model runs are made for a variety of boundary conditions and biota distributions. Results are then summed appropriately to give

budgets of sediment movement due to these processes for sequences of tides. The model is constructed within the ECoS modelling system (Gorley and Harris, 1998), allowing easy change of most of the process equations.

Model areas

This study is concerned with investigating simplified biotic-physical systems, rather than accurately reproducing conditions in particular estuaries. However, input parameters for the model have been based on two transects for which present-day and historical data on bed elevation does exist. The first transect is on the Skeffling mudflats on the north shore of the Humber (fig 1). This transect extends from the shoreline embankment to 3.5 km offshore.

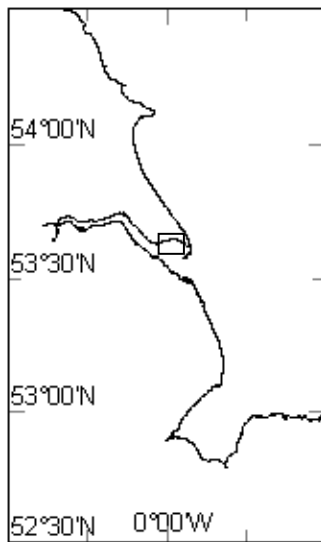


Figure 1 Location of Spurn Bight intertidal area

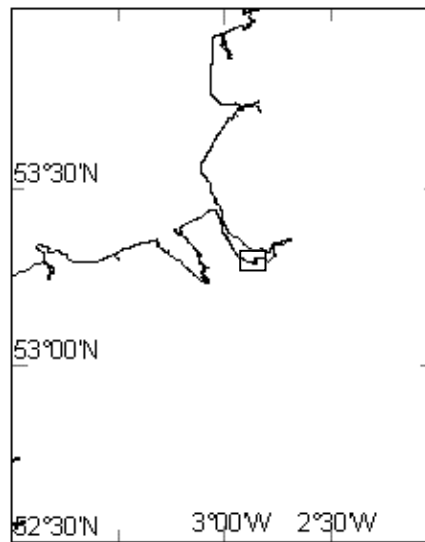


Figure 2 Location of Stanlow and Ince Banks intertidal area

Here, the intertidal area is wide and flat, and so velocity is expected to be predominantly cross-shore (Dyer, 1998). Bed heights have been obtained from profiles measured during the LISP experiment (Black, 1998). Ideally, the cross-shore bathymetry should be averaged over several kilometres of shoreline. To approach this, the bathymetry is smoothed, so that cross-cutting channels are not included. Spatial segments are 35m in length and the timestep is 60 seconds. The second transect is on the southern side of the Mersey near Ellesmere Port (fig 2). The intertidal area is narrow and steep, and reasonably extensive in the longshore direction. The modelled transect is located higher in the tidal frame than the Skeffling transect.

Model equations

The current speed at any time and place is calculated from conservation of volume (equation 1), assuming a flat sea surface across the intertidal zone, as described in Wood *et al.* (1998).

$$\frac{\partial \eta}{\partial t} + \frac{\partial}{\partial x}(u(H + \eta)) = 0 \quad (1)$$

where η =sea surface elevation, H =water depth, and u =current speed in the x direction (offshore).

Sediment transport is then calculated using an advection-diffusion equation (equation 2). This is implemented within the ECoS modelling package, with diffusion coefficients

set to zero. The numerical scheme is implicit in time.

$$\frac{\partial C}{\partial t} + \frac{\partial}{\partial x}(uC) = E - D \quad (2)$$

where C =suspended sediment concentration, E =erosion rate and D =deposition rate.

Sediment erosion rate (equation 3) is determined by current speed and Macoma density (number of 7mm or longer individuals per m^2).

$$E = k.(mxsed(n, u) - erodsed) \text{ if } |u| > ucrit_e \text{ and } mxsed(n, u) > erodsed \quad (3)$$

$$E = 0 \text{ otherwise,}$$

where $mxsed(n,u,x)$ is the maximum erodable sediment for *Macoma* density n and current speed u , $eroded(x)$ is the amount of sediment eroded since the erosion commenced, $ucrit_e$ is critical erosion speed, and parameters k and those in $mxsed$ are experimentally determined. The functions $mxsed$ and $eroded$ are described in Willows *et al.* (1998), along with the parameters from Skeffling field experiments which are used here.

Critical erosion threshold varies with chlorophyll concentration, according to a linear relationship, with parameters inferred from experimental data from Widdows *et al.* (2000a). The equation is:

$$ucrit_e = 0.01(0.4026c_{phyll} + 15.934) \quad (4)$$

where c_{phyll} = chlorophyll concentration in the surface sediment (μg per g dry wt of sediment), and $ucrit_e$ is in m s^{-1} .

Sediment deposition rate (equation 5) is calculated using the basic equation of Krone (1962) with a single settling velocity and critical deposition threshold based on experimental data from Widdows *et al.* (1998b) and Amos *et al.* (1998).

$$D = \frac{w_s}{H} C \left(1 - \frac{u_{10cm}^2}{u_{critd}^2} \right) \quad \text{if } u_{10cm} < u_{critd} \quad (5)$$

where w_s is settling velocity ($w_s=0.5\text{mm s}^{-1}$), u_{10cm} is speed 10cm above the bed and u_{critd} is critical deposition speed ($u_{critd}=0.12\text{m s}^{-1}$). The model does not include wave-induced erosion, although a wave component could easily be added to the erosional velocity.

The model starts from rest, with no suspended sediment, with the tide at low water.

Sea surface elevation and suspended sediment concentration are specified at the offshore boundary.

Output variables which are produced by the single tide model at every timestep are: current speed, suspended sediment concentration, and net sediment mass eroded or deposited within each segment in the transect.

The sediment erosion model has been tested using flume data for Skeffling (Willows *et al.* 1998). Velocities for the transect model have

been tested against Skeffling current meter data (Wood *et al.* 1998). There is very little data available to test the transect model predictions of net sediment transport over tidal cycles. At present, comparisons are being made with data from the INTRMUD project (Christie *et al.* 1999).

3. MODEL RESULTS

The net mass of bed sediment deposited or eroded at each grid cell during a single tidal cycle is taken as the model response. The main forcings within the model (tide height, bioturbator density and external sediment) have been varied individually to show the effect that each has on the response. Results show a strong spring-neap variation. Biota and external sediment supply are expected to vary less rapidly. So, to enable some scaling-up in time, results are summed over 29 days (using appropriate tidal heights), and converted to depth of net accretion or erosion. Most of the results presented are for Skeffling, where data is available on sediments, biota and velocities. A few results are shown for Ellesmere Port. They are illustrative of an application in another location, rather than predictive for the Mersey. These model runs have bathymetry and velocities appropriate for the Mersey, but parameters are otherwise taken as the Skeffling parameters.

4. SINGLE TIDE RESULTS FOR SKEFFLING (SPURN BIGHT)

The bathymetry for the Skeffling model is shown in figure 3. Modelled currents are fastest near mid-tide level at the time of flooding and drying there (when the rate of sea surface rise is greatest), and at flooding or drying of the flattest part of the profile (about 750m -1000m offshore). Speeds produced by the model show reasonable agreement with those observed during April 1995 (Wood *et al.* 1998). The spatial distributions of *Macoma* and chlorophyll in the model are also shown.

The maximum *Macoma* density along a transect at any given time is based on observations by Widdows *et al.* (1998b) in the Humber, and Beukema *et al.* (1998) in the Wadden Sea. The density of *Macoma* along the transect is calculated using a statistical formula from McGroarty and Yates (pers. comm. ,1999), based on bed height and bed sediment grain size. This formula (equation 6) was constructed statistically using data

observed in the Wash. It relates *Macoma* density to height of the shore and sediment particle size.

$$n = c \exp(A)$$

$$A = 1.72 + 0.121p + 1.486h - 0.01345ph - 0.001009p^2 - 0.2459h^2 \quad (6)$$

where n =*Macoma* density (no. of individuals per m^2), c =scaling factor to give required maximum density according to season and year, p =percentage of fine material in bed sediment, h =height of bed relative to ODN.

Seasonal values for the surface sediment chlorophyll concentration (as related to the density of diatoms) were chosen based on observations by Amos *et al* (1998) at Skeffling, and by Underwood and Paterson (1993) in the Severn and Widdows *et al.* (2000a) in the Westerschelde. The distribution of diatoms down the shore was based on measurements by Amos *et al* (1998) at Skeffling, and on particle size variation down the shore.

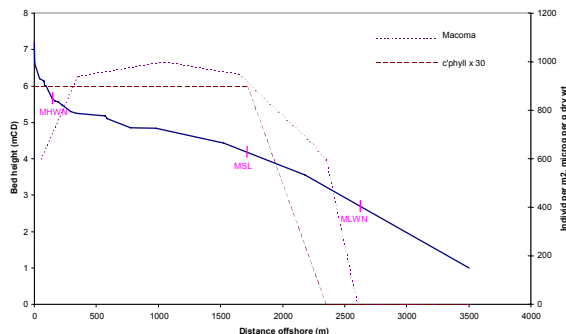


Figure 3 Bathymetry for Skeffling transect

5. EFFECT OF TIDE HEIGHT

Figure 4 shows net deposition during tides of six different amplitudes. For these runs, the peak *Macoma* density is 1000 individ m^{-2} , and the peak chlorophyll density is 30 $\mu g g^{-1}$ dry wt. The intertidal erosion and upshore transport gives a strong peak of deposition in the highshore zone. The height, spread and location of this peak are strongly dependent on the tide height, bed geometry of this zone, and on the deposition parameters used. A 4m tide gives 210 g dry wt m^{-2} of sediment deposition at 15m offshore. Brown (1998) observed similar magnitudes of up to 650 g dry wt m^{-2} of sediment deposited on the upper saltmarsh

during two tidal cycles. There is large intertidal sediment transport at springs, but very little transport at neaps (peak deposition reduces by a factor of 75 for a change in tidal amplitude from 4m to 2m). An increase in tidal amplitude from 3m to 4m gives a greater than three-fold change in maximum deposition. This shows that the higher tides will give a much greater contribution to the mass of intertidally transported sediment than the small to medium tides. In this model, ebb erosion exceeds flood erosion because of the different history of velocity during flood and ebb, and the dependence of erosion rate on the difference between sediment eroded and the maximum available for erosion at a particular water speed. Further comparisons with observations are needed to see if this is realistic

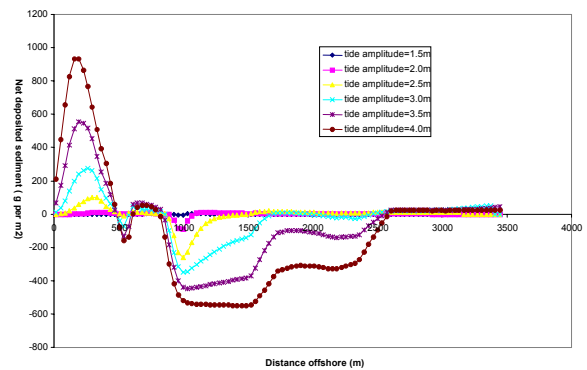


Figure 4 Net deposited sediment for different tide heights

6. EFFECT OF CHANGING EXTERNAL SEDIMENT

Figure 5 shows net deposition after one tide for three values of incoming suspended sediment concentration. For these runs, there is a maximum *Macoma* density of 100 individ m^{-2} , and a maximum chlorophyll density of 30 $\mu g g^{-1}$ dry wt. The tidal amplitude is 3.5m. External sediment is set to 0, 100 and 200 $g m^{-3}$. This is a reasonable range given that measured values of suspended solids in the Humber mouth vary from 20 to 1000 $g m^{-3}$. Sediment is deposited, using a constant fall velocity, while velocity is below a deposition threshold. Accretion shows a pattern of offshore increase, with rapid change in the high shore zone. At lower shore locations, the results are dominated by the difference in external sediment supply. At higher shore levels the response lines are close together showing that the deposition of intertidally

transported sediment is outweighing the contribution from externally sourced sediment here. At middle shore levels, the intertidal erosion of the bed can be countered by deposition of sediment advected from the subtidal channel. This shows that effects of intertidal sediment transport are more important at higher shore levels.

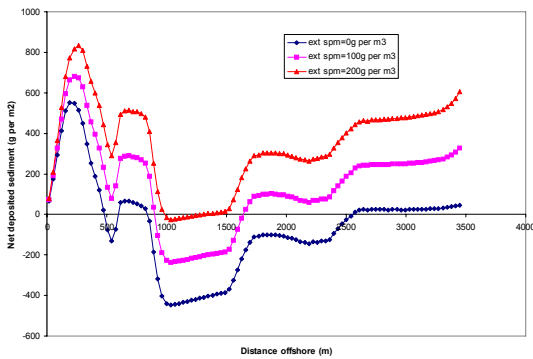


Figure 5 Net deposited sediment for different external spm concentrations

7. EFFECT OF CHANGING BIOTA

Figure 6 shows net deposition after one 3.5m spring tide for four different biota scenarios. Diatom numbers follow a seasonal pattern, with higher densities in spring and (sometimes) autumn. *Macoma* numbers show more interannual than seasonal variation, with high recruitment years tending to follow cold winters. High *Macoma* values tend to be associated with lower diatom values, due to increased grazing pressure. The responses show the hydrodynamics determining the spatial pattern of erosion/accretion, with biota strongly influencing the magnitude. Increasing the *Macoma* density from 100 to 1000 individ m^{-2} increases the peak deposition by five-fold. Further increases in *Macoma* numbers would not have as great an effect, since the erosion rate shows asymptotic behaviour in the presence of sufficiently high *Macoma* densities. The *Macoma* density affects erosion rate, whereas diatom density affects erosion threshold. So, increasing diatom density can prevent erosion in parts of the transect where it previously occurred; whereas changing overall *Macoma* numbers influences the magnitude, but not, primarily, the spatial distribution of erosion.

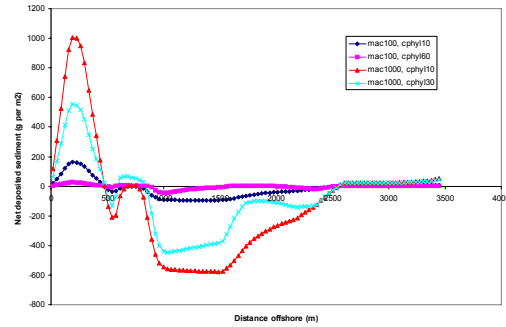


Figure 6 Net deposited sediment for various biota distributions

8. MONTH-LONG RESULTS FOR SKEFFLING

Model responses for the 1st to 29th November 1998 have been summed, using several biota populations and external sediment values, and taking tide heights from Admiralty tide tables. Using observed values of wet and dry sediment densities, the net deposition has been converted to depth of sediment accretion (figure 7). The green, dark blue and red lines all have the same value of external suspended sediment (100 g m^{-3}). With no intertidal erosion allowed (green line), the amount of deposition increases smoothly with offshore distance. The change of deposition with distance is steepest at the highest shore levels. Using a low density of bioturbators ($100 \text{ Macoma m}^{-2}$, dark blue line) changes the response by reducing deposition at the mid-shore range and increasing deposition at the high shore. High bioturbation ($1000 \text{ Macoma m}^{-2}$, red line) has a large effect on the response, giving a large peak in deposition below the MHWN mark, and a broad band of erosion and reduced deposition around mid-tide level. With no external sediment supply (brown line), the extensive areas of erosion can clearly be seen. These are determined by *Macoma* presence and high velocities. Comparing the red and purple lines shows that the high shore deposition associated with a high density of *Macoma* can exceed that given by a large offshore sediment supply. Integrating over a month has lowered and broadened the deposition peak.

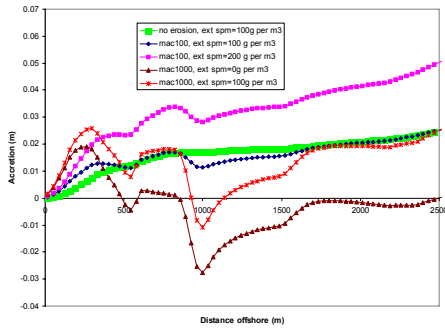


Figure 7 Depth of deposited sediment for 1-29 Nov, 1998

9. APPLICATION TO A TRANSECT IN THE MERSEY

The model has been applied to an intertidal transect near Ellesmere Port. The purpose is to provide a contrast to the Skeffling application, rather than to accurately simulate the area, partly because of the lack of required data for the model here, and partly because the section is on a bend in the estuary, not in a zone which is uniform alongshore. Here, because the intertidal zone is narrow, the major erosional velocity is expected to come from longshore currents. The model bathymetry is shown in figure 8. Erosional velocity and elevation are specified as functions of time, based on observations of current speed and elevation (West, 1980 and HR Report, 1990). Cross-shore advection velocity is calculated from elevation and bathymetry (as at Skeffling). *Macoma* density and chlorophyll are set to constant values along the transect.

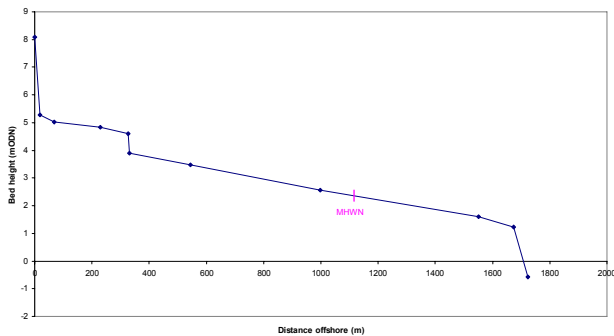


Figure 8 Bathymetry for Mersey transect

10. MODEL RESULTS, VARYING PHYSICAL PARAMETERS

Results are shown in Figure 9. The tidal amplitude is 4.5m, *Macoma* density is 100 individ m^{-2} and chlorophyll content is $2\mu g g^{-1}$ dry wt. As before, there is accretion on the upper shore, but here the response is almost

uniform offshore. Increasing the amount of external suspended sediment from 0 to 20 to 40 $g m^{-3}$ (yellow, purple and dark blue lines respectively) has a small effect on the deposition peak. However, there is a large effect on the offshore behaviour, causing it to change from erosion of about $10g m^{-2}$ to accretion of about $10g m^{-2}$. The brown line shows the effect of increased tide height, skewing the deposition peak and shifting it significantly towards the shore. To show the model sensitivity to the spatial profile of erosional (longshore) velocity, the light blue line plots results with a linear reduction in speed from the offshore to the onshore boundary. The deposition peak is heightened, and spread further offshore, but the overall pattern is similar to that yielded by the original velocity (yellow line).

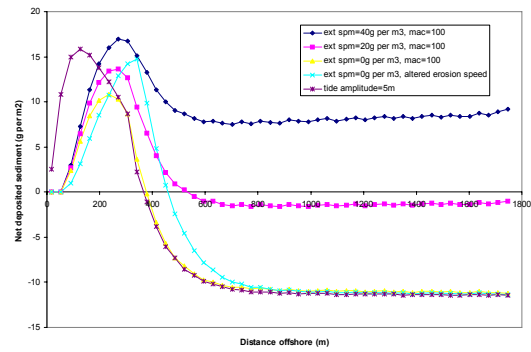


Figure 9 Mersey results, various physical parameters

11. MODEL RESULTS FOR THE MERSEY, VARYING BIOTA

The dark blue and purple lines (figure 10) show results with low (100 *Macoma* m^{-2}) and high (1000 *Macoma* m^{-2}) values, respectively. The increased bioturbation magnifies the deposition by a factor of ten for these parameters. The yellow line shows the results if erosional speed is taken as equal to cross-shore advection speed. The response is completely altered. The lower values lead to accretion everywhere, with maximum accretion over a large offshore zone.

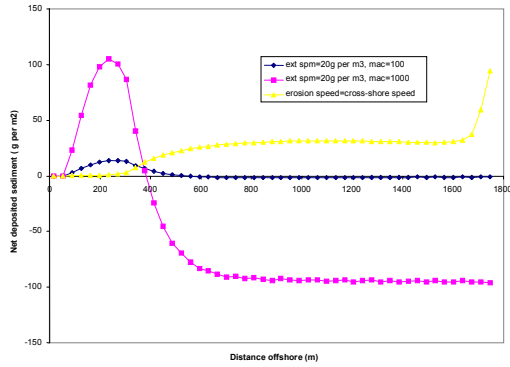


Figure 10 Mersey results, high and low Macoma

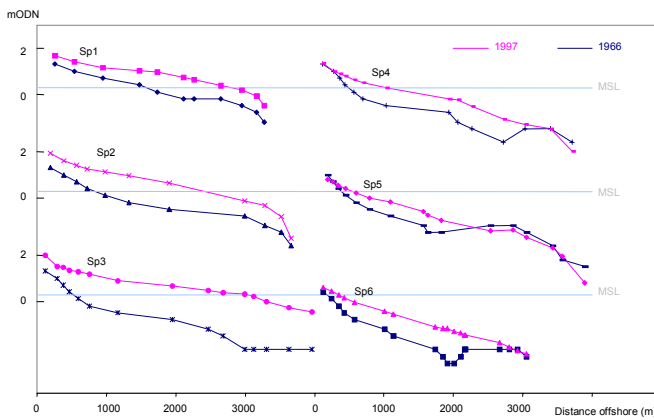


Figure 11a Spurn Bight bathymetry profiles for 1966 and 1997

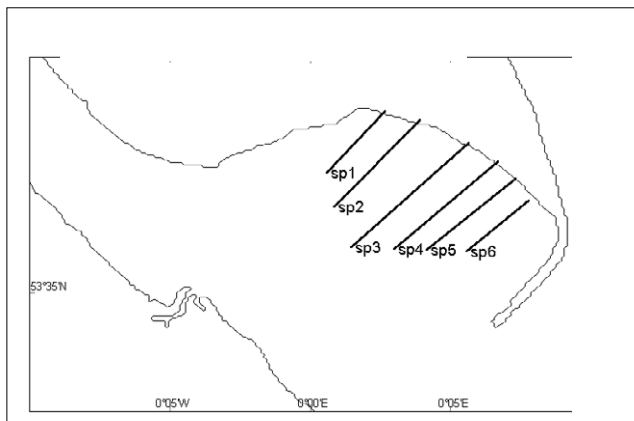


Figure 11b Location of Spurn Bight observation tracks

12. DISCUSSION

Observed data on Spurn Bight has been used to estimate bed heights along 7 transects for 1966 and 1997. Digitized contours from a chart of 1966 bathymetry (source: pers. comm. D.Price, ABP, 2000) and ABP bathymetric data for 1997 (for source, see EMPHASYS

database-Paper 1) were used. 1966 heights have been inferred where the 1966 contours cross the 1997 tracks. The 1997 data is a much higher resolution than the earlier data, so it was sampled and smoothed to give heights at the crossing points. The tracks are not shore-normal, they run south-westwards across the intertidal area from the shore (fig 11a). These show extensive accretion, with greatest accretion around mid-tide level. Bed profiles for the two times are compared in figure 11b. For the transect SP3, in the centre of Spurn Bight, the accretion varies from 0.5m to 2.35m. This would imply an average rate of change of between 1.3 and 6.3mm per month, which is lower than the modelled rates (which are in the region of 2cm per month, for an external sediment concentration of 100g m^{-3}). However, in the Severn estuary, Allen and Duffy (1998) have measured monthly changes in upper intertidal bed level for 2 years. This shows that the overall rate of change estimated over the whole period is up to five times smaller than the rate of change measured month-by-month. Individual sites show a spread of accretion and erosion changes over the 2 years.

The modelled net deposition is converted to net accretion, using the equation:

$$accn = 0.001depn \left(\frac{\rho_{drysed} - \rho_{water}}{\rho_{drysed}(\rho_{wetsed} - \rho_{water})} \right) \quad (7)$$

where accretion ($accn$) is measured in m, deposition ($depn$) is in g m^{-2} , $\rho_{water}=1025\text{kg m}^{-3}$, $\rho_{drysed}=2650\text{kg m}^{-3}$ and $\rho_{wetsed}=1325\text{kg m}^{-3}$.

Fig 12 compares model results for accretion (using 1-29th Nov 1998 tides and external sediment concentrations of 100g m^{-3} or 200g m^{-3}) to the accretion from 1966 to 1997 averaged over the number of months. The external sediment supply is in the same range as that observed by Christie et al. (1999) at mid-tide level at Skeffling. The observed accretion is the small difference of larger terms in the deposition-erosion balance. The observations do not extend far enough onshore to show the large accretion over the saltmarsh, which is known to have occurred over this period. Intertidal erosion removes sediment from mid-shore levels, where the deposition from external supply is plentiful, and redistributes it on the higher shore. The pattern

of intertidal erosion would change with the addition of a velocity component due to waves. It is also sensitive to the bathymetry, with greatest erosion occurring over flatter sections of shore.

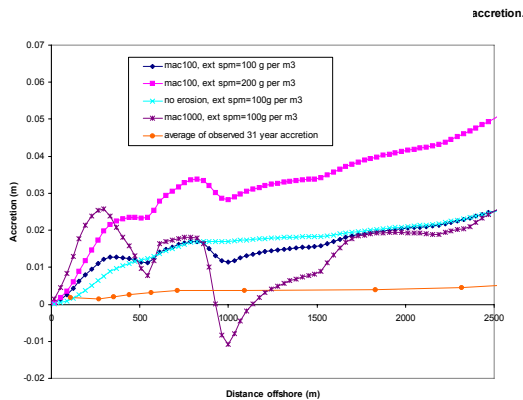


Figure 12 Comparison of modelled accretion for one month and observed average accretion

McGrorty (1999, pers. comm.) has statistically analysed measurements of bed level change within intertidal zones in the Wash and Humber, and has shown relations between accretion and inundation time, duration of strong onshore winds, and duration of strong winds in any direction. These are believed to relate to increased length of time for deposition, erosion due to wind-wave action, and deposition due to increased external suspended sediment supply. Strong winds are expected to increase the external sediment supply. Local winds will give wave-enhanced bottom stress, and are expected to give greatest erosion at the high shore levels (where the bed is subject to high orbital velocities for the greatest time), and where the shore steepens (i.e. high shore), where breaking waves can attack the shore. In contrast, during calm wind conditions, intertidal erosion will be greatest at mid-tide levels, and over the flattest sections of the shore, and will be enhanced by bioturbation (increasing erodability). The depth of bioturbation varies seasonally (being deeper in winter), and influences the extent of erosion by wave action.

Figure 13 shows bathymetry profiles along 6 shore-normal transects near Ellesmere Port for 1956 (dark blue lines) and 1997 (purple lines). The bathymetry for track EP1 is that used in the model. The observed pattern of higher

shore deposition and lower shore erosion is similar to that seen in the model results. The spatial distribution of accretion and erosion down a transect varies smoothly with transect's location along the bend in the river.

Model results and observed accretion are compared in Figure 14.

For both the Skeffling and Mersey transects, altering external sediment and bioturbation (i.e. local erodability), would allow the observed data points of average accretion rate to be fitted. This would give an approximation to average accretion rate, using a balance of deposition of externally-derived sediment, local erosion due to cross-shore (Skeffling) or long-shore (Mersey) currents, and deposition of locally-eroded sediment. The Skeffling transect requires an external sediment concentration of about 20 g m^{-3} , which then accounts for most of the intertidal deposition, excepting the region within 120m of the shore. This value of suspended sediment is 5 to 10 times lower than the observed values. This implies that the accretion does not proceed in a uniform way. The fit is not improved by allowing intertidal erosion in this case. Intertidal erosion does allow significantly more sediment to reach the upper bed levels, although not as far onshore as the observed peak over the saltmarsh. The location of the modelled erosion is sensitive to the bathymetry. The models yields more extensive erosion when the ABP 1997 height data from track SP3 is used than when the LISP project bathymetry at Skeffling is used. The best fit to the Mersey transect is given with little or no external sediment, so that local erosion is supplying almost all of the onshore accretion. Again, the accretion at the data point nearest to the shore is not reproduced by the model. This gives an indication of possible balances between the terms in the intertidal sediment budget. However, without the temporally-varying effect of wind waves, variations in external suspended sediment and the effects of surges and cycles longer than the spring-neap cycle on tidal height, only part of the budget is being obtained.

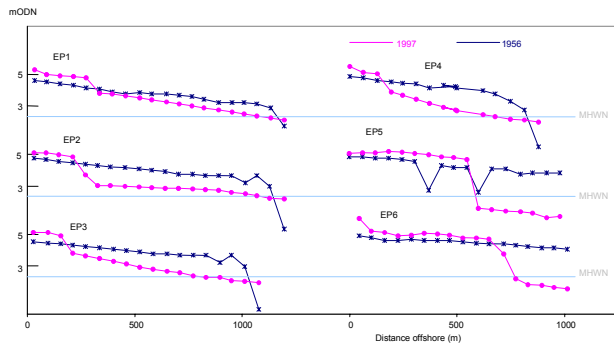


Figure 13a Ellesmere Port bathymetry profiles for 1956 and 1997

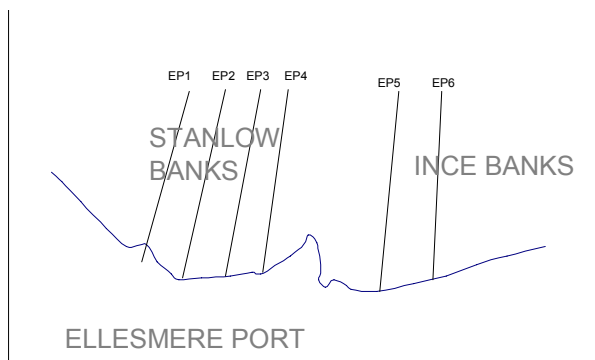


Figure 13b Mersey track locations

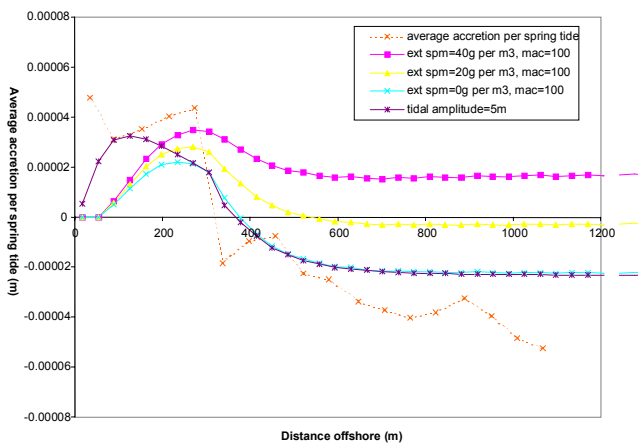


Figure 14 Modelled and observed accretion are compared in Figure 14

13. CONCLUSIONS

Observations of bed level changes in the intertidal zone show that net accretion or erosion over an annual or longer period is a combination of larger variations which act over shorter time-scales. In order to predict these effects over a time when the statistics may be expected to change, because of climate change and possibly other anthropogenic effects, it is necessary to gain quantitative

understanding of the component processes. Flume experiments show that bioturbating and stabilising biota have a dramatic effect on sediment resuspension. The BIOTIDE model shows that this process can increase upper shore deposition equivalent to doubling offshore sediment supply, and change the profile of net intertidal accretion during low wind periods. Further observations of bed-level change and biota are required to establish the statistical significance of biotic effects on a large spatial scale. These should be frequent enough to resolve the short-term changes in bed height.

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1D MODELLING OF THE HYDRODYNAMIC RESPONSE TO HISTORICAL MORPHOLOGICAL CHANGE IN THE MERSEY ESTUARY

Christopher Thomas

email: cgt@hrwallingford.co.uk

HR Wallingford, Howbery Park, Wallingford, Oxon, OX10 8BA, UK

1. INTRODUCTION

This study examines a long-term bathymetric data set of approximately 100 years to investigate the interaction between estuary form and process during a period of morphological evolution. The aim of the study is to examine the suitability of 1D modelling as an analytical approach to assess factors forcing morphological change. Historical bathymetries are employed as snapshots to analyse the degree of temporal variability and long term trends in form and process exhibited by the estuary system. Applying numerical hydrodynamic flow models to historical sequences of estuary bathymetry has provided valuable insight in previous studies to developing understanding of the interaction of estuary form with dominant processes (Roberts et al 1998).

The first stage of investigation comprises an analysis of morphological trends in the Mersey estuary of northwest England. The second element of the study employs a 1-D model to study historical changes in tidal properties in the estuary.

2. BACKGROUND

Previous studies, such as the classical O'Brien (1931) paper, suggest that estuaries tend to an equilibrium state characterised by a relationship between geometry and hydrodynamics or between the dimensions of various estuary morphological sub-units. Modification of estuary bathymetry can induce changes in flow characteristics within an estuary by altering the tidal prism, and by altering non-linear dynamics of system geometry distorting astronomic tidal constituents to create new compound tides and overtides (Parker 1991). The internal interaction between estuary form and process has been proposed as a key factor determining estuary equilibrium through influencing tidal asymmetry (Friedrichs and Aubrey 1994, Dronkers 1998), and thus flood or ebb

dominance which influences net gain or loss of sediment to the system (Dronkers 1986). However a range of external processes also exert a significant influence upon estuary morphology and require consideration, such as the interaction of the estuary with the broader seaward environment (Castaing and Allen 1981).

Study of the Mersey estuary (Thomas 1999) has demonstrated that morphological change is characterised by a trend of substantial accretion through the period 1906-1977 following significant civil engineering activity. Following 1977 however the estuary appears to have entered a new phase with slight erosion experienced between 1977-1997. This may be interpreted as the result of a new equilibrium state being achieved between tidal propagation and estuary geometry. However in the case of the Mersey, a physical model study indicated that hydrodynamic flow patterns, and hence sediment transport pathways, were altered in Liverpool Bay following construction of training walls in 1906 (Price and Kendrick 1963) suggesting that estuary accretion is controlled by sediment supply to the estuary mouth. This study develops previous work by comparing the relative trends in internal interaction between estuary form and process to draw conclusions on the factors controlling long term morphological evolution.

3. ANALYSIS OF MORPHOLOGICAL TRENDS

Bathymetric data from the years 1871, 1906, 1936, 1956, 1977 and 1997 was obtained in digital format and interpolated to form grid based contour maps using SURFER software (Golden Software 1997). Integrated geometric properties were calculated to examine parameters that characterise the behaviour of an estuary in terms of simple geometric properties.

Dronkers (1998) applied an analytical approach for a 1-D solution for an ideal estuary with linearised friction to derive a non-dimensional parameter, γ , indicative of flood or ebb dominance. Roberts et al (1998) applied Dronkers parameter to a historical analysis of changes in the Stour and Orwell Estuaries (UK) and found that it broadly reflected historical changes in flow characteristics derived from 2-D hydrodynamic models. Friedrichs and Aubrey (1994) identified geometrical parameters (ratios of tidal amplitude to mean depth a/h and channel volume to storage volume V_s/V_c) influencing tidal asymmetry based on computational modelling results. The results of analysis of

these parameters for the Mersey are shown in Table 1.

The trends demonstrated by Dronkers parameter are reconcilable with gross changes in estuary volume, indicating decreased ebb dominance of the system coinciding with a period of accretion between 1906-1956. The trends illustrated by Friedrichs and Aubrey's (1988) geometrical parameters are more complex. The parameter a/h suggests an increase in flood dominance from 1906-1997, whilst the parameter V_s/V_c suggests a decrease in ebb dominance.

Table 1 Parameters characterizing estuary behaviour

Year	γ Parameter	a/h	V_s/V_c
1871	1.41	0.571	2.624
1906	1.58	0.530	2.296
1936	1.53	0.529	2.325
1956	1.53	0.538	2.288
1977	1.34	0.558	2.564
1997	1.31	0.575	2.680

4. 1-D MODELLING OF ESTUARY HYDRODYNAMICS

Cross section averaged flow characteristics for each year were calculated by solving equations derived from the St Venant equations for shallow water waves in open channels using ISIS software (Halcrow/HR Wallingford 1999). 1-D models have been employed in other studies to predict velocity trends utilising system geometry and elevation data (Aubrey and Friedrichs 1988) providing a basis for an analytical technique to examine comparative changes in flow characteristics for historical sequences of estuary bathymetries.

Estuary geometry was represented as 160 cross sections (see figure 1) at replicated positions in the estuary for the years 1871, 1906, 1936, 1956, 1977, and 1997. Spring tidal elevation measurements made by West

(1980) were used to calibrate the 1977 bathymetry, it was validated using neap tidal elevation measurements. Freshwater flow was assumed to have little impact, as it is an order of magnitude less than tidal flows in the Mersey. Calibration conditions were repeated for other historical bathymetries, and from the resulting flow outputs the ratio of peak ebb speed to peak flood speed was examined with regard to its importance to net sediment transport in the estuary. The impact of reclamation was considered by modifying the 1906 bathymetry to account for reclamation undertaken along the estuary shoreline between 1906-1936. Sea level rise was also examined by modifying the 1871 tidal boundary condition by 10cm, to represent the modification of tidal conditions expected due to conditions of mean sea level rise of 1mm/year identified by Woodworth (1999).

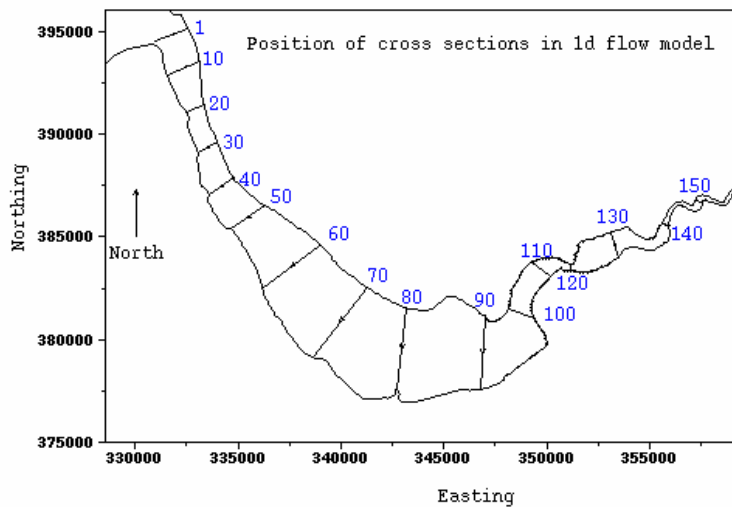


Figure 1 Schematisation of estuary cross sections for 1-D model

4.1. Historical changes in Ratio of Peak Ebb Speed to Peak Flood Speed

The results of the 1d flow model show a trend of ebb domination in the Narrows section of the estuary, which does not reflect flow observations demonstrating flood dominance, expected given a generally shorter duration flood tide. Although the 1d model employs the actual bathymetry the resolution relatively coarse, and draining and flooding of intertidal areas is a significant factor in hydrodynamic flow properties, which the model does not represent satisfactorily as it cannot reproduce lateral variations in water level. 1d flow results must therefore be treated with significant caution when employed to analyse changes in estuary hydrodynamics resulting from bathymetric modification, and the implications for sediment transport based on flow results.

The 1d flow results show that the Mersey estuary becomes increasingly flood dominant landwards, however no clear trend is evident in the patterns of change of ratio of peak ebb speed to peak flood speed. There is a tendency towards greater ebb dominance through the Narrows in 1936. The greatest fluctuations in ratio of peak ebb velocity to peak flood velocity are illustrated around section 61-70 where the Narrows widens into the estuary basin, also showing a tendency to increased ebb dominance in 1936. None of these fluctuations appear reconcilable with changes in estuary volume, which would require an increased flood dominance in the estuary during the period of maximum accretion, around 1936. The impact of reclamation and sea level rise also demonstrate no significant impact on flow conditions in the estuary except a very minor reduction in ebb dominance between sections 80-90 in the Upper Estuary.

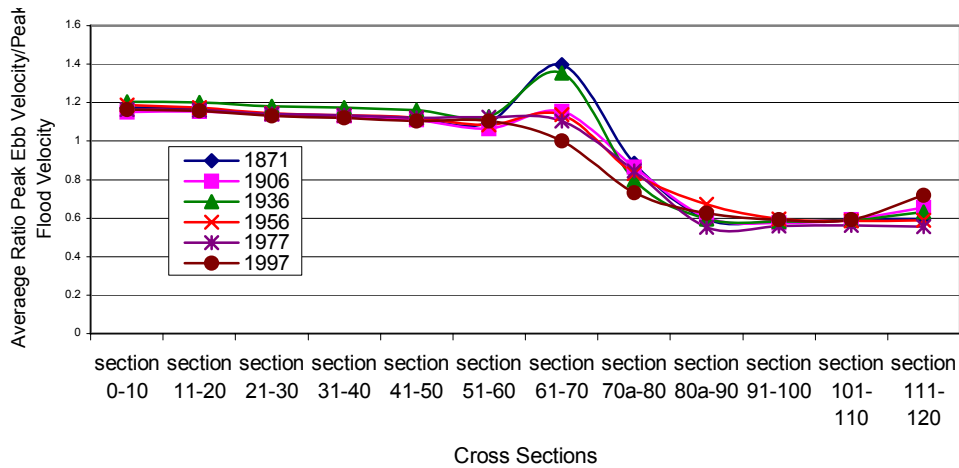


Figure 2 Ratio of Peak Ebb Speed to Peak Flood Speed for a Spring Tide

Trends for a neap tide (see figure 3) show little correlation with broad morphological changes and are of limited significance due to a lower capacity to transport sediment.

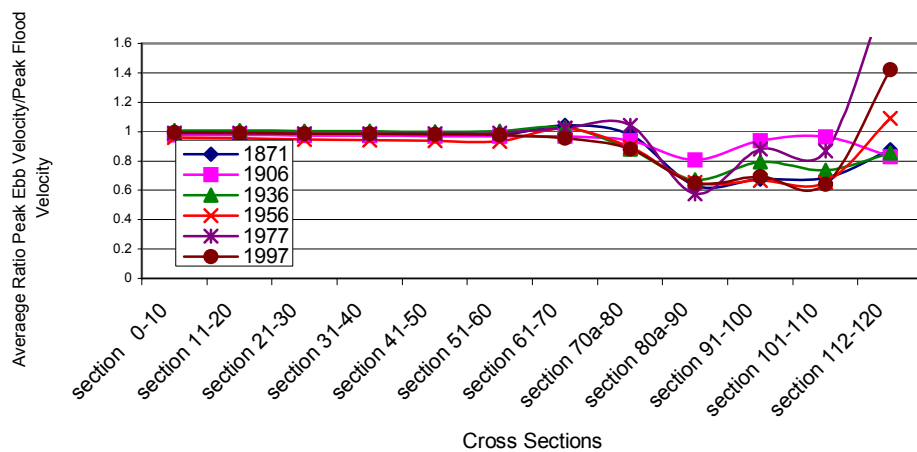


Figure 3 Ratio of Peak Ebb Speed to Peak Flood Speed for a Neap Tide

4.2. Impact Of Reclamation

The impact of reclamation was considered by modifying the 1906 bathymetry to account for reclamation of approximately 12Mm³ along the middle estuary shoreline (sections 40-80) between

1906-1936. The impact of reclamation on the ratio of peak ebb speed to peak flood speed in the Mersey is shown in Figure 4.

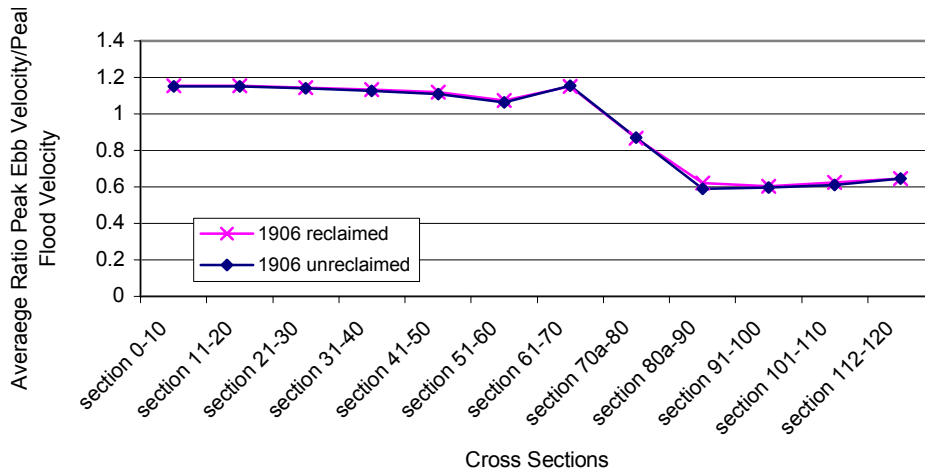


Figure 4 Comparison 1906 Average Peak Ebb to Peak Flood Velocity Ratios with and without bathymetry modified due to reclamation

4.3. Sea Level Rise

Sea level rise was examined by modifying the 1871 tidal boundary condition by 155mm, to represent the modification of tidal conditions expected due to conditions of mean sea level rise of 1.23mm/year identified by Woodworth (1999). The impact of sea level rise on the ratio of peak ebb speed to peak flood speed in the Mersey is shown in Figure 5, demonstrating no significant impact on the ratio of peak ebb speed to peak flood speed in the estuary.

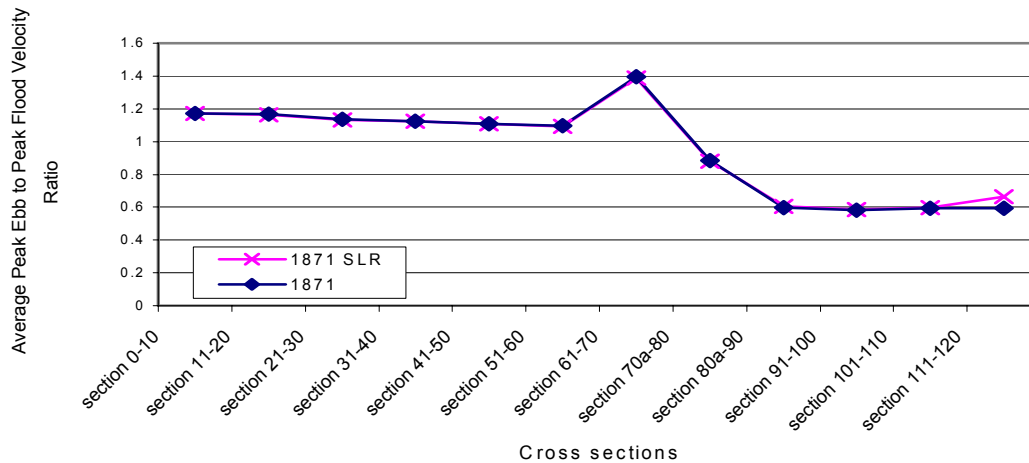


Figure 5 Comparison 1871 Average Peak Ebb to Peak Flood Velocity Ratios for 1871 with and without Sea Level Rise

5. DISCUSSION

Significant morphological change in the Mersey estuary has occurred through the course of the last century and has been recorded in the form of bathymetric surveys. This provides a significant resource for analysing detailed changes in estuary form, and developing insight to interaction with processes driving long term estuary change through the application of numerical hydrodynamic flow models.

Integrated geometric properties characterising the behaviour of the estuary in terms of simple geometric properties have demonstrated potential changes in the flow regime of the estuary. The trends demonstrated by Dronkers parameter are coincident with estuary behaviour and suggest a hydrodynamic response reconcilable with adjustment to a new equilibrium state. The trends illustrated by the parameters a/h and V_s/V_c are however less clear.

1D models are potentially well suited to modelling gross changes in flow characteristics through an estuary as they can be used to represent only the measured bathymetry without interpolation between measured points as in 2D and 3D models. A 1D model was employed as a diagnostic tool to examine cross sectionally averaged changes in hydrodynamic conditions in the estuary. The main value of this approach is as a comparison of changes in flow conditions resulting only from different geometrical configurations of the estuary which was the only model condition altered.

Based on the findings of this work however no clear conclusions may be drawn regarding the interaction of estuary form with hydrodynamic processes which could explain compatible changes in sediment regime. Although the 1d model represents water levels satisfactorily, its representation of flow velocity is limited as this is primarily a 2d, or even 3d effect. Moreover the approach taken is simplified, and neglects other processes occurring in the estuary, such as the interaction with the seaward environment which acted as the probable source of sediment entering the estuary.

To examine the effect of other processes, and resolve in greater detail the movement of sediment into and within the estuary a more complex modelling approach is required. Even if 1D models represent hydrodynamic flow accurately, they are not well suited to modelling of coarser sediments sensitive to near bed current profiles which anecdotal evidence suggests has formed the bulk of sediment accreted in the estuary. 2D (vertically-averaged) and 3D modelling approaches resolve sediment pathways more effectively by representing pronounced lateral depth variations and lateral depth variations with vertical current structure respectively. In addition 2D and 3D approaches are better suited to modelling an unconfined area such as an offshore boundary where it is not possible to impose cross sections. To consider in greater detail processes responsible for morphological change in the estuary a more complex modelling approach is therefore required.

6. CONCLUSIONS

- Dronkers morphological parameter demonstrates trends coincident with gross changes in morphology, indicating a response of estuary form and process to civil engineering activities reconcilable with a trend towards an equilibrium state.
- 1d modelling demonstrates substantial limitations in representing trends in hydrodynamic flow patterns, and does not allow clear conclusions to be drawn regarding the interaction of estuary form with potential process change responsible for the evolution of sediment regime.
- Reclamation and sea level rise induce only negligible changes in flow properties.
- To consider in greater detail processes responsible for morphological change in the estuary a more complex modelling approach is required.

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MODELLED CURRENTS OVER ESTUARINE CROSS-SECTIONS IN THE TAMAR SYSTEM

Reginald Uncles, John Stephens and Carolyn Harris

email: rju@pml.ac.uk

Plymouth Marine Laboratory, Prospect Place, West Hoe, Plymouth PL1 3DH, UK

ABSTRACT

A numerical model of the tidal flow over an estuarine cross-section, including the main channel and intertidal mudflats, was written to supply estimates of transverse distributions of currents and bed shear stresses. The model was applied to a cross-section of the Tavy Estuary (a sub-estuary of the Tamar). Ebb currents were computed to be dominant over the estuarine intertidal mudflats and this was verified by the observed data. The wide, flanking mudflats of the Tavy section comprised a muddy mixture of predominantly silt and clay. Surface sediment in the main channel, and on the upper shores of both banks, comprised a mixture of predominantly coarse, non-cohesive sediment, with very small fractions of silt and clay. POC contents were typically 2 – 3% on the mudflats. Much lower POC contents occurred in the main-channel and near-bank areas that were lagged by predominantly coarse, non-cohesive sediments. Bulk density was typically 1.2 – 1.4 g ml⁻¹ on the flanking mudflats. The modelled longitudinal currents showed that maximum flood and ebb stresses during a spring tide on 16 August 1988 were greatest in the main channel and were about 1.5 Pa and 0.5 Pa, respectively. Maximum stresses were flood dominant in the main channel and on the lower mudflats, and strongly ebb dominant on the upper mudflats. The results are consistent with the long-term depositional environment associated with rapidly rising sea levels of the early Holocene, and with the present, relatively slower rate of sea level rise.

1. INTRODUCTION

The Tamar Estuary in Southwest England forms the main stem of a large ria system. The Tavy, which is a tributary river and one of the Tamar's sub-estuaries (Figure 1), is a muddy creek and lateral ria. At low water (LW) the River Tavy meanders its way along a very narrow channel flanked by wide mudflats from the weir at

Lopwell to the Railway Bridge near its confluence with the Tamar Estuary (Figure 1).

The extensive mudflats in the Tavy appear to have been deposited during the last ~10 ka of the Holocene (e.g. Roberts, 1998). As such, the vast majority of deposited sediment reflects the changing physical conditions over that period, especially between 11.5 to 6 ka before present, rather than the modern hydrography. Visual observations indicate that small changes in the LW channel do occur, such as mudbank slumping following spate flows, but the dominant, qualitative impression on a decadal time-scale is one of mudflat stability.

Pethick (1984) has described how these mudflats may have formed in similar, generic creek systems. Essentially, turbid waters that flood over the mudflats deposit their sediments in the relatively slack waters there, especially over high-water slack, and then fail to resuspend all of them on the ebbing portion of the tide. Such a process describes a positive feedback, in which sediment deposition and mudflat accretion lead to slower currents over the mudflats, which in turn enhances deposition from those currents. The phenomenon is analogous to river flood-plain formation during spate conditions (e.g. Reid and Frostick, 1994).

This report describes a model that simulates the cross-estuary variations in tidal currents and demonstrates that much slower tidal currents do occur over the mudflats. The model results were compared with tidal cycle observations made at stations R1 and R2 on the mudflats at section BF to BC (Figure 1) and at a station in the main channel of the section. Extension of the model to incorporate sediment transport is planned.

The Tavy is fairly typical of many creek or lateral ria systems that exist in the drowned river valley systems of Southwest England. It is

approximately 5 km long from its head at Lopwell Weir to its confluence with the Tamar, just down-estuary of the Tavy Rail Bridge (Figs. 1). Its tides are derived from water level variations within the Tamar, where tidal ranges are 4.7 and 2.2 m at mean springs and mean neaps, respectively. The mean freshwater flow across Lopwell Weir for the period 1976 to 1990 was $6 \text{ m}^3 \text{ s}^{-1}$. Typical peak winter flows were $50 \text{ m}^3 \text{ s}^{-1}$ and typical minimum summer flows were $0.5 \text{ m}^3 \text{ s}^{-1}$.

Model output was compared with data collected during a spring tide on 16 August 1988. During the period of observations considered here (15 – 17 August 1988) the freshwater flows decreased from 3 to $2 \text{ m}^3 \text{ s}^{-1}$. The tidal range decreased during this period of decreasing spring tides, from 4.1 to 3.8 m, which compares with a mean, long-term tidal range of 3.45 m.

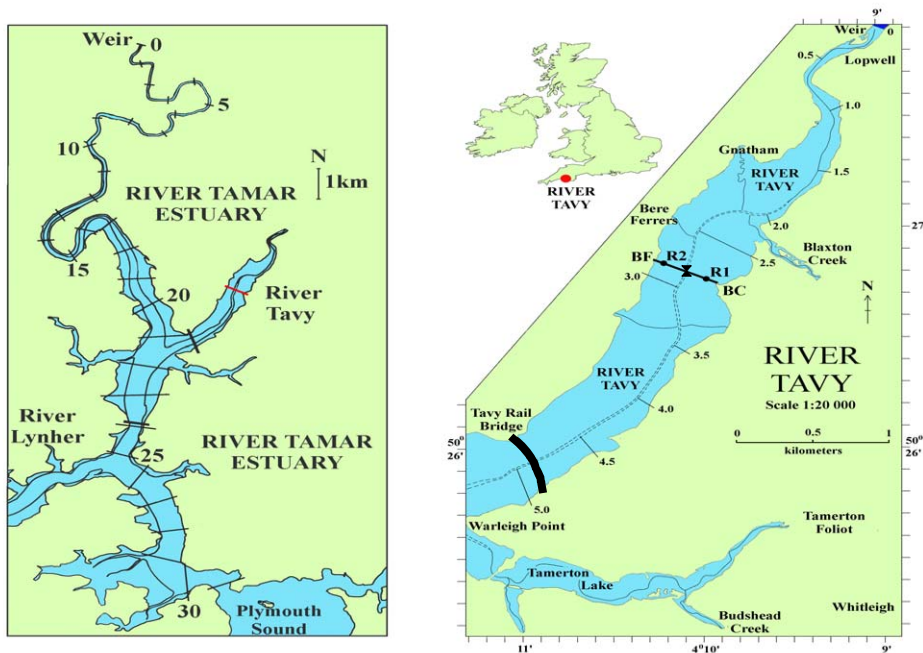


Figure 1 The Tamar Estuary, Southwest England. Distances from the head are shown (km). Modelled and measured data are presented for the highlighted section drawn across the central reaches of the River Tavy Estuary. Observational ‘Rig’ sites, R1 and R2 are shown on section BF-BC in the Tavy.

2. MATHEMATICAL MODEL

The momentum equation for depth-averaged, longitudinal currents, u , at any position, x , of depth $h(x)$ on the section was taken to be:

$$\begin{aligned} \partial u / \partial t = & -g \partial \zeta / \partial x - C_D u |u| / h - \frac{1}{2} g h \partial \ln(\rho) / \partial x \dots \\ & + h^{-1} \partial (h N_x \partial u / \partial x) / \partial x + h^{-1} \partial (h N_y \partial u / \partial y) / \partial y \dots \\ & - u \partial u / \partial x \end{aligned}$$

Symbols have their usual physical oceanographic meanings. The depth-averaged, longitudinal density gradient was deduced from the tidal cycle profiling data on 16 August 1988, and was approximated using the fact that the dominant intratidal variations in density, ρ , were

due to advection of the longitudinal density gradient by tidal currents. The longitudinal eddy mixing term was ignored compared with the other terms. The longitudinal advection term was approximated by:

$$u \partial u / \partial x \approx u^2 / L$$

where L is the distance between the cross-section and the tidal limit (2.9 km, Figure 1). The longitudinal, surface water-level (ζ) slope was deduced from the tidal cycle profiling data on 16 August 1988 by constraining the model to simulate exactly the observed, depth-averaged tidal currents in the main channel.

Environmental forcing data for the simulation comprised prescribed water level variations, ignoring transverse surface slopes, and the derived longitudinal, surface water-level slopes and density gradients.

Transverse currents across the section, v , were also computed, using continuity of water volume as water flooded onto and ebbed from the intertidal areas and ignoring transverse surface slopes. These currents were always very slow compared with the longitudinal currents, except when water depths became of the order of 0.01 m, by which time the assumption of zero transverse water-level slopes would have been untenable and the computed currents unrealistic.

The solution of the momentum equation involved dividing the experimental cross-

section (BF-BC, Figure 1) into width-height elements and solving a finite-difference, time-stepping equation for each element. The surface elevation of water level was prescribed from measurements. The oscillatory part of the surface slope was estimated by solving a local momentum balance at the deep-channel station near the centre of the cross-section. This was valid because of the relatively small influence of transverse eddy viscosity. The residual, tidally-averaged part of the surface slope was determined by ensuring that the correct (observed) residual water discharge was transported through the section. This requirement was satisfied by repeated trial and error adjustment of the residual surface slope, followed at each adjustment by solution of the longitudinal, momentum equation.

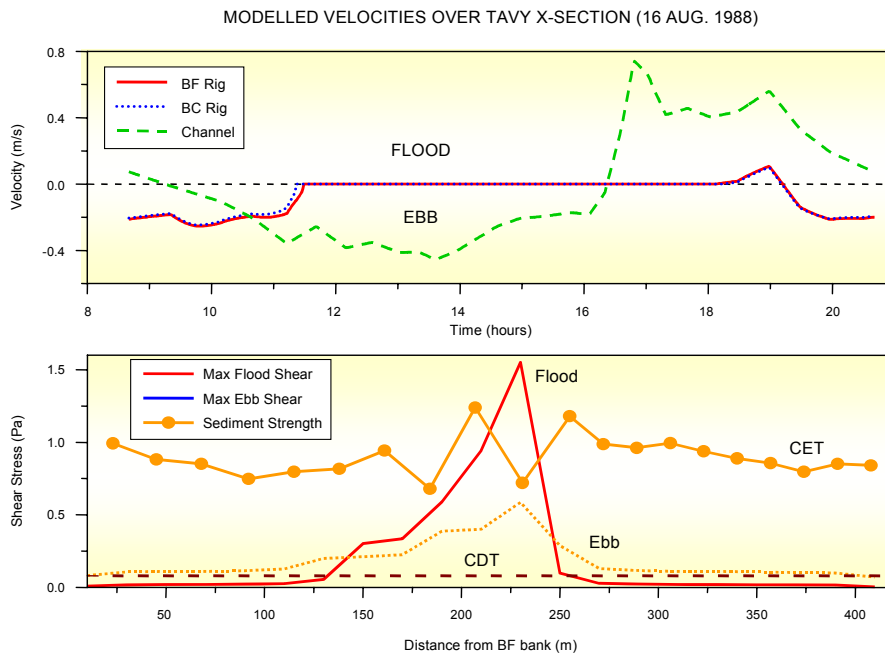


Figure 2 Transverse distributions of modelled current velocities and peak bed shear stresses during a spring tide on 16 August 1988. Top panel: Simulated longitudinal currents in the main channel and at the rig sites on the upper mudflats (Figure 1). Bottom panel: Transverse distributions of maximum bed shear stress during the flood and during the ebb. Also shown are the CDT and estimated CET over the section (see text).

3. RESULTS

The transverse distribution of depth-averaged, longitudinal current velocity was computed from the momentum-equation model. The spring tide of 16 August 1988 was simulated. The modelled longitudinal currents at both rig sites on the upper mudflats were very similar and had much slower peak speeds than the main-channel currents

(upper panel, Figure 2). The simulated rig currents were ebb dominant. These features, of greatly reduced peak currents and ebb-tide current dominance, were also features of the observed data.

The transverse distribution of longitudinal, bed shear stress was computed from the model.

Maximum flood and ebb stresses during the tide were greatest in the main channel (lower panel, Figure 2). Maximum flood and ebb bed shear stresses were about 1.5 Pa and 0.5 Pa, respectively. Maximum stresses were flood dominant in the main channel and on the lower mudflats, and strongly ebb dominant on the upper mudflats (lower panel, Figure 2). The critical deposition threshold (CDT; HR (1999)) for fine sediment was much greater than the simulated, peak, bed shear stresses on the upper mudflats during the flood (lower panel, Figure 2) implying fine sediment deposition there. CDT was less than the simulated, peak, bed shear stresses on the upper mudflats during the ebb, implying that fine-grained SPM remained in suspension during the ebb.

The estimated critical erosion threshold (CET) over the mudflats (based on the bulk density of the upper 0.01 m of bed; HR (1999); Delo (1988)) was much greater than the simulated, peak, bed shear stresses (lower panel, Figure 2) implying that these mudflats had considerable stability. Although a large error is anticipated in the estimated CET, even a four-fold overestimation of CET would not alter this implication. In the main channel, peak flood bed shear stresses exceeded the threshold of sand movement and peak ebb bed shear stresses were close to the threshold.

4. CONCLUSIONS

The modelled longitudinal currents at both rig sites on the upper mudflats were very similar, they were ebb-dominant and had much slower peak speeds than the main-channel currents. Maximum flood and ebb stresses during the tide were greatest in the main channel and were about 1.5 Pa and 0.5 Pa, respectively. Maximum stresses were flood dominant in the main channel and on the lower mudflats, and strongly ebb dominant on the upper mudflats. The CDT for fine sediment was much greater than the simulated, peak, bed shear stresses on the upper mudflats during the flood, implying fine sediment deposition there. CDT was less than the simulated, peak, bed shear stresses on the upper mudflats during the ebb, implying that fine-grained SPM remained in suspension during the ebb.

The estimated CET over the mudflats (based on the bulk density of the upper 0.01 m of bed) was much greater than the simulated, peak, bed shear

stresses, implying that these mudflats had considerable stability. A four-fold overestimation of CET would not alter this conclusion. In the main channel, peak flood bed shear stresses exceeded the threshold of sand movement and peak ebb bed shear stresses were close to the threshold.

The data indicated that vertically mixed, relatively high salinity, high turbidity waters flooded onto the upper mudflats during spring tides, and that the SPM largely settled to the bed there, both during the flood and over HW slack. There was little evidence of any subsequent strong resuspension of this sediment during the salinity-stratified ebb. However, circumstantial evidence indicates that turbid waters did drain from the mudflats into the main channel, and it is speculated that this drainage might have occurred as a very shallow, turbid, sheet flow. Such a process would have been much more effective on the greater slopes of the lower mudflats. It would have been much less effective on the upper mudflats, so that one would anticipate accretion of these areas in the long term, as proposed by Pethick (1984). This conclusion is consistent with the long-term depositional environment associated with rapidly rising sea levels of the early Holocene, and with the present, relatively slower rate of sea level rise.

It is planned to incorporate a sediment transport model into the momentum equation solver in order to investigate long-term changes in estuarine channel shape.

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ACCOMMODATION SPACE AND ESTUARINE EVOLUTION

Peter Balsone

email: p.balsone@bgs.ac.uk

British Geological Survey, Kingsley Dunham Centre, Keyworth, Nottingham, NG12 5GG, UK

1. INTRODUCTION

The 'accommodation space' in an estuary can be defined as the volume between the estuary bed and the level of high water and is therefore the maximum volume available for the deposition of sediments within the estuary at any given point in time. Over the long-term, changes in accommodation space are a function of three factors; estuary morphology, sea level change and the rate of sedimentation. As sea level has risen over the last few millenia former river valleys have progressively drowned to become estuaries. As this rise has continued the estuaries have been forced to migrate landwards in a process termed 'rollover' (Allen, 1990). This process, which continues to the present time, is constrained to a greater or lesser degree by the pre-existing or 'antecedent' topography of the estuary valley. In the future the natural, or geological, constraints will be enhanced by anthropogenic constraints as the result of development and flood defences. These will tend to reduce the rate of increase in available accommodation space as sea level rises and will significantly affect the ability of the estuary to 'rollover'.

To examine the interplay between sea level rise, antecedent topography and sedimentation, a model has been created to determine how potential accommodation space has changed through time for three UK estuaries. Using borehole and seismic reflection profiling data from the Humber Estuary, Mersey Estuary and Southampton Water the antecedent topography of each estuary valley has been modelled. Using data for long-term sea level rise the change in accommodation space through time has been determined and an intercomparison made between these three contrasting sites in order to better understand the primary controls on estuary evolution.

2. METHODOLOGY

The method used requires a knowledge of the basal topography of the estuarine sediments, the

elevation and gradient of the maximum potential water surface within the estuary and a plot of long-term sea level elevation within the estuary system. The necessary data to support this analysis was available for three of the six estuaries chosen for the EMPHASYS programme. The Humber Estuary, Mersey Estuary and Southampton Water were therefore selected for analysis. The production of the digital terrain models (DTMs) and the volumetric analysis of accommodation space were performed using Earthvision, a standard terrain modelling software package.

The DTMs of the base of the estuarine sediments (base Holocene) were produced using data derived from :-

a) *Borehole records*. Borehole records tend to be most numerous in the reclaimed areas of the estuary floodplains and especially in urban areas like the city of Hull. Most relate either to site investigations for engineered structures or from the water industry. The spatial distribution of borehole sites can therefore be very uneven within the area of the estuary and its floodplain. Occasional boreholes have been sited within the estuary channels associated with tunnels, bridges, pipelines and jetty structures. The borehole records utilised for this study came mainly from the National Geoscience Records Centre at the British Geological Survey (BGS) in Keyworth.

b) *Seismic reflection profiles*. Seismic reflection profiles provide a continuous analogue record of the subsurface sediment layers along a survey track line. The seismic equipment is towed behind a small survey vessel and therefore data can be obtained most readily within the estuarine channels with more limited data in the deeper parts of the intertidal area and shallower parts of the estuary. Seismic reflection data for the Humber and Mersey estuaries has been obtained, and is held by, the British Geological Survey; data for Southampton Water was supplied by ABP.

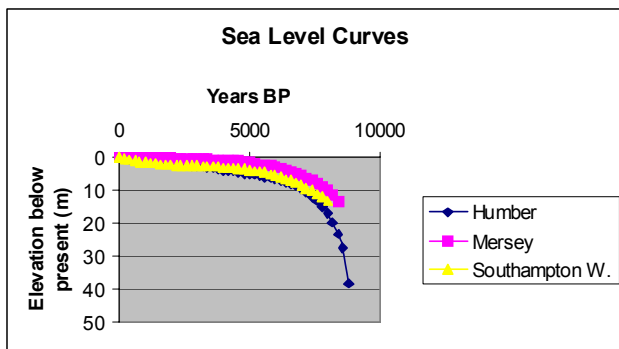


Figure 1 Sea level curves for the studied estuaries

The determination of the maximum water level was derived from the evidence of the maximum distribution of floodplain sediments rather than measured water elevations within the modern estuary. This approach is necessary because the model attempts to determine the natural rate of progression of accommodation space free from the artificial restrictions caused by reclamation and the construction of flood defences. The digitised limit of surveyed floodplain sediments on geological maps of the BGS was used to define the maximum limit of potential natural flooding within the estuary system. The elevation of this boundary was determined using a variety of methods including the use of intersections with contours on published topographic maps and elevations from levelled points. The data was then modelled using Earthvision to produce a planar surface representing the inferred maximum elevation of the water surface within the estuary.

Accommodation space is defined as the volume between the sediment and the water surfaces. It is only possible to determine this volume accurately where the form of both surfaces are known and this is only likely to be the case where good, modern bathymetric/topographic data exists. In most estuaries this data is only available for the last century or thereabouts and so the absolute volume of accommodation space cannot be determined for any particular time before this. Therefore in order to examine estuarine accommodation space for times prior to this a different approach is required. Assuming the base Holocene surface to represent the antecedent topography which was flooded as sea level rose it is possible to determine the incremental addition of accommodation space which was created as the water level rose within the constraints of the valley form. This analysis

produces a plot of the trend in the expansion of estuary volume available for sedimentation as the estuary gradually expanded.

The rate of sea level rise over the last 8000 years has varied from estuary to estuary. Determination of the sea level curves for many estuaries has been achieved by detailed analysis of core samples from within the estuarine sediments and have been published by numerous workers (e.g. Shennan et al., 2000). The estimation of past sea level is based mainly on evidence of the upper boundaries of dated organic peat layers which show a conformable transition with overlying mudflat sediments. The derived elevation and age data are then used to produce a best-fit curve which represents the long-term rate of sea level rise for the studied estuary. The present study has used published curves for each of the three estuaries to estimate the elevation of the water surface at 200 year intervals from 8000 years BP to present. (Figure 1)

The volume between the antecedent valley topography and the inferred water surface at each of these 200 year intervals was determined using the Earthvision modelling program. The difference between each derived volume therefore represents the incremental addition in accommodation space within the bounding confines of the valley form at 200 year intervals. This is the extra volume available within which sediments could be deposited depending on sediment availability. The amount of sediment deposited during any of these increments is unknown and is not considered within the model.

In addition the total volume of sediment present in the modern estuary (ie the total sedimentary deposition since the estuary was originally flooded 7000-8500 years ago) was determined using the volume difference between the basal Holocene surface and the a DTM of the modern sediment surface. The modern sediment surface was estimated from a combination of bathymetry for the intertidal and subtidal areas and topography derived from various data sources including levelled point data from borehole sites. This volume allows an estimate of the long-term, time-averaged deposition rate for an individual estuary to be estimated and provides a comparison with estimates of contemporary net sediment fluxes into the estuary.

3. RESULTS

The topography of the base Holocene surface for each of the three estuaries is shown in Figures 2, 3 and 4. These images represent the probable form of the antecedent topography within which the estuary has developed although it is of course possible that erosion during the evolution of the individual estuary may have modified its original form, and that therefore some parts may be deeper than they were initially. The modern high water mark is shown to provide a reference. In most cases it is clear that the modern estuary channel closely follows the deepest part of the valley form and in general the bathymetry and base Holocene topography coincide here indicating a lack of deposited sediment on the floor of the modern channel.

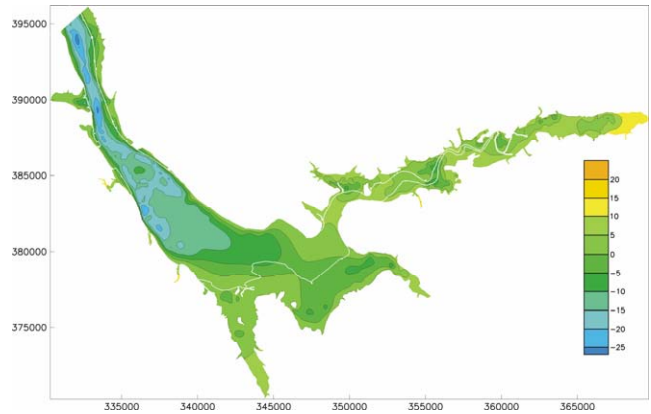


Figure 4 DTM of the base of Holocene estuarine sediments in the Mersey Estuary. Depth in metres below OD

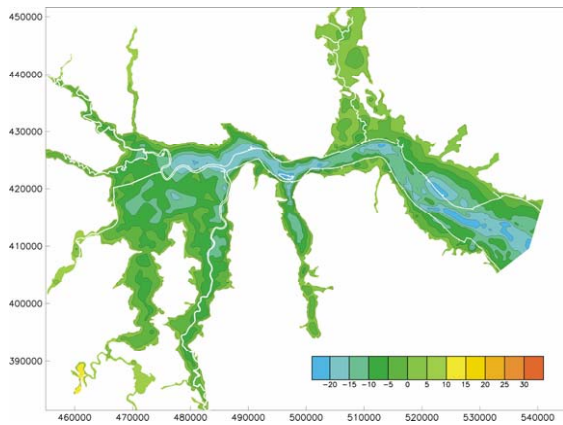


Figure 2 DTM of the base of Holocene estuarine sediments in the Humber Estuary. Depths in metres below OD

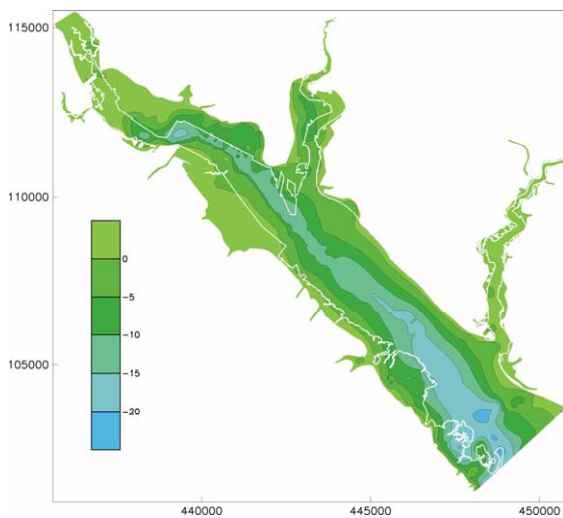


Figure 3 DTM of the base of Holocene estuarine sediments in Southampton Water. Depth in metres below OD.

The accommodation space curves derived from the model for each of the three estuaries are shown in Figures 5,6 and 7. The curves depict the annual increase in accommodation space against time. Note the large difference in the scale of volume increase between the three estuaries. The annual increase in volume within the Humber estuary peaks at a value of around $4.7 \times 10^6 \text{ m}^3$ 7400 years ago; a value which is approximately 54 times the equivalent value for Southampton Water. In order to more easily compare the trends of volumetric change the data has been normalised to produce the plot shown in Figure 8. This plot clearly shows contrasts and similarities between the trends within the three estuaries. The Humber estuary (Figures 5 and 8) shows an initial increase in rate of volume change from 8400 to 7400 BP. The rate of increase declines steeply to about 3000 BP before increasing slightly again from 1600 –800 BP. The rate declines again from 600 BP to present. A similar pattern is seen in the curves for Southampton Water (Figures 6 and 8) although the period of lowest rate of increase occurs earlier in the curve (4500-3000BP) and the smaller peak between 1200 and 600BP more clearly marked than in the Humber. By contrast the curve for the Mersey Estuary shows no secondary peak and a simple monotonic decrease in rate from 8000BP to the present time.

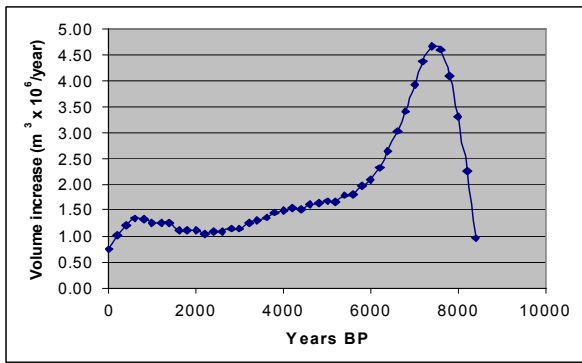


Figure 5 Rate of increase in accommodation space in the Humber Estuary

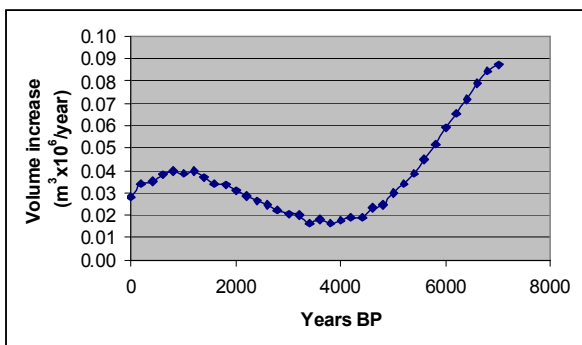


Figure 6 Rate of increase in accommodation space in Southampton Water

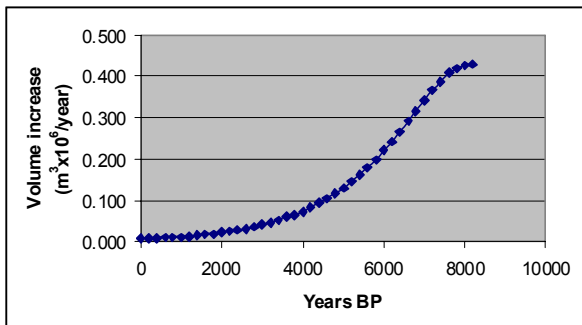


Figure 7 Rate of increase in accommodation space in the Mersey Estuary

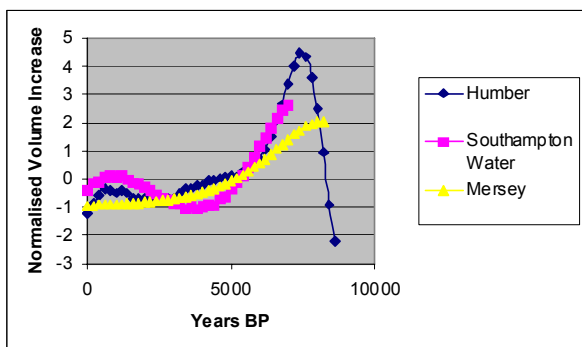


Figure 8 Normalised rate of increase in accommodation space in the three studied estuaries

The plots can be considered as the result of the interaction of two curves. One curve representing the cross-sectional form of the estuary valley and a second curve representing the rate of sea level rise. The monotonic form of each of the sea level curves is similar although the rates of increase are different (Figure 1). Each starts with an initially high rate of change which progressively diminishes as sea level approaches its present day level. The curve for Southampton Water shows a slight increase in the rate of sea level rise from about 3000BP onwards which might be partially responsible for the accentuation of the secondary peak mentioned above.

4. DISCUSSION OF FUTURE TRENDS

The plots described above have assumed a natural estuary system with a floodplain unconstrained by man made flood defences. The model predicts the increase in floodplain accommodation space resulting from long-term rates of sea level rise. With rates of sea level rise predicted to increase dramatically in the next 100 years and with the natural floodplain almost completely reclaimed in the three studied estuaries the model can be used to examine the differences between the natural trends within the estuary system and the likely trend within the modified estuary. For this part of the study it has been assumed that existing defences will be maintained. It is thus a relatively simple matter to calculate the increase in accommodation space which will result from a 50cm sea level rise with the water restrained by the existing flood defences. In the three studied estuaries the high water mark is already largely coincident with the line of defences so to a first approximation the accommodation space increase can be determined by multiplying the area defined by the high water mark by the vertical rise in water level. In order to produce Table 1 this estimate has been refined by determining the area which lies outside of the defences for each estuary. The values in Table 1 show that the modern flood defences reduce the increase in accommodation space very significantly; up to 79% in the case of the Humber Estuary. The implication is that a very much smaller sediment supply is required in order to fill this additional space than if the defences were not there. Where sediment supply exceeds available accommodation space, sediment bypassing may occur which may affect the morphology and overall sediment balance within the estuary. Managed setback of small

areas of floodplain will have the effect of returning accommodation space to the estuary system and would be expected to have further,

albeit probably very small, effect on the sedimentary evolution of the estuary.

Table 1 Future increase in accommodation space in the studied estuaries assuming a 0.5m rise in sea level

	Humber Estuary	Southampton Water	Mersey Estuary
increase in accommodation space assuming no defences (10^6m^3)	673	50	75
increase in accommodation space assuming existing defences (10^6m^3)	143	17	43
'lost' accommodation space (10^6m^3)	530 (79%)	33 (66%)	32 (43%)

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AN INVESTIGATION OF THE GROSS PROPERTIES OF UK ESTUARIES

Ian Townend, Adrian Wright and Darren Price

email: IHT@research.abports.ac.uk

ABP Research & Consultancy Ltd, Pathfinder House, Maritime Way, Southampton SO14 3E, UK

1. INTRODUCTION

Estuaries world-wide appear to exhibit some consistent relationships between several of the properties that reflect their size and shape. The best known of these is the prism-area relationship, often referred to as the O'Brien relationship. Such a relationship was first proposed by LeConte in 1905 and subsequently expanded on by O'Brien in 1931. Since then there has been numerous papers providing additional data and seeking to increase the explanatory power of the relationship, eg by including littoral drift effects, river inputs, etc (O'Brien, 1969; Jarrett, 1976; Hume & Herdendorf, 1993; Byrne et al. 1980; Mayor-Mora, 1977; Bruun & Gerritsen, 1960; Eysink, 1991; Gerritsen et al. 1990; Gao & Collins, 1994). More recently, Kraus has sought to provide a process-based model to explain the coefficients in the empirical relationship (Kraus, 1998). In the UK, some work has been done on East coast estuaries (Pethick, 1994) but there has been no systematic national analysis undertaken.

Alternative relationships have also been explored. Renger and Partenscky (1974) examined the relationship of basin plan area (ie the area at high water) with both volume and plan area at low water. Dronkers has suggested that the condition of tidal symmetry is reflected in the balance between hydraulic depth and surface areas at high and low water, hence providing a measure of flood/ebb dominance (Dronkers, 1998). Friedrichs and Aubrey (1988) adopted an approach based on a number of numerical model simulations. They examined the relative importance of tidal amplitude as a proportion of hydraulic depth and storage volume as a proportion of the channel volume in explaining tidal asymmetry and hence flood/ebb dominance within estuaries.

This study used the data compiled for the EMPHASYS database to carry out an initial exploration of these types of empirical relationship for UK estuaries. To allow the data

to be classified, information was also taken from the NCC estuaries database (Davidson et al. 1991). Most effort was directed towards the prism-area relationship but plan area and volume were also examined, as were certain derived parameters such as hydraulic depth.

2. DATA PREPARATION

The main source of data used in the analysis was the digital bathymetry and estuary coastline provided by C-Map and included in the EMPHASYS database. The original source of these data was Admiralty charts and so the data were to chart datum and in latitude and longitude. Projection facilities within the GIS were used to convert the data to the National Grid projection and an automated routine was developed to adjust the data from chart datum to Ordnance Datum (Newlyn).

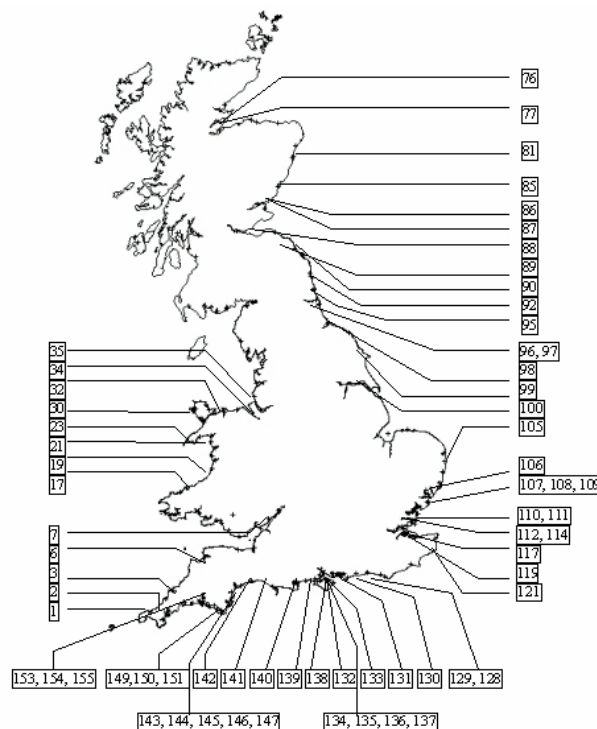


Figure 1 Estuaries used in this study

For the calculation of cross-sectional areas, volumes and plan areas, a water surface was constructed based on a prescribed water level at the mouth. The bathymetry was then interpolated using the ‘minimum curvature’ procedure and standard routines were used to compute the areas and volumes. Values were computed at low water, mean tide level and high water. A full listing of the results is provided in Townend, Wright and Price, 2000.

From the EMPHASYS data set, information is available for a total of 79 estuaries. However, only 75 have information at high water and only 66 have estimates of the prism and cross-section area parameters at mean tide level.

2.2 Quality Assessment

There are a number of difficulties in compiling a consistent data set. These relate to the extent of data coverage, the choice of seaward and landward limits and alignment of the ‘mouth’ cross-section relative to the channel. An examination of the C-Map data also highlights the fact that as a chart based source it provides reasonable data coverage below LAT but very little information over the intertidal areas. The data coverage gets relatively worst the smaller the estuary and in a few cases there is only data to define the line of the main channel and a high

water boundary. To provide a brief assessment of the likely error arising from the approach adopted, the data for a small sub-set of estuaries were compared with estimates compiled from more detailed studies undertaken at ABP Research. In all data were available for nine estuaries, including the Humber, Alde/Ore, Stour, Orwell, Blackwater, Thames, Chichester, Southampton Water and Medina. The resultant average differences for a selection of bulk parameters is summarised in Table 1

Table 1 Percentage differences in estimates based on a sample of 8 estuaries

Cross-sectional area		Surface area		Volume		Prism
High water	MT L ⁴	High water	Low water	High water	Low water	
153	95	113	34	27	28	28

In general the C-Map data gives rise to higher estimates. For values to low water the differences are generally quite modest (less than 30%) and might reasonably be put down to different boundary definitions, etc. However the high tide and mean tide level values show much greater differences, highlighting the fact that the C-Map data has little information on the intertidal and consequently the resolution of volume and area is poor.

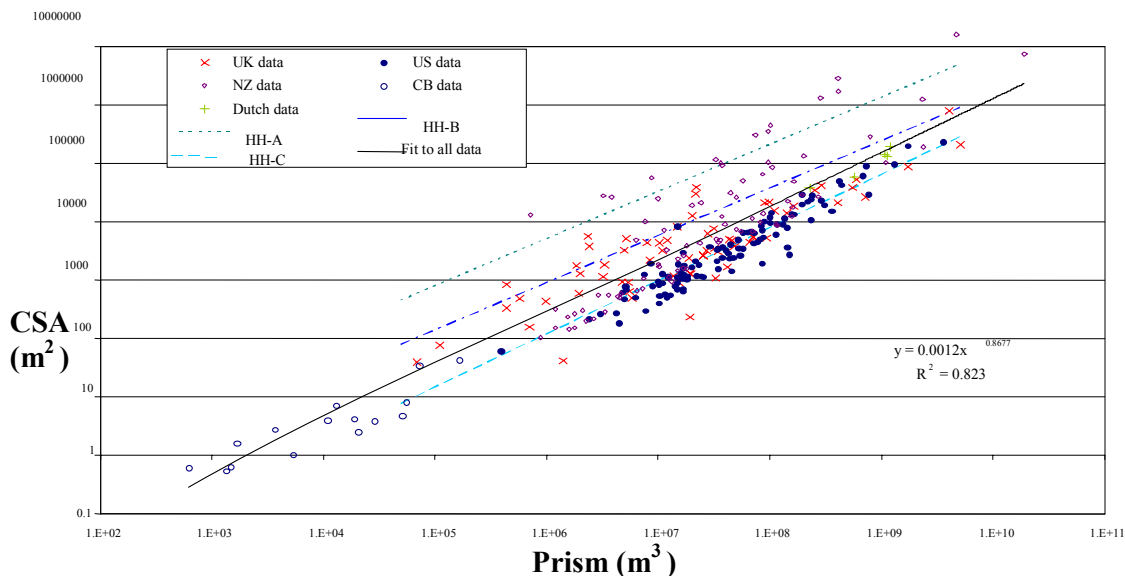


Figure 2 United Kingdom data plotted against American, New Zealand and Dutch data estuaries. (CB - Chesapeake Bay)

⁴ Mean tide level

This highlights the need for much better estuary bathymetry before top-down models can be reliably developed. The analyses that follow must be regarded as a first evaluation, providing an indication of probable trends. Numerical values associated with regression fits to the data should however be treated with **great caution** at this stage.

3. PRISM-AREA RELATIONSHIP

The empirical relationship proposed by O'Brien (1931) between the spring tidal prism (amount of water entering and leaving the system on a tide) and the cross-sectional area of the entrance at mean tide level has the general form:

$$A = C \cdot P^n$$

where A is the cross-section area (m²) and P is the tidal prism (m³) and C and n are empirical coefficients. For the data examined by O'Brien he obtained $A = 0.041 \cdot P^{0.85}$. In his 1969 he modified this to $A = 0.0656P$, when inlets with jetties or controlling groynes/breakwaters were excluded from the data set.

3.1 Other data sets

The most extensive data set is for the US (Jarrett, 1976) and covers inlets on the Atlantic, Gulf and Pacific coasts with no, one or two jetties controlling the inlet. As presented, Figure 2, the data have been converted to metric units and where there was more than one estimate for an estuary, an average value has been used. The fit

to all the data proposed by Jarrett was $A = 5.74 \times 10^{-5} P^{0.95}$. However by setting the exponent, n=1, a similar regression coefficient is obtained ($r^2=0.91$) with a fit based on $A = 7.01 \times 10^{-5} P$. The US data set can be usefully extended by including the data of Byrne et al (1980), which, is for small tidal inlets within Chesapeake Bay on the east coast of the US, as this extends the range of scales covered.

Another extensive data set has been published for New Zealand (Hume & Herdendorf, 1993). This makes use of their earlier work on estuary classification to relate variations in prism-area to estuary type - summarised (Hume & Herdendorf, 1988). Data for Dutch estuaries presented by Gerritsen et al (1990) has fewer samples but is included on for comparison.

3.2 UK data set

When the UK data is plotted alongside the US, NZ and Dutch data, Figure 2, the most obvious difference is the high degree of scatter and the extensive range of scales covered. The latter is a welcome attribute and reflects the diverse range of estuary systems to be found on the UK coast. The scatter may also reflect diversity, as found for the NZ estuaries, or it may be a consequence of the data quality. To explore this further the data were classified in terms of geographical location, isostatic land movement, tidal range, estuary type (as defined by Davidson et al, 1991), and estuary length.

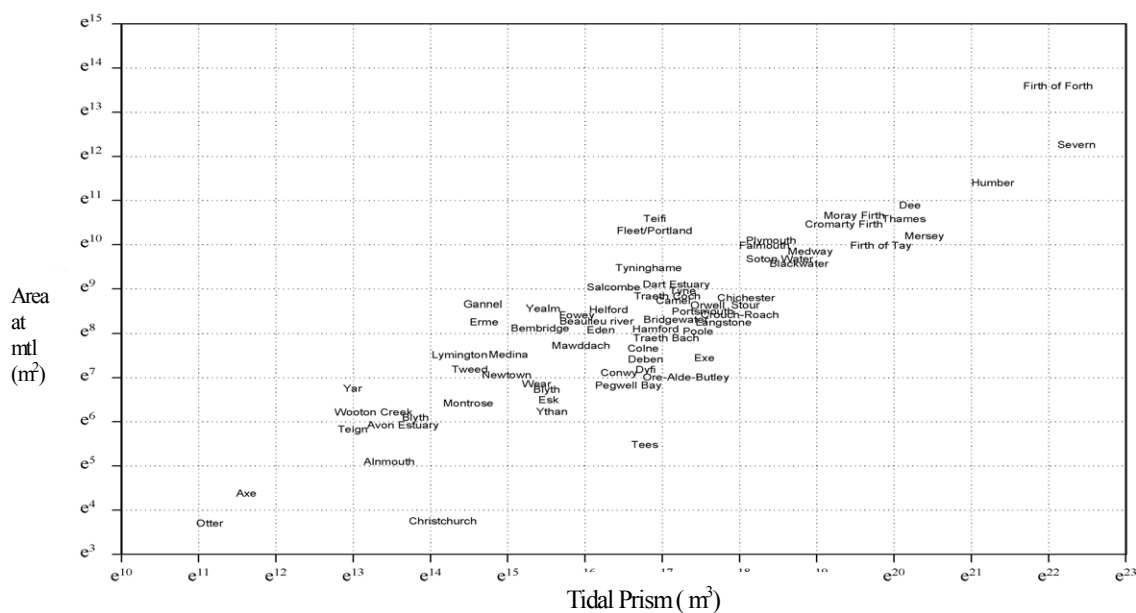


Figure 3 UK prism-area data, identifying location

To aid in the identification of outliers, a plot of prism-area was prepared with each point tagged with the estuary name, Figure 3. The regression line for the data set as a whole is:

All data $A = 0.024P^{0.71}$, $r^2=0.75$

3.2.1 Geographical location

The data, when examined under this classification suggested a weak sub-division into two groups; SW+SE and W+E+Sc. The former group also predominantly varies as a function of estuary length, whereas the rest show no particular trend. The regression lines for these two groups are:

SW+SE $A = 0.051P^{0.68}$, $r^2=0.75$
 W+E+Sc $A = 0.003P^{0.82}$, $r^2=0.78$

3.2.2 Isostatic land movement

The data were grouped into three classes of upward, downward and minimal land movement, based on the trends provided by the UK map presented by Shennan (1989). The resulting classes were evenly distributed around the best-fit line and showed no particular trend.

3.2.2 Tidal range

Plotting in classes of supra (>9m), macro (4-9m), meso (3-4m) and micro (<3m) also revealed no particular trend. Plotting tidal range against prism similarly revealed a high degree of scatter and suggested that tidal prism is largely independent of tidal range.

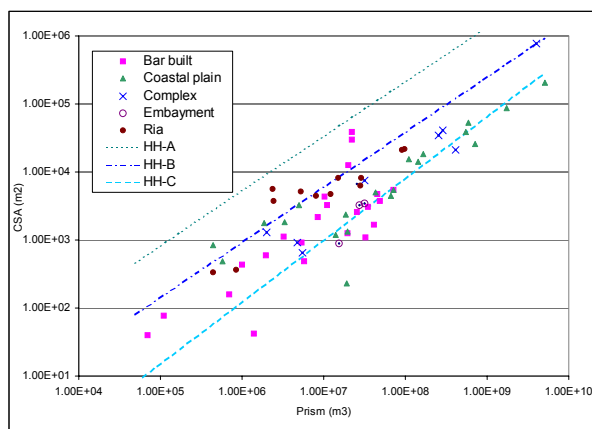


Figure 4 UK prism-area data classified by estuary type

3.2.3 Estuary type

The classification of estuary type developed by Davidson et al (1991) was used. This is not as comprehensive as that of Hume and Herdendorf

(1998) but mapping from one to the other is reasonably straightforward. In particular, taking the three groups identified by Hume and Herdendorf, (namely A - open embayments, B-elongated embayments, C-inlets/estuaries/ rivers, TYPE2 - lying in between B and C representing headland enclosed estuaries), it is possible to make out some similar trends in the UK data. See Figure 4.

Coastal plain and complex estuaries appear to divide into two groups. One group along with the Rias roughly follows the group B line. The second group of coastal plain and complex estuaries along with embayments follow group C and the US inlet trend lines. The bar built estuaries predominantly lie between the trend lines B & C. The UK data are thus broadly consistent with the characterisation identified by Hume and Herdendorf, with the exception of embayments being close to group C. There are no data for fjords or fjards in the EMPHASYS data set but such data would be useful as a further test of the classification; the expectation is that they should fall close to group A.

Exploring this apparent division by estuary type, four groups were defined and three of these were plotted, see Figure 5.

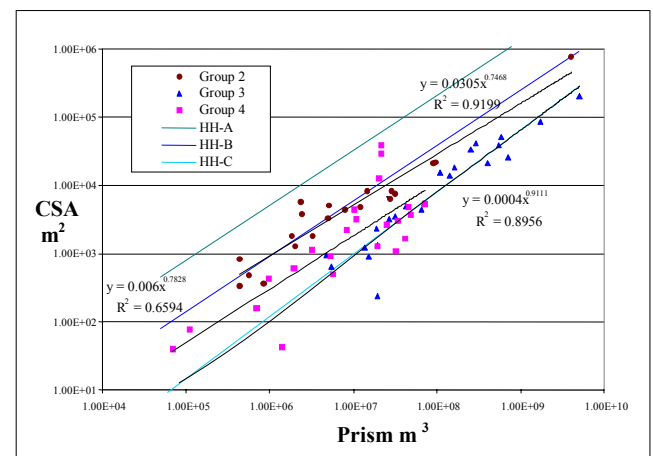


Figure 5 UK prism-area data with refined classification by estuary type

Group 1 comprised fjords and fjards for which no data were available in this study.

Group 2 comprised Rias, coastal plain estuaries of the Solent and selected complex estuaries; 21 in total.

Group 3 comprised all other coastal plain and complex estuaries; 20 in total.

Group 4 comprised the bar built estuaries; 23 in total.

Groups 2 and 3 compare favourably with groups B and C of Hume and Herdendorf, in both position and slope. The respective scale and shape parameters are summarised in Table 1.

Table 1 – Fit parameters for UK and NZ data sets

	UK data set		NZ data set	
	C	n	C	n
Group2/ Group B	0.0305	0.747	0.0123	0.811
Group3/ Group C	0.0004	0.911	0.0004	0.913
Group4/ Type 2	0.0060	0.783	0.00007	1.054

Group 2 of the UK data appears to conform to the type of system that have only limited sedimentary influence at the mouth and it is suggested are in an early stage of Holocene development. Similarly group 3 are taken to be coastal plain and complex estuaries that are similar to the river mouth class found in New Zealand, where the Holocene sediments are already dominating the form of the estuary.

The complex estuaries that fall into group 2 are either, deep and wide near the mouth, such as the Firth of Forth, or long narrow channels with little of no intertidal as in the case of the Tweed and the Tyne. Coastal plain estuaries included in this group are those in the Solent with the exception of Southampton Water. Key attributes of these estuaries are the sheltered nature of their location, the fact that they all have relatively high aspect ratios with wide mouths as a proportion of their length and they have relatively low fresh water inputs. Such attributes are perhaps akin to the funnel shaped estuaries defined by Hume and Herdendorf, which were seen to fall in group B, although some samples lay between groups B and C. This requires further investigation.

The more difficult group to explain is the bar built estuaries. They lie between groups 2 and 3 and might therefore be evolving towards Holocene sediment dominance. From a descriptive assessment, one would however expect them to be closer to group 3 as they are barrier enclosed rather than headland enclosed systems. In a similar vein US inlets with two jetties could be construed as Type 2 but clearly lie along the Group C line. This is presumably because they are essentially inlets formed in

Holocene sediments which were in regime when the jetties were constructed and changes in conditions to-date have not yet had any effect.

To develop this analysis further, a re-appraisal of the existing UK geomorphological classification is required. The work in New Zealand used the prism-area distribution to help resolve some of the overlaps when classifying estuaries (Hume & Herdendorf, 1993) and it would now be appropriate to undertake a similar study for UK estuaries.

3.3 Process based analysis

For a sinusoidal wave propagating in a channel, the amount of water passing a given section in half the tidal period equates to the tidal prism. Using simple wave theory, the prism can therefore be obtained by integrating the discharge over half a tidal cycle. For a rectangular section, the section discharge at any instant is then given by $D = u(A + \eta W)$, where u is the velocity, A is the area at mean tide level, η is the surface elevation and W is the width of the channel. Initially cases for a simple progressive and standing wave were investigated and found to markedly under-predict the area. To introduce friction the approach adopted by Pillsbury (1956) was used, representing the phase difference between elevation and velocity by angle ϕ . This results in a relationship of the form:

$$A = \frac{4\pi}{\lambda} \frac{h}{\eta_o} \left(\frac{1}{4 \cos \phi - \frac{\eta_o \pi}{h} \sin \phi} \right) P$$

Where η_o is the maximum tidal elevation at the mouth, h is the hydraulic depth at the mouth and λ is the tidal wave length. The value of ϕ was estimated based as a function of friction, tidal amplitude and the hydraulic depth as derived by Pillsbury. However it should be noted that with the data available this had to make use of the average hydraulic depth of the estuary as a whole, rather than the value at the mouth. This continues to under-predict the area, the discrepancy being greatest for the smaller estuaries. This is likely to be because the value of ϕ is overstated, based on the estimate of hydraulic depth used, and possibly also indicates the need to take account of estuary shape in this estimate.

In a similar vein Kraus (1998) has suggested a process-based derivation of the prism-area relationship. He reasons that at equilibrium the rate of change of volume and hence area in the inlet must tend to zero. Using an estimate of the sediment transport rate of the form proposed by Watanabe et al (1991), he derives an equation of the form:

$$A = \left(\frac{\alpha \pi^3 C_k^3 m^2 W_e^{4/3}}{Q_g T^3} \right)^{0.3} P^{0.9}$$

Where α and C_k are empirical coefficients close to unity, m is Mannings coefficient, W_e is the width corresponding to the equilibrium area, Q_g is the gross alongshore transport and T is the tidal period. This derivation depends crucially on the use of a bottom friction coefficient of the form $c_f = gm^2/h^{1/3}$ and the elimination of the depth, h from the resulting equation. Indeed, if one instead eliminates W then the resulting expression has $A \propto P^{3/2}$. Using the expression as derived by Kraus provides quite a good representation ($r^2=0.87$) but the fit still has a residual regression line of $y=8x^{0.72}$ (the scale and shape coefficients should approach unity for the equation to be a good predictor). If instead we use the friction proposed by Perroud (1959), the friction term has the form:

$$c_f = \frac{8}{3\pi} \frac{g}{C^2 R}$$

and we take the Chezy coefficient $C=R^{1/6}/m$, then the resulting expression is:

$$A = \left(\frac{\alpha \pi^3 C_k^3 m^2 W_e^{7/3}}{Q_g T^3} \right)^{0.23} P^{0.69}$$

This expression has a smaller residual, $y=5.9x^{0.82}$ and provides a slightly better fit ($r^2=0.89$). Further experiments using the hydraulic radius, R rather than the hydraulic depth, h , gave similar results, suggesting that the prism-area relationship as derived, depends on how the friction is expressed and this in turn needs to reflect the cross-sectional shape of the estuary.

A number of other parametric relationships have been examined, these are presented in Townend, Wright and Price 2000.

4. ASYMMETRY RELATIONSHIPS

Using the hypothesis that morphological equilibrium equates to a uniform tide, Dronkers (1998) derived an asymmetry ratio based on certain estuary form parameters:

$$\gamma = \left(\frac{h+a}{h-a} \right)^2 \cdot \frac{S_{hw}}{S_{lw}}$$

where h is the mean hydraulic depth of the estuary given approximately by $h=a+V_{lw}/S_{lw}$ (Roberts et al (1998) found that it was better to use $h_{hw}=V_{hw}/S_{lw}$ and $h_{lw}=V_{lw}/S_{lw}$), a is the tidal amplitude, S_{lw} is the surface area at low water, S_{hw} is the surface area at high water and V_{hw} and V_{lw} are the volumes at high and low water. A value of one suggests a uniform tide, with values greater indicating flood dominance and less ebb dominance. The line of tidal symmetry, along with the UK data is plotted on Figure 6.

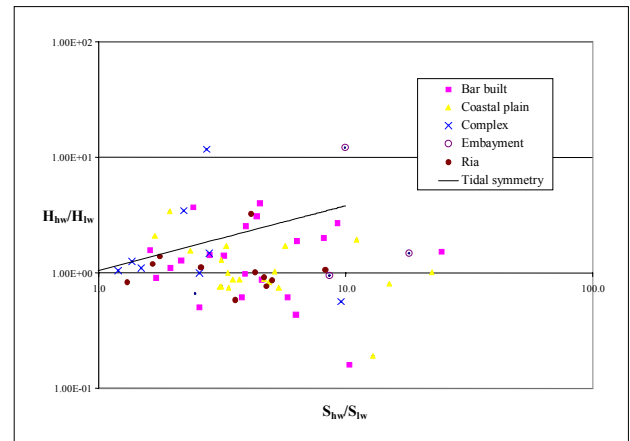
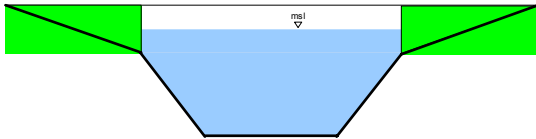


Figure 6 Dronkers ratios for tidal symmetry

Most noticeable is the scatter in the data. For the Dutch estuaries presented in Dronkers' paper the range of the x-axis (S_{hw}/S_{lw}) is 1 to 5 and the y-axis (h_{hw}/h_{lw}) is 1 to 3. In contrast the UK data require axes of 1 to 400 and 0.1 to 12. Some of this scatter may be a consequence of the data quality and the sensitivity of this relationship to estimates of volume and plan area at high. Taken at face value, the data appear to indicate that a large number of UK estuaries are ebb dominant. The large range of scales encompassed by the data also indicates the diversity of UK estuaries. There is also some indication of a division into two sub-sets; one group which shows very little change in the depth ratio as the plan area ratio increases and the another which exhibits a more marked decrease in the depth ratio with increasing plan area ratio.

Another approach to asymmetry has been proposed by Friedrichs and Aubrey (1988). Based on a series of simulations using a prismatic cross-section, they explore the influence of storage volume to channel volume, V_s/V_c , and the M_2 tidal amplitude and the hydraulic depth, a/h . They relate variations in these two ratios to the amount of tidal distortion as identified from the ratio of M_4/M_2 amplitudes and the relative phase as given by $2M_2-M_4$ phases. In developing these ratios it is important to take care with the definition of the variables used. V_s is the storage volume over the intertidal (green shaded area in sketch below). V_c is the volume of the channel at mean tide level (blue shaded area in the sketch below), a is the “offshore” M_2 amplitude and h is the average depth of the channel at mean sea level.



Typically values of M_4/M_2 less than 0.01 suggests little tidal distortion or overtide. For the relative phase, values in the range $0 < 2M_2 - M_4 < 180$ indicate flood dominance and when between $180 < 2M_2 - M_4 < 360$ indicate ebb dominance. The results showed that the range and scatter of the data extended beyond the range considered as a basis for studying US estuaries. The surface amplitude ratio, when plotted suggested that there is significant asymmetry in the majority of UK estuaries. In addition, the phase is such that these are flood dominant, largely because of the very large values of a/h exhibited by so many UK estuaries (amplitude to depth ratios are typically in the range 0.3 to 3). This is quite contrary to the interpretation provided by Dronkers γ . This is an area which would merit further investigation focusing on the particular attributes of UK estuaries. The work of Prandle (2000), which develops solutions specific to the length and depth attributes of UK estuaries, may be able to explain some of the anomalies noted here.

5. CONCLUSIONS

5.1 Findings of the study

Whilst the gross parameter to low water, derived from the data sources used for this study, provide estimates consistent with those derived from more detailed studies, the high water parameters appear to be much less reliable. This is largely

because of the poor, or in some cases, non-existent definition of the intertidal, so that the estimates are heavily dependent on the definition high and low water marks.

Despite the uncertainties in the data, the analysis reveals a remarkable robustness in parameters examined. Although there remains considerable scatter the data do exhibit the trends expected and would appear to be consistent with similar analyses undertaken in the States, New Zealand, Netherlands and Germany. The main findings were:

- (1) The prism-area relationship appears to divide into sub-sets that are consistent with geomorphological type. There is then a transition group between those that are relatively immature in terms of their Holocene evolution and those that are relatively mature.
- (2) The prism-area relationship shows a dependence on estuary length and this can be accounted for by modifying the simple O'Brien relationship to include the length as a ratio of the tidal wave length (this is equivalent to L/\sqrt{h}).
- (3) The process-based relationship proposed by Kraus was found to have reasonable predictive power but was noted to be crucially dependent on the form of friction coefficient used in the derivation. Some experiments with other formulations provided some improvement and it was concluded that there would be merit in examining further how best to represent the hydraulic radius to take proper account of the section shape, particularly for the smaller estuaries.
- (4) The relationship to basin plan area exhibit a slightly different slope to those presented by Renger and Partensky for German basins. This may again be a consequence of poor estimates of high water parameters so some caution is required in the application of the relationships derived.
- (5) Whilst a similar caution is required when using the other relationships derived, it was noted that the relationships which use tidal prism rather than basin area, appear to exhibit less scatter.
- (6) The asymmetry analyses using the methods of Dronkers and Friedrichs & Aubrey both reveal a large amount of scatter and a range far greater than those examined by the

original authors. This might again be a weakness of the data set but may equally reveal the diversity of the suite of UK estuaries examined. Given also the conflicting results from the two methods, this is an area that would merit a more detailed investigation.

5.2 Recommendations for further research

From the above it is clear that the priority has to be the establishment of a UK data set that brings together as many terrain and bathymetry data sets as possible to improve the resolution of the digital ground models. The scope to use remote sensing sources such as the LIDAR data sets currently being compiled by the Environment Agency should be investigated further. Ultimately it may be necessary to commission some surveys, particularly of the intertidal of some of the smaller estuaries.

Whilst the geomorphological classification proposed by Davidson et al (1991), reveals some of the variability noted in this study there are some deficiencies. When undertaking the same process in New Zealand, Hume & Herdendorf made use of the prism-area relationship, along with a range of other data, to help delineate within their classification system. From the results obtained in this study it would appear that there would be considerable merit in repeating the classification along similar lines.

Process-based derivations of the prism-area relationship and the various asymmetry relationships examined, lead to the conclusion that greater account needs to be taken of the estuary shape and influence of friction. This would appear to be particularly important in the relatively small and shallow estuaries that are to be found around the UK. The work of Prandle & Rahman (1980) and Prandle (2000) point to a possible way forward and this should be explored further.

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PREDICTING THE SHAPE AND FUTURE EVOLUTION OF ESTUARIES

John Pethick and Jeremy Lowe

email: John.Pethick@ncl.ac.uk

Department of Marine Sciences, University of Newcastle, NE1 7RU, UK

1. INTRODUCTION

A geomorphological model should be capable of achieving two broad objectives:

- predict changes in morphology at a spatial scale which encompasses the entire estuarine system;
- predict morphological changes over a period measured in decades to centuries.

Geomorphological, or top-down, models attempt to predict the equilibrium state of a geomorphological system; such an equilibrium is seen as a dynamic state in which constant adjustments take place to the overall morphology of the system so that the landform is able to function efficiently. Definition of functional efficiency is therefore central to any attempt at top-down modelling. Many definitions of estuary function can be proposed. In this work we have adopted a simplistic view that the estuary system will tend towards minimum work per unit bed area: that is will reduce the stresses applied by tidal flows and waves by increasing bed area until such stresses lie below some threshold level.

Prediction of an equilibrium form for any landform, and particularly for a large scale system such as an estuary, assumes that the long term steady state is superimposed upon short to medium variable state - that is such predictions are of a dynamic equilibrium. Changes may be due to the differing time scales for the sub-units of the system (e.g. mudflats may adjust to spring neap tidal events while channel-reaches in which the mudflats are located adjust to freshwater storm discharges). Even more difficult to predict are internal adjustments in which the system goal-seeks but cannot goal-maintain, so that periodic oscillations around a theoretical equilibrium morphology are exhibited. Finally, system adjustments may be due to long term trends in independent variables such as sea level, storminess or sediment supply resulting in continuous adjustment of all sub-components as well as in the overall form. This means that

geomorphic models may be expected to predict the long-term average condition but will not be able to determine short-term variation or small-scale differences.

Two models have been developed. They are:

- Regime model;
- Sea level response.

The basic principles and results of each of these models are described in the following sections.

Top-down approach

The overall intention of a top-down approach is morphological goal seeking: what is the likely equilibrium form that the estuary will evolve. This is complemented by bottom-up models, which provide rates at which these morphological goals are obtained. This only works if the temporal development is sequential (i.e. estuary may merely 'thresh-around' randomly until it reaches a goal, not work steadily towards it).

The ideal equilibrium morphology for an estuary is one in which inputs of sediment and water are exactly balanced, over some characteristic time, by exports. A balance of sediment leads to consideration of energy balances in which all kinetic energy inputs are exported while potential forms are converted to lower forms such as noise and heat. This complex balance is achieved by the evolution of a number of nested morphological forms, including sub-tidal channels, inter-tidal flats, salt marsh and mudflat creek systems, and estuarine meanders. The total system response to such an energy balance has been referred to in previous work as regime theory.

Over a short period, in geological terms, of a decade or so, an estuary might be seen to alter significantly – with the position of ebb and flood channels changing and erosion or deposition of material on sand and mud banks. These changes may be due to episodic or continuous processes. However, over a longer period the estuary may often be considered stable, with neither a gain nor a loss of material from

within the estuary. In this case, the estuary can be considered to be in regime.

2. THE REGIME MODEL

Function and approach

A number of regime relationships have been proposed. These can relate the estuary cross section to peak discharge, or can consider the manner in which the estuary acts to reduce the energy of the tidal wave. Using a regime relationship it is possible for long-term predictions to be made about the development of an estuary without considering the iterative changes associated with individual events responsible for the changes. The choice of regime relationship must be based around a sound understanding of the hydrodynamic and sedimentary processes occurring in the estuary which is being studied.

There are two basic assumptions that underlie regime theory:

- the estuary will achieve some form of dynamic equilibrium;
- there is a characteristic function that describes the equilibrium relation.

Simple power law relations have proved effective. These relate tidal discharge or tidal prism, Ω , to mouth area, A_m :

$$A_m = k\Omega^n$$

The evaluation of k and n in these studies describes the estuary in broad terms but is difficult to apply to particular estuaries. This is due to the nature of the assumptions made about the form of the regime function and requires calibration data.

Estuaries used for verification were Tamar, Medway, Duddon, Dee, Exe, Blackwater, Kent, Dovey, Crouch/Roach, Orwell/Stour, North Norfolk, Ribble, Taw/Torridge, Thames, Humber, Mersey, Parret, Newtown, Yarmouth, Medina, Beaulieu, Kings Quay, Hamble, Chichester, Langstone, Portsmouth Harbour, Southampton Water, Lymington, Bembridge Harbour, Wooten Creek

Close examination of the general relationship between tidal prism and mouth area does indicate that a number of regional groups can be

identified (Figure 1) in which the general form of the relationship is modified only by the intercept.

Several sets of estuaries (East coast UK; South coast UK, North Norfolk, Solent;) have been identified. Each set appears to produce a different intercept to the regression which has been interpreted as an indication of the characteristic grain size for the environment (sandier environments giving higher intercepts) although this is merely a preliminary hypothesis. Regression slopes are however reasonably constant over wide range of environments. Thus for each of these estuarine groups, the overall cross sectional area of the estuary mouth may differ from other groups but the rate of change of this area as tidal prism changes is similar for all groups. This difference appears as a scaling factor in which differences in sediment type and the wave energy on the coast of these regions combine to produce regional differences in estuarine mouth size.

The initial best-fit regression to the complete data set showed a major disparity between the slope of the Solent estuaries regression and those to the three other data sets. The sub-sample appeared however to consist of two distinct estuarine types: the Isle of Wight/outer Solent group and Chichester/Langstone harbour. Individual regression lines fitted to these two groups showed that regression slopes were similar to other data sets. Chichester/Langstone appear to fall on a general south coast UK regression (the Gao and Collins data set). The outer Solent group (Newtown, Yarmouth, Medina; Hamble and Beaulieu) all fall on a line with a much higher intercept than that for other estuarine environments but with a similar slope. Within this group Yarmouth appears to have a reduced mouth area and this is probably due to constricting training walls at its entrance.

The reasons for the high intercept are not yet identified. The implication is that their mouth areas are wider than would be expected from other environments. Sediment type may be the reason (sandier? Less sediment transport across the mouth?) or some form of intervention (reclamation would reduce tidal prism to give over-wide mouths but this applies to other estuary groups too). The Chichester/Langstone estuaries fall well within the confidence limits for other south coast estuaries despite their separation (they were once part of a single system) and the reclamation which has taken place within their inter-tidal area)

The outer Solent/Isle of Wight group of estuaries is identified as having a coherent morphological relationship to their tidal prisms. The Chichester/Langstone group is clearly identified as belonging to a distinct group.

Area versus width issue

The generic relationship provides the constants for the basic tidal prism/channel cross section relationship (Figure 2). Using these constants it is possible to predict what the channel cross sectional area is for any given tidal prism along its length.

Assuming a width depth ratio for the estuary channel it is possible to transform this non-spatial relationship into a spatial one. The width depth ratio was based upon observation of estuaries within each regional group. Since it is possible to predict the change in area associated with the change in tidal prism between two arbitrarily located cross sections along the estuary, the length between these two profiles can be calculated. This provides a spatial scaling constant for the estuary. Next, since a constant width/depth ratio is assumed, it is possible to dissociate the area changes along this length into changes in width and depth so that a planimetric plot of the estuary form can be made.

This approach allows a theoretical planimetric form to be calculated for a given estuary. Note that no attempt has been made to simulate sinuous channel forms; the existing plan form is used. In the initial model, the predictive method adopted assumed a constant width-depth ratio. In most cases such an assumption is justified, but in some cases, particularly at mouth sections, width depth ratios may be relatively small. This is probably a response to long shore transport on the adjacent open coast shore moving across the estuary mouth. The estuary response must be to increase shear stress at the mouth in order to maintain its channel, in order to achieve this, the cross section area and the width depth ratio decreases resulting in a local increase in shear and therefore in sediment transport. Similar changes in the width/depth ratio will occur wherever grain size varies in the estuary or where sediment inputs, for example from fluvial sources, occur.

In order to provide a realistic prediction of such changes in the estuarine morphology, a shear stress component was introduced into the model.

This allows prediction of the depth needed to provide a critical erosion or deposition shear stress at any given location along the estuary. Since the cross sectional area can be predicted from the model, identification of the critical depth allows the width to be calculated.

3. THE ROLL-OVER MODEL

Function and approach

The development of the Severn estuary was described by Allen (1990) as a stratigraphic rollover. Allen noted that the entire estuary appeared to have transgressed landward as a response to Holocene sea level rise and that sediment was moved from the outer to the inner estuary as part of this process.

Pethick (1996) applied the concept to the Blackwater in Essex that receives significant sediment inputs from the North Sea. Pethick found the Blackwater had transgressed longitudinally but had also moved vertically upwards thus keeping its position in the tidal frame as sea level increased. The sediment budget showed that sediment from erosion of the outer estuary balanced that deposited in the inner estuary less an amount equivalent to the vertical movement that consequently must have derived from North Sea sources.

Work on the sediment budget of the Humber for the eSMP by Townend and Pethick suggests that sediment is being eroded from the outer estuary and that simultaneously deposition is occurring on the upper inter tidal areas. However, in contrast to the Blackwater, the Humber estuary sediment budget is in deficit so that, if sediment transfer from outer to inner estuary is taking place this is more than offset by net export from the estuary as a whole. Thus, although a general transgression appears to be occurring in the Humber in response to sea level rise, the system behaviour is quite distinct from that of the Severn or the Blackwater.

Sea level rise coupled with the effects of coastal squeeze is the most obvious externally induced change to which processes may have responded. Evidence from other east coast estuaries suggest that the natural estuarine response to sea level rise is for the estuary to 'roll-over'. The increase in water depth associated with sea level rise results in:

- an increase in wave energy at the landward limit of the inter-tidal zone, resulting in erosion of the upper mudflat and salt marsh edge;
- a decrease in the shear stress on the bed of the sub-tidal channels, resulting in a net accretion of

sediment here. Most of this sediment may have been eroded from the upper inter-tidal zone by wave action and swept down the inter-tidal slope by tidal currents;

- an increase in tidal energy entering the estuary due to the deeper water at the estuary mouth and in the nearshore zone. The result is recently deposited sediment is swept landwards to be deposited in the inner estuary;
- the overall morphology of the estuary undergoes a spatial translation in two directions: landwards and upwards to maintain its position in the energy frame;
- a nodal point somewhere along the estuary which divides the eroding outer estuary from the accreting inner estuary.

Prediction of the magnitude of the transgression that will occur as a result of sea level rise was performed using a modification of the regime model. Increases in tidal prism due to sea level rise are calculated using existing morphology. The increased tidal prism can then be used as input into the regime model described above. The resultant widening and deepening of each cross section in the estuary is, in effect, a form of transgression in which a more landward section adopts the existing morphology of a given section. Identification of these two sections and calculation of the distance between them forms the basic component of the predictive model.

The increase in tidal prism because of sea level changes forms the critical input to the model. Increases in the overall tidal frame within a trapezoidal cross section will result in increased tidal prism although this can be partly negated if vertical movements of high and low water both occur over the same inter tidal slope

Estuaries used for verification were the Humber, Blackwater and Crouch/Roach

Results

Both the inner Crouch and the Roach are relatively narrow and deep. The main pattern in these estuaries appears to be a response to sea level rise with the mouths (located on the north and east sides of Wallasea) widening as the estuaries transgress landward (Figure 3). The intertidal in these areas is limited and most of the erosion is occurring in the subtidal. This sediment appears to be transported up the estuary

and is deposited in the subtidal channels of the inner parts of the estuary.

The outer Crouch is not so constrained by sea walls and is relatively wide and shallow, while the tidal prism of the estuary has been much reduced by the reclamation that occurred in the inner Crouch and Roach. Analysis of the cross-sections shows that the estuary is narrowing seaward of Wallasea Island. This is probably a response to the past reduction in tidal prism and may, in the future, be increasingly compensated for by sea level rise. Deposition appears to occur mainly on the intertidal, perhaps being fed by suspended sediment from the Thames embayment.

In the long term, as sea level rises, both the inner and outer estuaries will tend to widen as the estuaries transgress landward (rollover model). For the inner Crouch and the Roach the effects may be more immediate with increased stress in the mouth areas along the banks of Wallasea Island. The lack of intertidal in the upper parts of the inner Crouch band Roach means that sediment deposited in these areas is tending to fill the subtidal channels rather than raise the intertidal flats (Figure 4)

Work by Pethick (1997) on the Blackwater estuary in Essex demonstrated that outer estuary erosion over the past decade was balanced by inner estuary deposition, as predicted by the rollover model. Applying the model to the Humber estuary the Geo II group showed that such a rollover response to a 6mm per year rise in sea level would be a landward transgression of 11m per year at the estuary mouth, decreasing to 7m at the head. This variation indicates that a change in overall estuarine morphology is superimposed on the landward transgression.

Results show that the migration distance decreases landwards, indicating that the landward transgression is accompanied by a change in planimetric shape, the estuary becoming more flared in outline as well as migrating landward. The mean migration rate of the estuaries as a whole was predicted to be about 1 m per 1 mm rise in sea level or 6 m per year assuming a 6 mm per year rise in sea level.

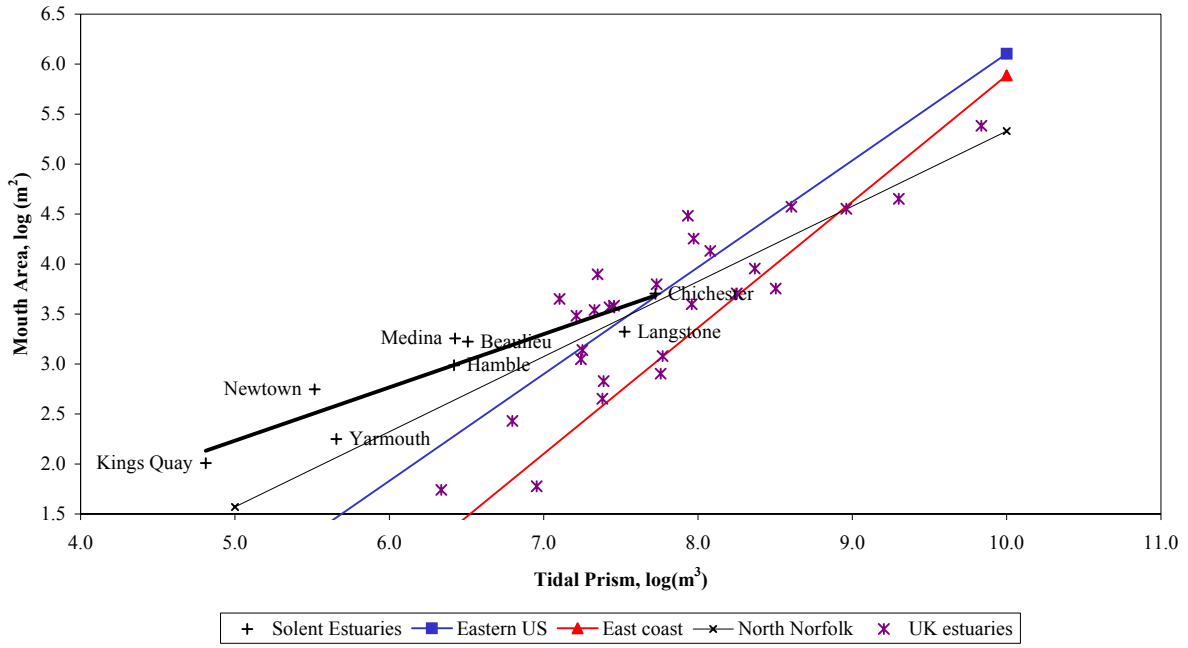


Figure 1 Regime relationships for UK regional groups and for the Solent estuaries

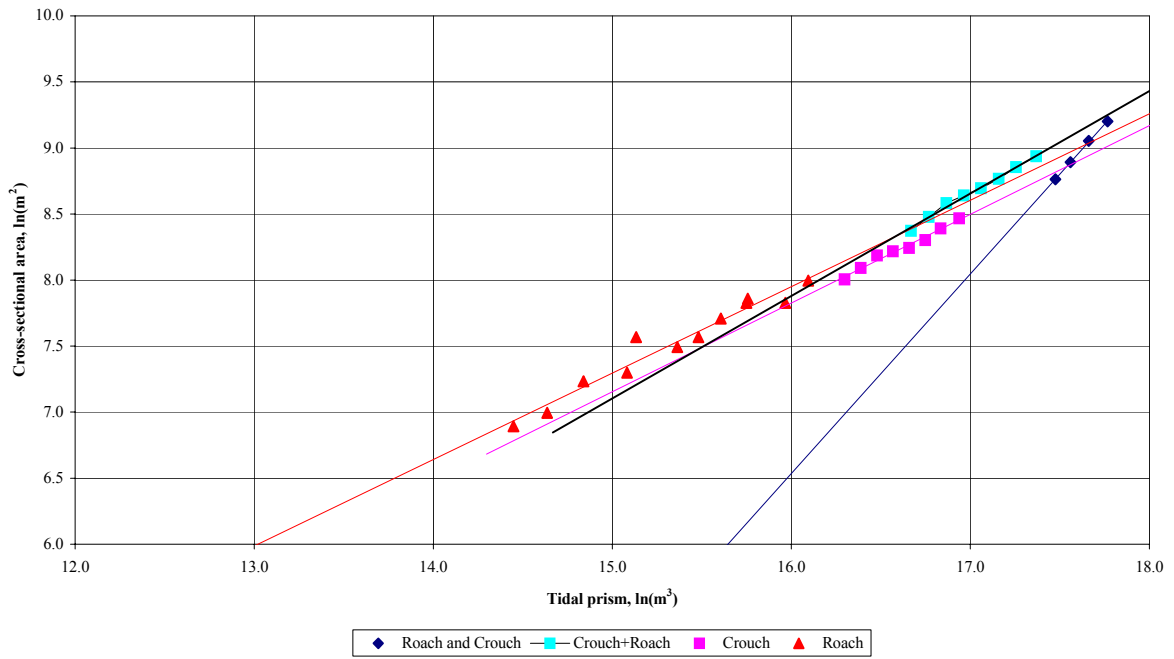


Figure 2 Regime relationships for the Crouch and Roach estuaries

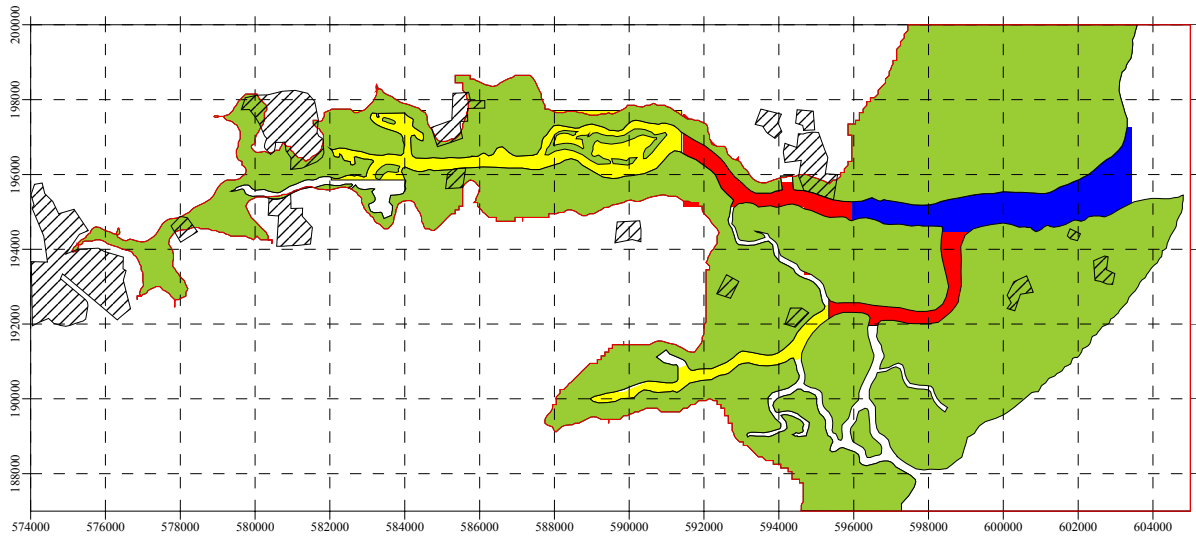


Figure 3 Change in cross-sectional area for the Crouch and Roach estuaries (blue – intertidal deposition, red – erosion, yellow – subtidal deposition)

HISTORICAL TREND ANALYSIS (HTA) AS A TOOL FOR LONG-TERM MORPHOLOGICAL PREDICTION IN ESTUARIES

Ken Pye and Daphne van der Wal

email: k.pye@gl.rhul.ac.uk

Department of Geology, Royal Holloway, University of London, Egham, Surrey,
TW20 0EX, UK

1. INTRODUCTION

The work undertaken at Royal Holloway, University of London, as part of the Estuaries Research Programme (ERP) has employed two related, integrated approaches which we refer to as Historical Trend Analysis (HTA) and Expert Geomorphological Assessment (EGA). This paper focuses on the benefits and limitations of HTA for describing and predicting morphological change in estuaries, based on evaluation undertaken in Phase I of the ERP.

The HTA method essentially involves the interrogation of time series data, obtained at regular or irregular intervals, to identify directional trends and rates of processes and morphological change, over varying time periods. The data may relate specifically to processes (e.g. tidal levels, wind or wave records) but more frequently relate to morphology. Maps, bathymetric charts, air photographs, satellite images, LIDAR, CASI, conventional beach profiles and echo sounder hydrographic data can all provide useful subject material. Data from more than one type of source can readily be combined using GIS, and quantitative comparisons made with relative ease and consistency.

2. METHODS

Investigation of medium to long term morphological changes in five of the six ERP estuaries (Ribble, Mersey, Southampton Water, Blackwater and Humber) involved sequential analysis of hydrographic surveys, supplemented by data from ground surveys, CASI and LIDAR. Admiralty and Port Authority charts were digitised, and the bathymetric data were converted to X, Y, Z values, within the National Grid, and reduced to Ordnance Datum (Newlyn).

In addition, data were obtained from the EMPHASYS data base. Data from Admiralty Charts of the Ribble Estuary were

complemented by data from other hydrographic surveys. Data were obtained on a 50 year interval from 1850 to 2000, and, where possible, information from smaller time-scales was superimposed. The data were interpolated to a grid, with 50 by 50 m cells (with the exception of the Humber data, which were interpolated to a grid with 200 by 200 m cells) to create maps, allowing direct comparison. The information was stored and analysed in a PC-based ArcInfo/ ArcView Geographical Information System (GIS), and additional analysis was performed using Surfer.

The bathymetric charts were first compared in a qualitative way to gain an overview of changes in, for example, the pattern of banks and channels. In addition, a number of parameters were derived from sequential charts to quantify coastal change, such as:

- sediment volumes (e.g., total sediment volume, relative to an arbitrary lower plane, and intertidal sediment volume) to obtain rates of accretion and erosion
- tidal prism
- areas (e.g. intertidal area, area between mean high water neap and mean high water, which is approximately the potential area for salt marsh growth in muddy environments)
- coastline positions (e.g., the position of mean low water spring and mean high water)
- slopes (e.g., foreshore gradient)
- the deepest point of a (subtidal) channel, thalweg.

An error assessment of the material and methods described above was made. Hydrographic data used for Admiralty Charts are primarily acquired for navigation purposes, and a number of problems arise when using hydrographic data to identify morphological change. Sources of error and uncertainty include the time of survey (recent Admiralty Charts are

usually based on several surveys of different date), surveying techniques, sampling strategy (especially the intertidal zone may not be densely surveyed), interpolation and simplification during compilation of the chart and chart projection. Probably the largest error stems from the non-uniformity or poorly defined levels to which the depths on the charts are reduced. However, the error assessment showed that the charts are suitable for studying patterns of morphological change in estuaries, such as shoal and channel migration. When comparing sediment volumes above or below fixed planes corresponding to particular tidal levels, it should be noted that these levels vary both in time and space, and that volumes of actual zones (e.g., the intertidal zone) may, therefore, differ. Nevertheless, this approach and assessment of the other parameters described above can provide valuable information about morphological change. However, our work has shown that quantitative sediment budget estimates from bathymetric charts or sequential sea bed surveys are very sensitive to errors in original data set production and subsequent manipulation. Therefore, such estimates should be treated with caution.

Testing of the HTA approach was undertaken by comparing two or three 19th or early 20th century surveys and using the observed changes and trends to make predictions about subsequent change. These predictions were validated through analysis of the most recent available survey.

Results from four estuaries (i.e., the Ribble, Mersey, Southampton Water and Humber Estuary) are illustrated below.

3. RIBBLE ESTUARY

Assessment of morphological change

The Ribble is a broadly funnel-shaped estuary, which experiences a macrotidal energy regime and moderate wave energy in the mid and outer estuary. Bathymetric charts of 1847, 1904, 1951 and 1994 provide an overview of its morphological development in the past 150 years

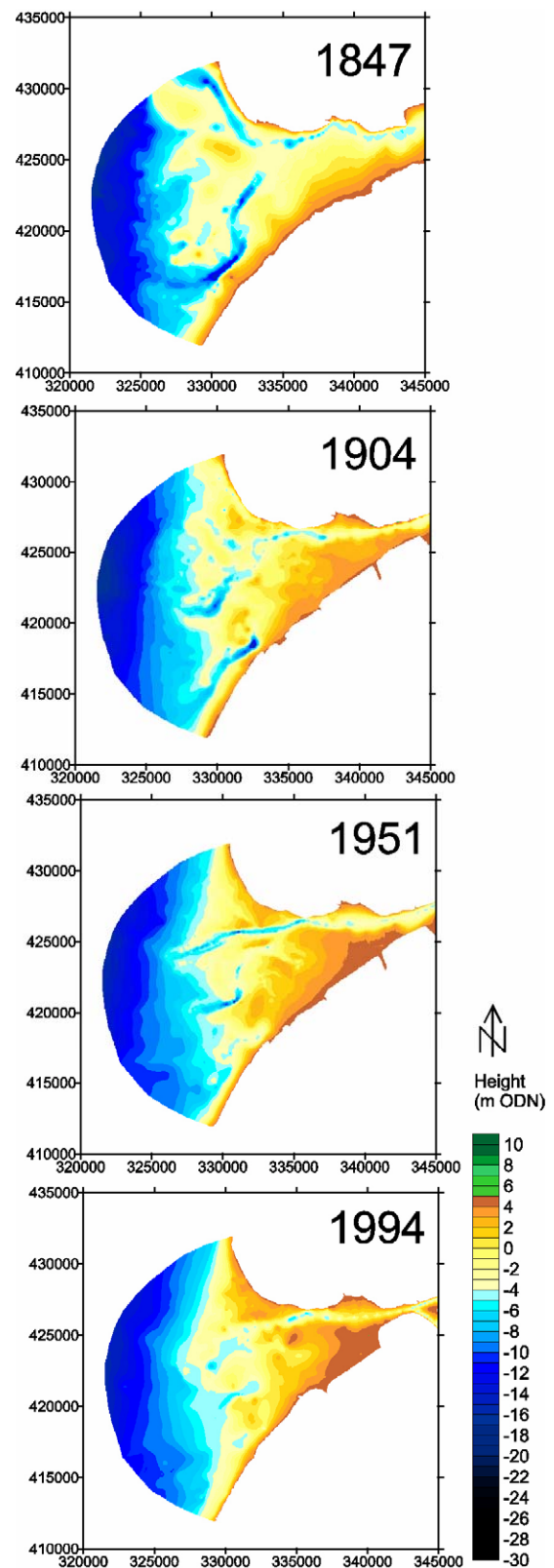


Figure 1 Bathymetry of the Ribble Estuary. (For source, see EMPHASYS data base.)

(Figure 1). In 1847, the inner estuary was dominated by the single main channel of the Ribble, which split into the North Channel and South Channel in the outer estuary, separated by extensive intertidal sand flats. By 1904, a navigation channel was forced through the banks, and trained. As a result, the North Channel was infilled, leaving the relict North Hollow. The South Channel was partly infilled, but a small deep channel ran at Southport pier (Boghole). A new (flood) channel (Penfold Channel) developed. In the outer estuary, there were both zones of erosion and deposition. Between 1904 and 1951, the trained navigation channel deepened, aided by repeated dredging. The North Hollow infilled completely to form Crusader Bank (Figure 2), and South Channel and Boghole further reduced in depth (Figure 3). The Penfold Channel moved to the south, and deepened. Accretion was dominant on the main intertidal sand banks and salt marshes. Between 1951 and 1994, the navigation channel was also subject to infilling. The Penfold Channel further moved to the south and became shallower. The Boghole disappeared, and the South Channel became a relict feature. Accretion on the intertidal area in the south continued.

The sediment budget of the Ribble, as derived from bathymetric charts, is positive (Figure 4). In all time intervals, net infilling of the estuary was found. Overall, the sediment volume in the subtidal zone was maintained, with only a relatively small net gain. Evidence from charts, plans and cross-shore profiles reveals that accretion is especially apparent in the upper intertidal zone (including the salt marshes), whereas parts of the lower intertidal zone maintained a more or less constant sediment volume (Figure 5).

A comparison of outlines of the estuary (mean high water spring contour) revealed a steady decrease in estuary area between 1847 (239 million m²) and 1994 (217 million m²). This was mainly due to embanking and reclamation (especially between 1847 and 1904 and between 1951 and 1994), rather than due to natural coastline changes. The net effect of both reduction in estuary area and overall infilling of the estuary was a reduction of the tidal prism by about 19% on spring tides between 1847 and 1994. The net effect of changes in areas due to infilling and reclamation was maintenance of

the area above mean high water neaps, and a reduction in area of the lower intertidal zones between 1847 and 1994 (Figure 6).

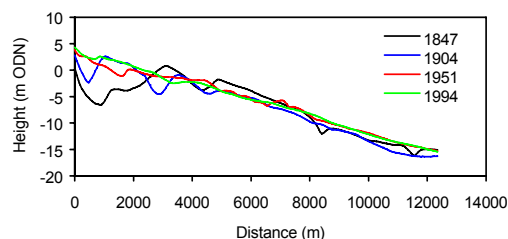


Figure 2 Infilling of the North Channel to form Crusader Bank, Ribble Estuary

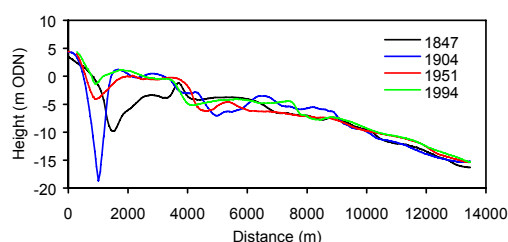


Figure 3 Development of the Boghole Channel, Ribble Estuary

Prediction of morphological change

The prediction for 1994 was based on the observed changes between 1847 and 1904 and between 1904 and 1951. Net sedimentation was predicted to continue between 1951 and 1994, but at a slower average rate, and with a continuing trend of marked vertical accretion in the mid and higher intertidal zone. Analysis of the 1994 chart and more recent survey data have confirmed that this indeed has happened, although human interference has changed the outcome to some extent; this will be discussed in a separate paper.

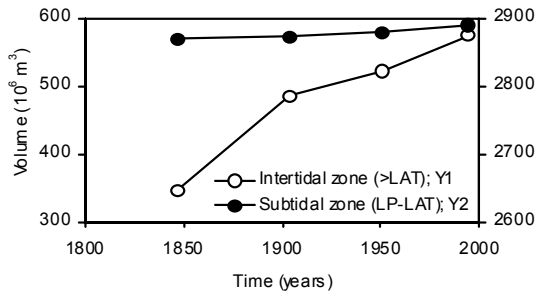


Figure 4 Intertidal and subtidal sediment volume changes in the Ribble Estuary

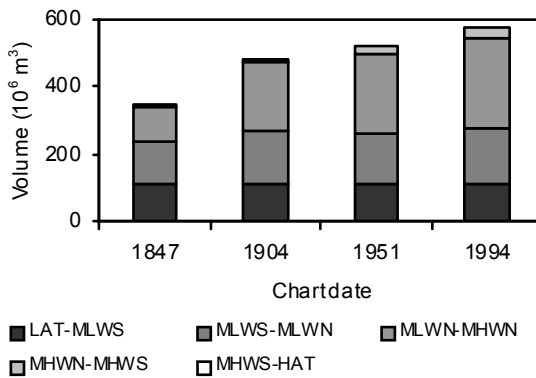


Figure 5 Changes in intertidal sediment volume in the Ribble Estuary

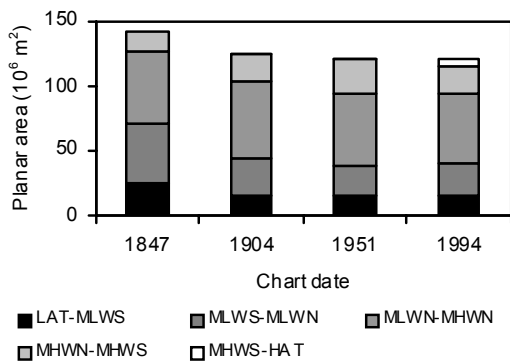


Figure 6 Changes in intertidal planar area in the Ribble Estuary

4. MERSEY ESTUARY

Assessment of morphological change

The Mersey Estuary consists of a bottle shaped inner estuary, which narrows near Liverpool (the Narrows), and a wide outer estuary, which forms part of Liverpool Bay. The estuary is subject to a macrotidal regime. Figure 7 shows the digitised charts of the estuary for 1900, 1950 and 1980. In 1900, the main feature was Crosby Channel, which reached over 20 m below ODN

at its deepest point. In 1909, Taylor's Bank revetment was constructed on its northern side. In the north, a channel (Formby Pool and Formby Deep in the south, and Formby Channel in the north) ran approximately southeast-northwest. West of Crosby Channel, an extensive intertidal area, the Great Burbo Bank, was present. It was intersected by two small channels. South of this bank, a channel called the Rock Channel, with its entrance (the Rock Gut), ran approximately east-west, hugging the North Wirral coastline. The River Mersey deepened at the Narrows, with the deepest point (-28.20 m ODN) near Liverpool. In this zone, intertidal flats were virtually absent. The inner Mersey Estuary was characterised by three channels: Eastham Channel in the south, Garston Channel in the north and the main channel of the River Mersey, known as Middle Deep, in the centre. The inner estuary was fringed by flats and salt marshes: these were Ince Banks and Score Bank in the south and Dungeon Banks in the north. In 1950, Crosby Channel remained in the same position (although it was lowered) (Figures 7 and 8); the training wall had been extended, and a new training wall constructed on the south side of the channel. Taylor's Bank had eroded at its west point, to move eastward. The Crosby Channel was still connected to Formby Deep and Formby Pool. Formby Channel had infilled (Figures 7 and 8) and become intertidal, its entrance had moved to the west. Parts of the northern part of the Great Burbo Bank had been eroded. The Rock Channel infilled (Figures 7 and 8), leaving the Rock Gut open. However, one of the channels through Great Burbo Bank (intersecting the Great Burbo Bank and the old North Bank) had deepened up. This channel is presently called the Rock Channel. There were no major changes in the Narrows. The intertidal flats on the south side of the inner estuary, Ince Banks and Score Bank, increased in area and height, whereas the intertidal area in the north, Dungeon Banks, decreased in area, associated with lateral channel migration. Upstream of Widnes, the Mersey did not experience major changes. By 1980, the Crosby channel had maintained its depth, aided by further training and dredging. Taylor's Bank had moved further to the east and had become connected to the Sefton coast. Formby Pool, Formby Deep and Old Formby Channel had infilled completely. Great Burbo Bank further decreased in area. The Rock Gut and the new Rock Channel were

still present. In the inner estuary, the Eastham Channel had moved to the south, eroding Ince Banks and Score Bank, although the southern parts of these marshes continued to accrete vertically. In the north, Dungeon Banks accreted again. The Middle Deep had infilled to some extent, possibly aided by the dumping of dredge spoil, and the Garston Channel had become more important.

Sediment volume calculations show that in the outer Mersey the total sediment volume increased between 1900 and 1950, but the intertidal sediment volume decreased (Figure 9). In the inner Mersey, both the total sediment volume and the intertidal sediment volume increased. Between 1950 and 1980, total sediment volume in the outer estuary was maintained, and there was a further decrease in the intertidal sediment volume. In the inner Mersey, sediment volume was maintained between 1950 and 1980, with only a slight increase. However, there is evidence of erosion during the past decades in the inner estuary (Figure 10).

Prediction of morphological change

A prediction for 1980 based on extrapolation of long-term directional trends observed between 1900 and 1950, accurately identified further infilling of the Rock Channel and Formby Channel, northeastward movement of Taylor's Bank, and further erosion of Great Burbo Bank. However, it was not possible to accurately predict the change in the rate of infilling. In addition, cyclic changes in the lateral migration of the low water channel within the inner estuary, resulting in a switching of the pattern of erosion and accretion, could not be accurately predicted based only on the two charts.

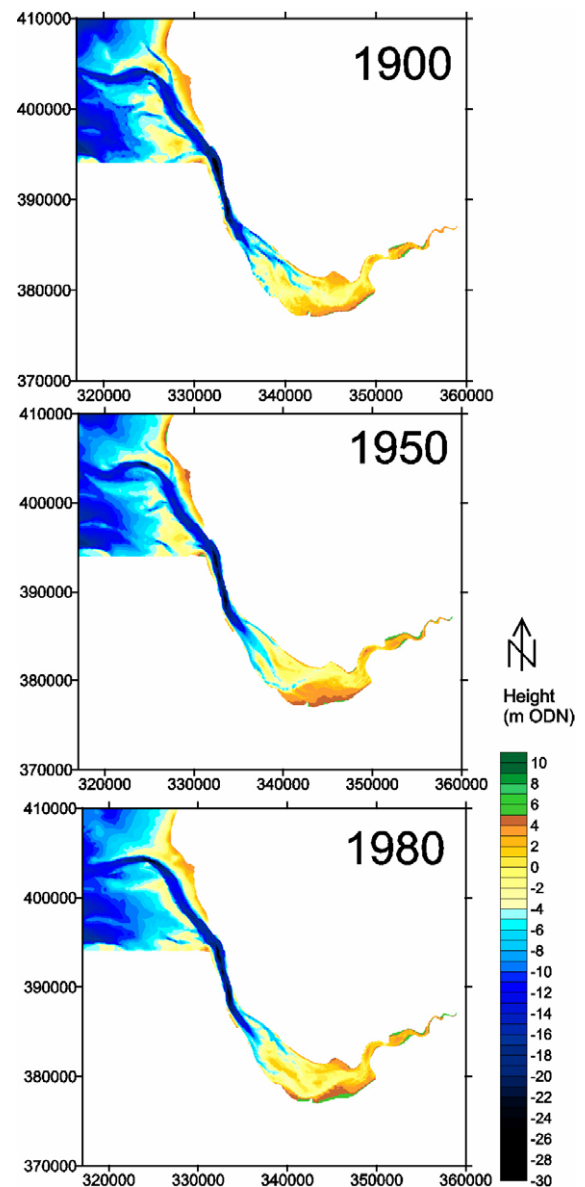


Figure 7 Bathymetry of the Mersey Estuary (For source, see EMPHASYS data base)

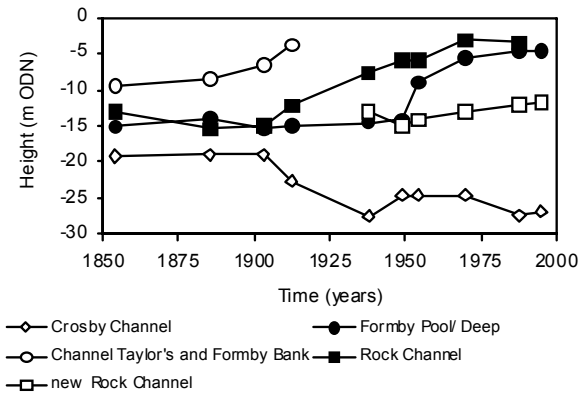


Figure 8 Deepest point of subtidal channels in the outer Mersey Estuary

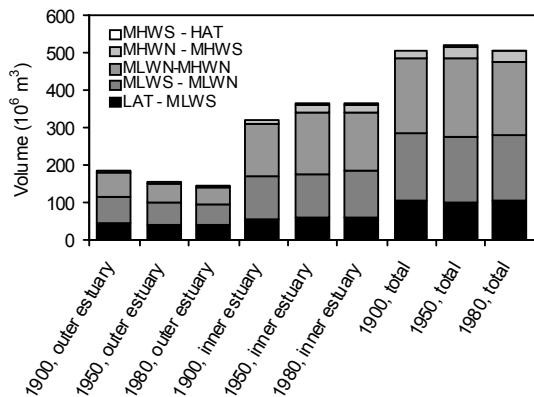


Figure 9 Changes in the sediment volume within the intertidal zone of the Mersey Estuary

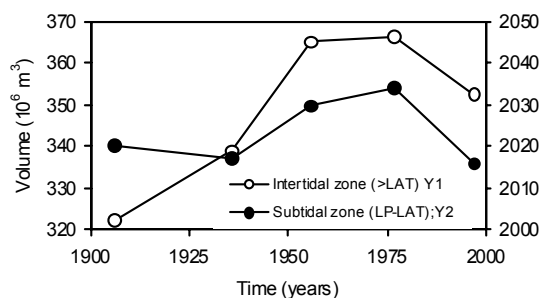


Figure 10 Intertidal and subtidal sediment volume changes in the inner Mersey

5. SOUTHAMPTON WATER

Assessment of morphological change

Southampton Water is situated on the south coast of England, and is sheltered by the Isle of Wight. The estuary is mesotidal, partially mixed, and ebb dominated. Figure 11 shows the morphology of the estuary between 1911 and 1996. It is characterised by a deep main

channel, bordered by intertidal mud flats and fringing salt marshes. The approach channels to the port of Southampton have been subject to change, albeit largely artificial (i.e., caused by dredging, dock development and reclamation). Morphological changes in the intertidal areas on the west side of Southampton Water are poorly defined due to lack of bathymetric data of the upper intertidal areas, resulting in large interpolation errors on all maps, except that for 1996, when the intertidal area was covered by a number of surveyed cross-sections. Hythe marsh accreted vertically between 1976 and 1996, but there is insufficient data for this area to identify trends for earlier periods. At Weston Shelf and East Mud some sediment accumulation occurred in the periods 1932-1951 and 1976-1996, whereas net erosion and retreat of the intertidal zone was found in other periods. Overall, areas of erosion exceeded areas of deposition in the subtidal areas.

The subtidal sediment volume shows a decreasing trend over time (Figure 12). The trend in intertidal sediment volume is less clear, although a decrease in volume can be perceived. However, due to scarcity of data points in the intertidal zone, these results should be treated with caution.

Prediction of morphological change

Based on the extrapolation of trends between 1911 and 1951, further erosion in both the subtidal and intertidal zone was predicted, a trend confirmed by analysis of later surveys.

6. HUMBER ESTUARY

Assessment of morphological change

The Humber Estuary is a well-mixed macrotidal estuary. The outer Humber is dominated by a three channel system (Hawke, Bull and Haile) at the mouth, and a single deep channel (Sunk Channel) leading further into the estuary. Further upstream, the estuary is flanked by extensive sand and mud flats. The morphological development of the Humber Estuary between 1851 and 1998 is shown (Figure 13).

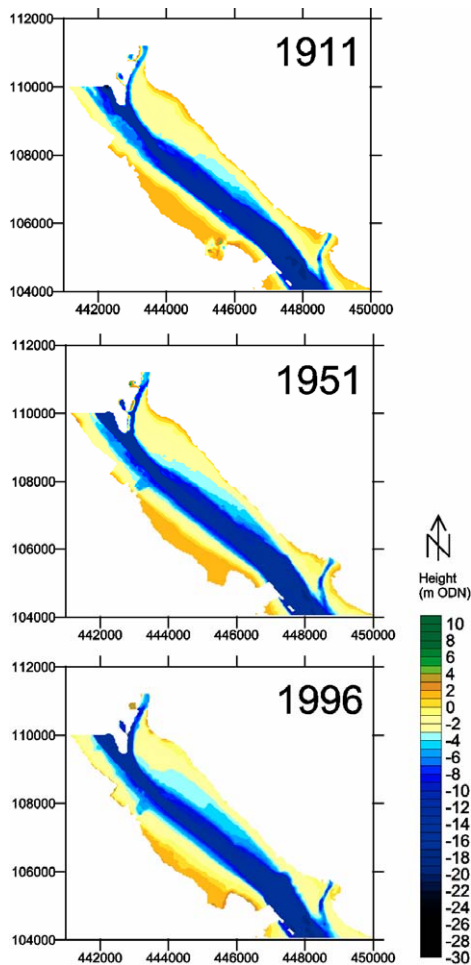


Figure 11 Bathymetry of Southampton Water. (For source, see EMPHASYS data base.)

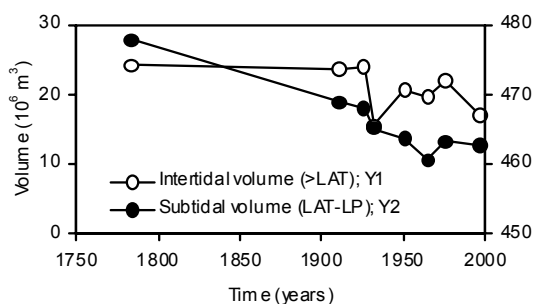


Figure 12 Intertidal and subtidal sediment volume changes in Southampton Water

In the outer estuary (defined here as the area from Spurn Point to Salt End), significant changes occurred in the pattern of channels and shoals. Apart from infilling of North Channel just north of Spurn Head, changes in Sunk Sand and Trinity Sand are merely due to interpolation errors. The development of Foulholme Sands is

also apparent. The middle Humber (the area from Salt End to the Humber Bridge) is dominated by changes in the intertidal Skitter Sand area, with a spit advancing seaward. In the inner Humber, Whitton Sands have been gaining sediment since 1851, with recent development of salt marsh in the high intertidal zone. There is evidence for a cyclic trend near Read's Island, reflecting fluctuations in channel position and size.

The Humber as a whole has shown long-term net accretion. However, there have been large spatial and temporal differences in the rate of infilling (Figure 14). In the outer estuary, for instance, the sedimentation rate of the subtidal zone between 1850 and 1900 was greater than between 1925 and 1975. In addition, there was a marked reduction in subtidal sediment volume between 1900 and 1910 and between 1976 and 1986, respectively. The subtidal sediment volume in the middle reaches of the Humber showed a slight erosional trend, but there were fluctuations in sediment volumes. In the inner Humber, a cyclical trend, superimposed on a long-term accretional trend of the subtidal zone, can be perceived, although the data are too limited to determine precise rates and magnitudes.

The trends in the intertidal zone (Figure 14) roughly correlate with trends in the subtidal zone: there has been long-term accretion in the Humber Estuary as a whole, although the lower intertidal zone remained essentially constant. Accretion was apparent in the intertidal zones of both the inner estuary (with steady accretion) and the outer estuary (with net accretion, but with fluctuations in sediment volume). In the middle reaches of the Humber, there has been a slight erosional trend, but, again, with fluctuations.

Despite the overall gain of sediment in the Humber Estuary, net loss of intertidal area was apparent over the last 60 years, notably at Foulholme Sands, Hawkin's Point and Haile Sand. However, the intertidal area in the inner Humber has increased in this period, providing some support for the concept of 'stratigraphic rollover'.

Prediction of morphological change

A prediction for 1998, based on the extrapolation of trends observed between 1850 and 1900 and 1900 and 1950, suggested accretion in the outer and inner Humber, and stabilisation or erosion in the middle Humber. Based on historical fluctuations in the location and size of subtidal channels, cyclical fluctuations with little net change in the middle Humber was predicted. These predictions were confirmed by analysis of past 1950 charts.

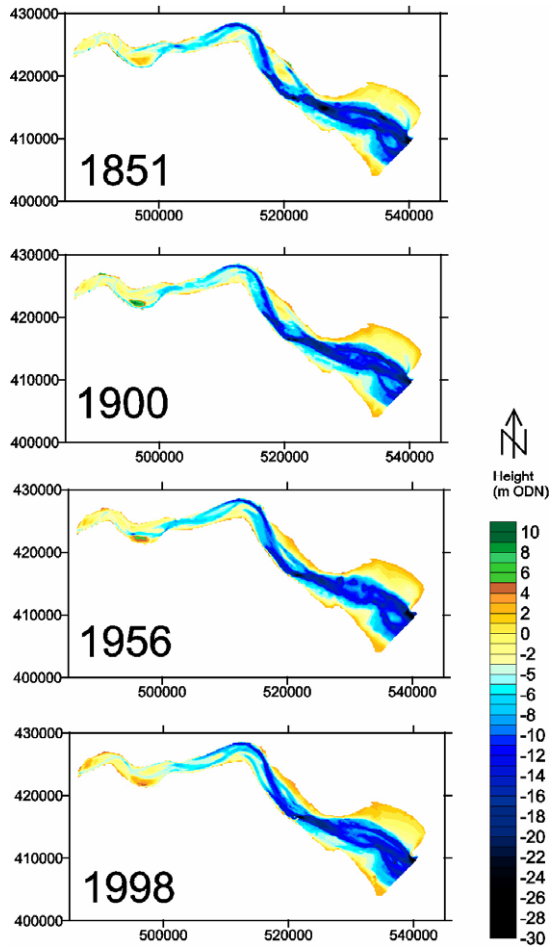


Figure 13 Bathymetry of the Humber Estuary. (For source, see EMPHASYS data base.)

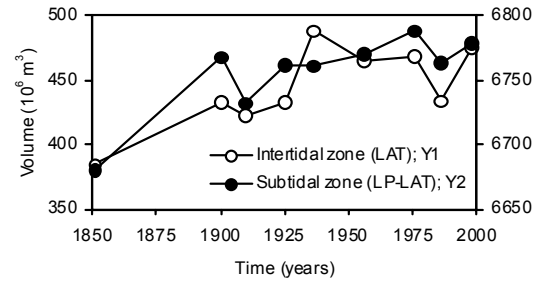


Figure 14 Intertidal and subtidal sediment volume changes in the Humber Estuary

7. CONCLUSIONS

Historical trend analysis of morphological changes based on sequential bathymetric charts is a potentially valuable tool, but is frequently constrained by the small number of available surveys. Errors arise from the incomplete nature of many surveys and difficulties associated with interpolation; estimates of sediment volume changes, therefore, need to be treated with caution, but identified historical trends relating to changes in channel depth, position and width can be considered with greater confidence. Simple linear extrapolation of historical trends is rarely justified, owing to the naturally cyclical nature of many estuarine morphological changes and also to the fact that the boundary conditions within estuaries have been continually changing, especially due to human influence in the past 150 to 200 years. Long-term data sets with sufficient temporal resolution, combined with an understanding of the causes of morphological change, are required for accurate prediction of future change.

EXPERT GEOMORPHOLOGICAL ASSESSMENT (EGA) AS A TOOL FOR LONG-TERM MORPHOLOGICAL PREDICTION IN ESTUARIES

Ken Pye and Daphne van der Wal

Email: k.pye@gl.rhul.ac.uk

Department of Geology, Royal Holloway, University of London Egham, Surrey,
TW20 0EX, UK

1. INTRODUCTION

The work undertaken at Royal Holloway, University of London, as part of the Estuaries Research Programme has employed two related, integrated approaches which we refer to as Historical Trend Analysis (HTA) and Expert Geomorphological Assessment (EGA). The latter incorporates HTA and may be regarded as a sub-type of a broader, integrated appraisal and prediction method known as Expert Scientific Assessment (ESA).

EGA incorporates output from HTA (which is discussed more fully in a separate paper in this volume) but goes further in that it also takes into account information about current physical, chemical and biological processes, about geological constraints and sediment properties, and about general relationships between processes and morphological responses determined through previous work in the field or laboratory. A conceptual model of the working of a particular estuary or length of coast is developed, and a qualitative assessment made of the 'current state' of the estuary, including the causes of past, present and likely future change. 'Expert' predictions can be made on this basis of the likely impacts of any intrinsic or extrinsic change, their likely time scales and magnitude. Testing of the approach can be undertaken by comparing data for at least two historical periods as a basis for prediction, and by using data for a third period to assess the accuracy of the predictions. This assessment can be undertaken using a combination of qualitative, semi-quantitative and quantitative methods.

2. METHODS

Investigation of medium to long term morphological changes involved sequential analysis of hydrographic surveys, supplemented by data from ground surveys, LIDAR and CASI. Additional information relevant to the EGA, e.g., wind/wave climate and tidal records, sedimentological evidence, dredging records and

reclamation schemes was obtained from a combination of published and unpublished archival sources. The information is stored and analysed in a PC-based ArcInfo/ArcView Geographical Information System (GIS).

The approach followed to assess morphological change is discussed in a separate paper (this volume). Possible causes of morphological change have then been identified and evaluated. These comprise changes in natural forcing factors over the period, such as changes in relative sea level, changes in wind/wave climate and changes in tidal levels, and human factors, such as reclamation, dredging, and training wall construction. In addition, constraints, such as antecedent geomorphology, sediment supply from offshore and fluvial sources and sensitivity of the system to change have been taken into account. Figure 1 gives an overview of the forcing factors and their interaction and impact on morphology.

By comparing the timing, magnitude and location of coastal change to the changes in forcing factors, certain factors can be eliminated and identified as causes for the observed morphological changes. The historical trends are then extrapolated within constraints imposed by an understanding of 'top down' relationships and 'process-response' associations, to give predicted future scenarios.

In this paper, EGA is illustrated by reference to two estuaries: the Ribble and the Mersey. Further information is given in two RHUL internal reports (Van der Wal & Pye, 2000a, b).

3. RIBBLE ESTUARY

Morphological change

Detailed bathymetric information of the Ribble Estuary is available from 1847, 1904, 1951 and 1994, supplemented by more frequent partial surveys undertaken by the Port of Preston Authority. Between 1847 and 1904 accretion was

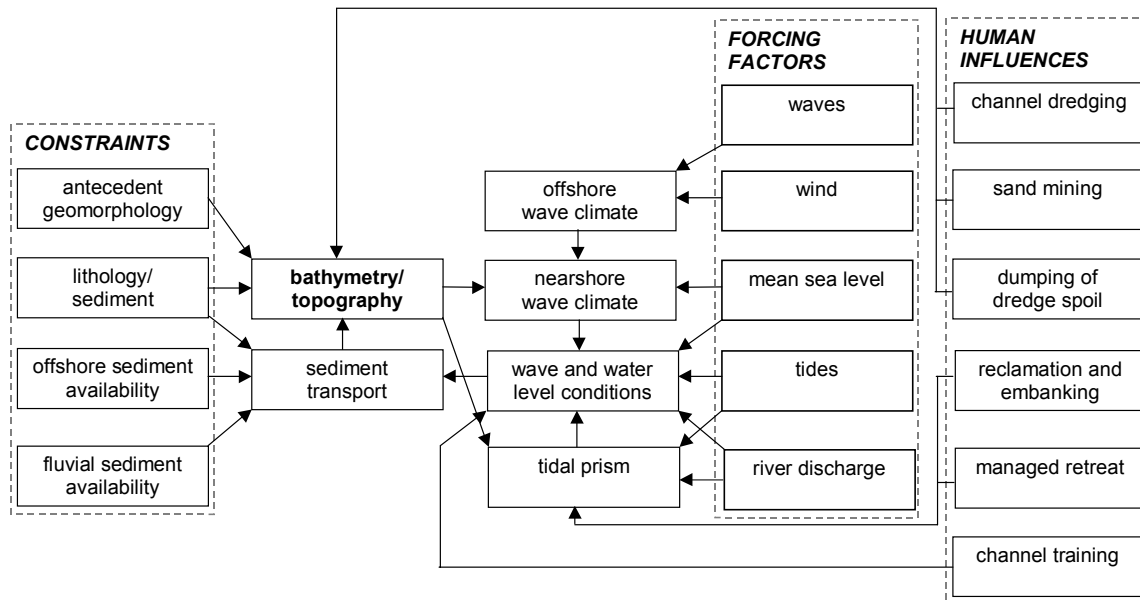


Figure 1 Schematic representation of factors affecting morphological change in an estuary

rapid. There was major infilling of the estuary channels, whilst a new navigation channel was forced through the sand banks. Between 1904 and 1951, accretion was found to continue, albeit in a lower rate.

The sediment accumulated especially in the intertidal zones above mean high water neap tide level, while the lower intertidal areas maintained a fairly constant sediment volume. In the outer estuary, there were both zones of deposition and erosion, but the subtidal sediment volume was maintained. The overall accretion was, however, less than in the previous period. In the period between 1951 and 1994, accretion of the mid and higher intertidal zone continued, and sedimentation also occurred in the navigation channel.

Causes of morphological change

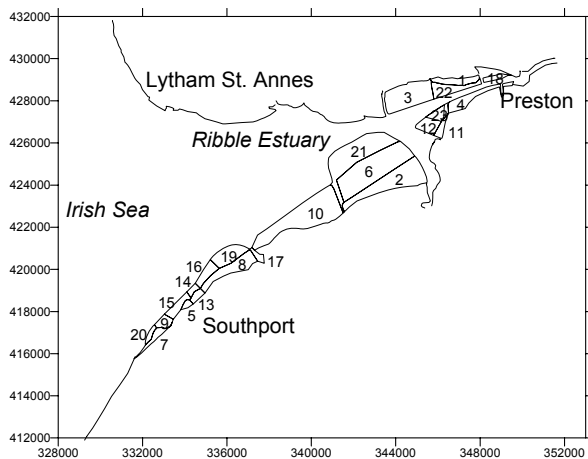
The accretional trend in the Ribble Estuary over the last 150 years reflects continuation of a pattern which started soon after the modern estuary was created in the early to mid Holocene. The accretion in the estuary requires the continued landward movement of sediment from further offshore. The supply of sediment from the River Ribble is negligible, the tidal prism being orders of magnitude greater than the river discharge. The floor of the southeast Irish Sea is veneered with a mantle of largely sandy sediment derived from tidal current and wave reworking of glacial sediments. Sea bed drifter, current meter

and circulation studies in the Irish Sea indicate long term onshore movement of sediment at present, and on the basis of geological evidence it is considered safe to presume that this large scale pattern was essentially the same during the whole of the late Holocene.

Prior to the early nineteenth century, the estuary of the River Ribble experienced a high degree of quasi-cyclical fluctuation, superimposed on a slow net accretional trend. The estuary can be considered to have been close to a state of equilibrium. However, after circa 1820, the regime of the estuary changed markedly, associated with rapid and geographically extensive morphological changes. Evaluation of all available evidence suggests strongly that these changes resulted very largely from human interference. Effects of sea level rise and changes in storminess on the estuary have been minor. The initial triggering factor was embanking and reclamation (Figure 2), commencing in 1810, which progressively reduced the tidal prism and tidal current velocities within the estuary. This caused a reduction in the mean wave and tidal energy in the inner estuary, leading to increased accumulation of mud at the expense of sand. Much of the inner and mid estuary has experienced vertical and lateral accretion of salt marshes. Salt marsh growth was further enhanced by *Spartina townsendii* introduction in 1932. However, the rate of change progressively slowed down between 1950 and 1980, as the

estuary approached a new condition of dynamic equilibrium.

The considerable reduction in size of the navigation channels of the Ribble estuary, both in depth and in extent, prompted the construction of training walls in the outer estuary. The cutting of the main navigation channel and the associated construction of training walls between 1847 and 1910 had led to the concentration of the ebb flow in the trained channel, allowing strengthened flood tides outside the trained channel to move sediment inshore (Barron, 1938). The erosion observed in parts of the outer estuary may well have represented the local reworking of sediment landward into the mid and inner estuary.



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

Figure 2 Enclosure of land in the Ribble Estuary between 1847 and 1994

Dumping of dredge spoil from the Mersey Estuary, (especially in the Ribble Indraught, the subtidal extension of the South Channel and Boghole, which brought material into the estuary on the dominant flood tide) has also contributed to accretion in the Ribble Estuary. The main channel of the Ribble Estuary was also dredged, mainly after 1905. First, the dredge spoil was disposed just off the mouth of the estuary (within the study area), but was later taken further offshore. These activities probably led to accelerated accretion in the River Ribble, due to enhancement of the flood tidal component and reduction of the tidal prism. The recent accretion in the navigation channel was accentuated by cessation of dredging in 1980, following the closure of the Port of Preston.

Prediction of morphological change

On the basis of the changes between 1847 and 1904 and between 1904 and 1951 and their likely causes, we predicted that net sedimentation would continue between 1951 and 1994, but, as the estuary had adapted to the training works, at a lower average rate. Furthermore, vertical accretion in the mid and higher intertidal zone was predicted to continue.

Analysis of the 1994 chart and more recent survey data has confirmed that this indeed has happened, although the closure of the Port of Preston and cessation of dredging in 1980, have to some extent changed the outcome by initiating a process of hydrodynamic and morphological adjustment. Since the abandonment of dredging, the main navigation channel has become blocked by southward growth of a large spit / bank complex off Lytham St. Annes, and the South Gut and Penfold Channel in the central part of the estuary have begun to re-establish themselves. It is likely that these trends will continue over the next 10 to 20 years as the estuary continues to adjust to the past dredging and training regime.

4. MERSEY ESTUARY

Morphological change

The Mersey estuary also experienced major accretion over the last 150 years, with net accretion both in the inner and outer estuary. However, the rate of accretion was much higher between 1900 and 1950 than between 1950 and 1980. Furthermore, there were large spatial differences in accretion, and there were also areas of net erosion. The intertidal area of the

outer Mersey, especially, was subject to erosion, both between 1900 and 1950 and between 1950 and 1980. In the inner Mersey, migration of the low water channel produced an alternation of lateral erosion and sedimentation of salt marsh areas.

Causes of morphological change

The main source of sediment is found in the glacial and fluvio-glacial deposits covering large parts of the eastern Irish Sea bed. Fluvial supply of sediment to the estuary is small compared to the supply from offshore sources, and the mean freshwater flow is orders of magnitudes smaller than the tidal influx. Nevertheless, the magnitude and duration of freshwater discharge may affect migration of low water channels in the inner estuary.

Like the Ribble Estuary, the Mersey has been infilling since the end of the last glaciation, to compensate for overdeepening of its channels produced by glacial and river actions when mean sea level was lower and river gradients were much steeper than at present. At present, rates of relative mean sea level rise are about 1 mm/y at Liverpool (Figure 3). Simultaneously, the tidal range has increased, with a significant increase in high water level, which might have been amplified by anthropogenic modifications. It has been suggested that the estuary was filling with sediment at a rather slow rate, compared to the rates experienced in the early twentieth century. This is confirmed by the present study: the rates of infilling were especially high between 1900 and 1950. Therefore, it is likely that other factors than sea level rise have affected the development of the estuary in this period.

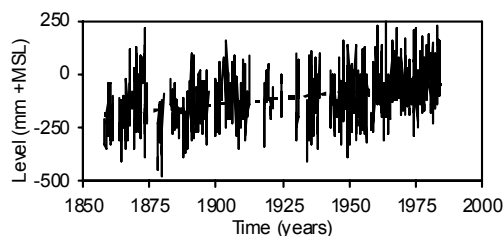


Figure 3 Change in relative mean sea level at Liverpool (combined data from Georges Pier and Princes Pier) (data from PSMSL, 2000)

The outer Mersey is susceptible to storm surges because of the shallow nature of the north-eastern Irish Sea, and storm wave activity is also

important because the area is fetch-limited. Storm intensity and extreme wave height have increased throughout England and Wales in the last three decades. Although there is some evidence that the wind climate was stronger between 1900 and 1940 than in the subsequent period 1940 to 1960 (e.g., Pye & Neal, 1994), and variations in wave energy could be related to onshore movement of sediment into the estuary, there is no conclusive evidence that this has been a major factor.

In the outer estuary, a large channel training scheme was carried out. In 1909, a training wall was constructed along the face of Taylor's Bank. The intention was to prevent the continued northward movement of the Crosby channel, and also to prevent a smaller channel from breaking through Taylor's Bank. Between 1910 and 1957, the training walls were extended, and new training walls were built. An important objective of the training works was to concentrate the flow in the main navigation channel. As a result of the increase of the ebb flow in this channel, the ebb flow in the Rock Channel was reduced, and the flood-dominated zones adjacent to the trained channel extended and moved inshore (Price & Kendrick, 1963). Consequently, especially the Rock Channel and Formby Channel infilled at an accelerated rate. The reduction of the ebb flow over Great Burbo Bank enhanced sediment movement into the inner estuary by the strengthened flood tide. Sequential bathymetric surveys have shown that this was associated with a decrease in both volume and area of Great Burbo Bank from 1900 onwards. The construction of the training walls corresponds to the increase in the rate of accretion between 1912 and 1950, and is therefore believed to be the most important factor in the morphological development of the estuary in this period of time. The net effect of these engineering activities was, thus, to accelerate the process of infilling.

Due to the importance and development of the Port of Liverpool, the approaches to the River Mersey have been dredged since 1833, with regular dredging since 1890. Amounts of material dredged at the Mersey Bar and from the sea channels were especially high between 1900 and 1950, i.e. 435 million hopper tons, versus 174 million between 1890 and 1910, and 191 million between 1950 and 1988 (Figure 4). The intensified dredging activities caused shoals to encroach on the navigation channel, which

prompted the extension of the training walls. The training walls indeed succeeded in decreasing the dredging effort. However, dredging has brought about a substantial redistribution of sediment in both the outer and inner Mersey. Pye & Neal (1994) show that dredging (and dredge spoil dumping) contributed to an increase in wave attack on Formby Point.

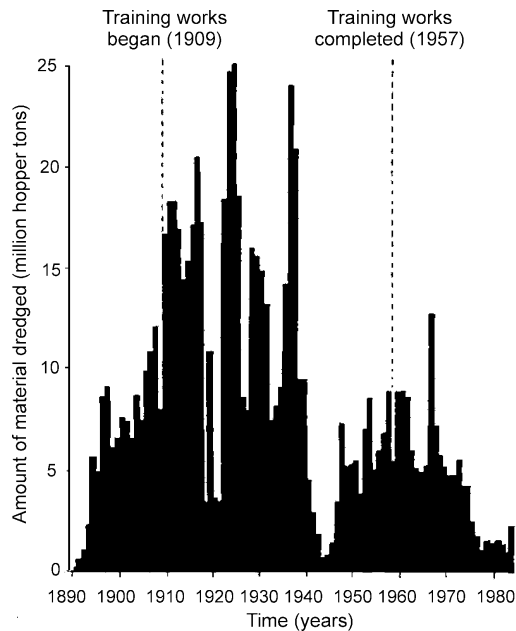


Figure 4 Amounts of material dredged from the approaches to the Mersey (after Smith, 1982)

Dredged spoil from Liverpool docks and the approach channels was deposited at various sites in Liverpool Bay, including sites on the eastern and western side of Great Burbo Bank and on sites north and north west of Taylor's Bank. At present, maintenance dredge spoil is dumped west of Jordan's Bank, and more substantial dredge spoil material is dumped offshore in Liverpool Bay. Within the Mersey, spoil is dumped at Garston Rocks and in the Middle Deep off Eastham. Drifter studies revealed a long-term drift from the dredge spoil site north west of Taylor's Bank towards Taylor's Bank and Formby Point. Therefore, dredge spoil contributed to the shoaling in Formby Channel. Dredge spoil was also trapped behind the main channel revetments, and part, in increasingly finer form, continued its way into the estuary. Indeed, when the site west of Great Burbo Bank was abandoned in 1961, the amount of material to be dredged was halved. Pye & Neal (1994) demonstrated the change in wave patterns and subsequent erosion at Formby Point due to the

development of Jordan's Spit as a result of the dumping of dredge spoil. It is likely that the changes of Great Burbo Bank were also amplified by the dredging activities.

Prediction of morphological change

Based on the changes and their causes between 1900 and 1950, the estuary was predicted to experience continued accretion between 1950 and 1980, but at a lower rate, as the estuary has become more adapted to the training walls and dredging scheme. Infilling of the Rock Channel and Formby Channel was predicted to continue. Taylor's Bank was predicted to move further to the north east, and to amalgamate with Formby Bank, with associated erosion on its west side. Similarly, Great Burbo Bank was predicted to erode, but eastward movement is prevented by the presence of training walls. In the inner Mersey, cyclic channel migration was predicted to continue, affecting the extent and distribution of salt marsh area, although no prediction could be made as to the time-scale of this process. Subsequent analysis of past 1980 surveys and air photography has confirmed that these changes have occurred and are still in progress.

5. CONCLUSIONS

Expert Geomorphological assessment is an integrated approach to morphological assessment and prediction which utilises a combination of historical trend information, 'top-down' concepts of regime relationships and an understanding of process-form interactions to provide qualitative or semi-quantitative predictions of future change. Its great strength is its broad-scale, long-term perspective. However, the capacity of the method to predict detailed, more local scale changes is more limited and successful application of the method is heavily dependent both on the quality of the background information and data available and to the skill and expertise of the individual or organisation responsible for the assessment.

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EXPERT ANALYSIS MODEL OF AN IMPACTED ESTUARY: SOUTHAMPTON WATER

Adonis Velegrakis and Michael Collins

email: ra3@soton.ac.uk

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

1. INTRODUCTION

This short contribution summarises the methodology and presents the results of an expert analysis model used to identify environmental characteristics and long term-morphological evolution (together with smaller time-scale trends and cycles) in an ‘industrialised’ estuary. It also shows how the available information can be integrated in order to identify particular characteristics and technique limitations, which may affect the diagnostic and prediction ability of such models. Expert analysis models use all available environmental information. This information can be: (i) primary (i.e. original data sets); (ii) secondary (published or unpublished accounts of previously collected information); and (iii) modelling results. Its major limitations are related to (a) the need for rigorous validation (which is a universal requirement for all realistic morphological models) and (b) high degree of expertise required to synthesise information from different sources and obtained through diverse analytical methods.

The procedure was applied in Southampton Water (Figure 1), one of the selected estuaries of the EMPHASYS Project. Southampton Water is a ‘channel-like, ria-type coastal plain estuary, which although forms the largest estuary of the southern coast of England is a relatively small (up to ≈ 10 km long and 2 km wide) and shallow estuary (up to 20 m below OD). It receives freshwater inputs from the Rivers Itchen, Test and Hamble; however, these inputs contribute very little to the estuarine tidal prism, as the combined mean daily freshwater flows rarely exceed $20\text{m}^3/\text{s}$ (EMPHASYS Database). The area around Southampton Water has undergone significant industrial, residential and leisure development during the last 50 years, resulting in major effluent discharges (sewage discharge of $\sim 0.15 \times 10^6$ m^3/day) into the estuary (Figure 1), particularly along its western shore (Croudace & Cundy, 1995). Moreover, as Southampton Water is well-

protected from the Atlantic swell is a very attractive harbour for high tonnage shipping. Thus, major capital dredging programs took place in the estuary around the turn of the last century, between the two world wars, in 1950, 1962 and 1997-1998. Nevertheless, the estuary can still be regarded as quite ‘natural’ morphologically, compared with other industrialised European estuaries (e.g. Mersey, Seine (France) and Bilbao (Spain) estuaries):

2. THE DATA

The field information used in the present study includes: (1) the bathymetric, hydrological, hydrodynamic and sedimentary data collated within the EMPHASYS Database; (2) all the other available information from published and unpublished work carried out in the area; and (3) new observations collected during the present study, such as hydrodynamic/turbidity time-series from the intertidal flats of the area (2 sites, see Figure 1). In terms of modelling, the outputs of 2-D (Price & Townend, 2000; Shi, 2000) and 3-D (Shi, 2000) hydrodynamic models together with the ABP Research bedload sediment transport model were used to provide information on the spatial and temporal distribution of the energy and sediment transport within the estuary. Finally, the results of the ABP Research ‘top-down’ model were also examined, in order to gain an increased insight to the long-term estuarine morphological development. It has to be noted, that the calibration and validation of all the available hydrodynamic and sediment transport models from the area have been based on limited field observations and, therefore, they may require further field data in order to improve their accuracy.

3. RESULTS AND DISCUSSION

3.1 Large-scale morphodynamics

3.1.1 Modern estuarine development

Southampton Water (Figure 1) is flanked by intertidal flats, which are generally wider along its western shore. At the confluences of the Itchen and Hamble Rivers with the Southampton Water, small ebb tidal deltas occur; a recurved barrier spit (Calshot Spit) and an ebb delta (Bramble Bank) incised by the major shipping channel (maintained by frequent dredging) form the tidal inlet of the estuary. The comparison of the available morphological evidence (including the eight historical bathymetric data sets from the EMPHASYS Data Base) carried out as part of the present investigation showed significant morphological changes between 1783 (the first set) and 1996 (the last set). These changes were found to be mostly associated with: (i) the downstream sections of the Test and Itchen Rivers, where more than 340 Ha of intertidal flats have been reclaimed (see also Hooke & Riley, 1987); (ii) the middle section of the western coast of the estuary, where c. 350 Ha of flats have been reclaimed; and (iii) the estuarine channel, which has been subjected to major capital and maintenance dredging. The analysis showed a general reduction of the intertidal flat area along the estuary and the 'marine' side of the tidal inlet. An interesting feature of the inlet's morphological development is the well-documented erosion of the Tertiary coastal cliffs behind the Bramble Bank (e.g. Hooke & Riley, 1987); this suggests that the coastal protection offered by the ebb delta bank may not be sufficient to halt the (mainly) wave-induced erosion behind it. In contrast, Calshot Spit appears to be very stable both in long and medium temporal scales: statistical (Empirical Orthogonal Function) analysis of a 10-year seasonal time-series of beach profiles (provided by New Forest District Council) carried out during this study showed that the spit is extremely stable.

The most important bathymetric changes appear to have taken place along the middle section of the western side of the main estuarine channel, where significant accretion (in some areas more than 2 m) was found to have taken place between 1926 and 1996. Some of this accretion was reversed by the major 1998 capital dredging scheme (Elderfield, 1999). Flood (1981), also found significant bathymetric changes in the same area on the basis of the analysis of

sequential bathymetric data ('chart-differencing'): he estimated that the accretion in some areas along the western channel wall exceeded 4 m between 1939 and 1967, having an average accumulation rate of some 10 cm/yr. However, geochemical evidence from the same area suggests that such accretion rates might be a gross overestimation with the mean sedimentation rates estimated to be 0.5 cm/yr; higher rates (c. 2 cm/yr) were estimated only for the periods of rapid accretion which followed the capital dredging (and reclamation) schemes associated with the Esso industrial complex in the early 1950's (Croudace & Cundy, 1995).

The apparent differences observed between results of the sequential bathymetric data sets and the geochemical analysis of sediments highlight the limitations of the 'chart differencing' analysis. Although space constraints do not allow the in-depth discussion of these limitations, the error sources include: (i) the variable spatial resolution of the bathymetric surveys; (ii) the different co-ordinate system used in the older surveys; (iii) the limited accuracy of point-measurement positioning and the variable tidal referencing, particularly during the older surveys (see Bowyer, 1992); (iv) the different depth measuring techniques used in the historical surveys (i.e. lead-lines or echo-sounding); (v) the practice of rounding off the water depths to shallower depths (as navigational precaution); and (vi) the interpolation techniques used to reduce the different data sets prior to the comparison.

The latter errors may be present even when good quality, modern data sets are compared. The "chart differencing" technique involves the transformation of the depth point measurements from different surveys into grids with common geographical co-ordinates, using a more or less complex interpolation algorithm. The water depths at each node are then compared, with positive residuals showing areas of net deposition and negative residuals indicating areas of net erosion. However, significant errors may be introduced, as the sets are not compared at the points of actual measurements, but at the grid nodes where the depths are interpolated. The magnitude of these errors depends upon the density of the original point measurements, the slope of the seabed and the interpolation technique (Davis, 1986).

3.1.2 *Quarternary development*

The oldest solid formation outcropping in the area is the Cretaceous Chalk, followed by fluvial, estuarine and shallow marine Paleogene sedimentary sequences; no Neogene sediments are present in the area, with the unconsolidated Quaternary deposits resting directly on the Paleogene sediments (Velegrakis, 2000). The present estuary is the result of the Flandrian inundation of a substantial tributary of the "Solent River, a lowland river which, during the Pleistocene lowstands, drained the Hampshire Basin (Velegrakis et al., 1999). Comparison of the Holocene sea level rise (Long & Tooley, 1995) with the elevation of the basement of the unconsolidated sediments suggests that a significant part of the present Southampton Water may have been inundated by 7000 years BP. During the last 2000 years, the average sea-level rise rate over the area has been estimated as 0.1-0.15 cm/year; this rate has increased (to 0.4-0.5 cm/year) in the last 40 years (Long & Tooley, 1995).

The analysis of the substantial data set of core-logs from the area (SOES Database) showed that, although the thalweg of the original Pleistocene fluvial channel was positioned along the western side of the present estuary, most of the transgressive tidal/estuarine facies that overlapped the lowstand profile have also aggraded there (see also Hodson & West, 1972). This apparent lateral migration of the main locus of sediment deposition, which accompanied the 'roll-over' estuarine phase, suggests the introduction of particular hydro- and sediment dynamic gradients across Southampton Water during the Holocene. Although the forcing responsible for these gradients can not be ascertained on the basis of the available evidence, it may be related to: (i) changes in the tidal regime of the enlarging estuary around 7000 BP, when the tidal prism of the Solent changed radically, in response to the opening of its western entrance (Hurst Narrows) (Velegrakis, 2000); (ii) gradients in the distribution of the modern wave energy across the estuary; (iii) tidal inlet controls; and (iv) particular relationships between the volume and nature of the sediments entering the enlarging estuary.

3.2. Hydrodynamics

Southampton Water is a partially-mixed estuary, with a tidal prism of $1.03 \times 10^8 \text{ m}^3$ and $5.31 \times 10^7 \text{ m}^3$ during spring and neap tides, respectively (Westwood, 1982). Although the semi-diurnal

constituents are dominant, higher harmonics are also important (Figure 2); their combination results in a complex regime, characterised by a double high water and a young flood stand (Figure 3). Large asymmetries occur between the duration and flow strength of the ebb and flood, with the peak ebb and flood currents at the tidal inlet predicted by numerical simulations to reach speeds of 1 m/s and 0.7 m/s, respectively (Price & Townend, 2000). There are also spatial and temporal gradients in terms of stratification (Figure 3) and (vertical and lateral) flow structure (e.g. Dyer, 1982a; Sylaios & Boxall, 1998; Sharples, 2000; Shi, 2000). Numerical simulations (validated by limited number of observations) show that the ebb dominance decreases in an upstream direction (Price & Townend, 2000; Shi, 2000). They also show that the flow over the fringing environments (channel walls and intertidal flats) is to the opposite direction (i.e. towards the estuarine entrance) than that of the main estuarine channel in the young flood, particularly during the more energetic tides. The complex circulation patterns and temporal and spatial variability of the flow structure in the area suggest that 3-D simulations are required to model realistically the estuary.

The hydrodynamic data collected during the present investigation on the fringing intertidal flats (Figure 1) showed complex flow patterns. At both the western (Hythe) and eastern (Weston) sides of the upper estuary, the tidal flat flow patterns (in terms of direction) during the energetic tides appear to be in a general agreement with those identified by the numerical simulations. The data collected along a transect across the Hythe intertidal flats also showed that: (i) the ebb is characterised by stronger currents; (ii) the flow during the young flood is largely towards the estuarine entrance; and (iii) the flow is characterised by significant lateral shear. These patterns are present during most of the spring-neap cycle, but they are more profound during the more energetic tides (Figure 4).

3.3. Sedimentology

The surficial sediments are mainly fine-grained, originating from both fluvial and marine sources (Algan, 1993); coarser sediments are found only along the coasts and in the vicinity of the tidal inlet (Velegrakis, 2000). The examination of the available information showed that, in spite of the significant amount of research carried out in Southampton Water, there is no sufficient data to

compile a map of surficial sediments of good accuracy and resolution. Most of the available information is outdated (e.g. Dyer, 1969), or collected over different temporal and spatial scales and, therefore, can not be used with confidence, particularly as the seabed of the area has experienced large human-induced changes during the last decades (see below and Figure 5)). These limitations in data quality diminish our confidence on the sediment transport pathways identified by Algan (1993) on the basis of grain-size trends (Figure 6); according to this technique, sediment transport patterns can be inferred on the basis of particular trends in the mean, sorting and skewness of the sediments (for a technique description, see Gao and Collins, 1992; for limitations see Brampton *et al.*, 1998)).

Similarly, our knowledge on the thickness of the estuarine unconsolidated sediments is based mainly on core-logs from the fringing environments of the estuary, as geophysical information is very sparse and fragmented. Over the tidal inlet of the estuary, in particular, there is very limited information and, therefore, the thickness of the medium- and coarse-grained sediments in this area can not be established. Nevertheless, the available data show that the unconsolidated sediments attain substantial thickness mainly along the western estuarine margin, where, in some cases, thickness of more than 15 m has been estimated (see Section 3.1.2). Within the estuarine channel itself, the unconsolidated sediment thickness is, in most areas, negligible; this is particularly true following the last capital dredging operations when the channel was dredged (in some cases) down to the Tertiary bedrock (Elderfield, 1999). With regard to modern sediment accumulation rates, a significant variability has been observed over the different sedimentary environments of the estuary. Sedimentary/geochemical observations (Cundy & Croudace, 1995; Cundy *et al.*, 1997) show that: (i) modern accumulation rates within the non-dredged areas of the estuarine channel do not exceed 0.5 cm/yr (see also Section 3.1); (ii) saltmarsh accumulation rates vary between 0.4 and 0.9 cm/yr, with the highest rates found at Hythe; and (iii) the tidal flats at the offshore side of the marshes are under erosion.

Side-scan sonar information (Figs. 1 & 5) revealed some interesting characteristics of the sedimentary morphology of the estuary. First,

most of the sub-tidal bed of the estuary shows evidence (Figure 5) of an extensive and varied usage (i.e. capital and maintenance dredging, shellfish fishing, extensive mooring, pipelines etc). Large areas are covered by large scour marks with a relief, in some cases, of more than 1.5 m; this suggests that the natural sedimentary processes of the estuary can not keep pace with the human interference. Secondly, bedforms have been identified in the area, including several mud furrow fields (e.g. Flood, 1981; Dyer, 1982b; Elderfield, 1999) and small isolated fields of small and medium sub-aqueous (sand) dunes within the estuarine channel and in the vicinity of the ebb delta of the estuary. The relief and spacing of the former increase with the water depth (Figure 5(b)), whereas the field dimensions of the latter, as well as the spacing and height of the constituent bedforms appear to be substantially smaller than those identified during previous investigations (e.g. Flood, 1981). The direction of asymmetry of the observed sub-aqueous dunes is towards the estuarine entrance (during most stages of the tide), indicating that the dominant direction of (sand) bedload transport is offshore (Figure 6); this is in good agreement with previously suggested pathways in the estuary (Price & Townend, 2000). However, the decrease in the field and individual bedform dimensions observed during the present investigation may suggest that less medium-grained sediments are available for transport within the estuary. This may be transient feature, resulting from the abstraction of significant quantities of sediments during the capital dredging operations which took place few months before the sonograph survey.

Suspended Particulate Matter (SPM) concentrations in Southampton Water range between 2 and 50 mg/l under normal hydrodynamic conditions; these concentrations can rise considerably under increased wave activity, reaching values between 80 and 140 mg/l (Lecouturier, 1995). There is also some evidence to suggest a tidal signal in the SPM concentrations (Figure 2), which agrees with observations showing increased shear (and SPM resuspension) within the water column during the change of the tide in the main estuarine channel (Sharples, 2000). Unfortunately, as there is no information of sufficient spatial and temporal resolution, the (scalar) SPM fluxes in and out of the estuary can not be estimated.

The analysis of the hydrodynamic and turbidity time-series collected over the tidal flats (Figure 1) showed some interesting characteristics. First, current speed and turbidity are poorly correlated (see Figure 4), with the stronger ebb currents associated consistently with low turbidity. These observations do not support the results of a rough estimation of the resuspension potential of the tidal flat sediments (based on the flow data and simple assumptions regarding the near-bed flow structure, bed roughness and sediment nature and grain-size distribution), which showed that the flow present should be sufficient to suspend the bed sediments during most part of the (immersed) tidal cycle. Secondly, the near bed turbidity was found to be higher (by a factor of, at least, 2) during the early stages of the flood. Thirdly it appears that the sediment fluxes from the intertidal flats is towards the fringing saltmarshes during the early flood.

The processes involved in the sediment suspension and transport over the tidal flats appear to be complicated. The fact that the highest turbidities are observed during the young flood, when the currents are relatively weak (Figure 4), suggests that the SPM (i) is advected to the intertidal flats from the adjacent deeper water environments; and/or (ii) consists mostly of very fine-grained material ('fluff') deposited during the final stages of the ebb and resuspended immediately after the tidal invasion of the flats. In any case, it appears that the tidal currents alone may not be able to suspend the main body of the intertidal sediments in large quantities. However, short turbidity time-series from the deeper estuarine environments (Lecouturier, 1995), together with visual observations indicate that the low erodibility of the tidal flat sediments may increase considerably during high wave activity. Unfortunately, there are no suitable data sets in such conditions, as: (i) the available measurements are of lower frequency (0.5 Hz) than that required to study the high frequency estuarine waves (both natural and human-induced (from shipping through the navigation channel); and (ii) the July experiment was carried out during calm weather and the March time-series were collected along the protected (western) side of the estuary). Therefore, the effect of the waves on sediment erosion and transport cannot be evaluated on the basis of the available field information. However, as this effect may be significant and its parameterisation

could provide a valuable insight into the estuarine morphodynamics (e.g. higher wave activity may explain the preferential sediment aggradation along the western (protected) part of the estuary) SOES has planned to collect such information in the near future. Finally, the high turbidities associated with the inshore currents of the young flood and the shear flows (Figure 4) across the flats may explain both the 'healthy' accretion rates on the marshes (Long & Tooley, 1995; Cundy & Croudace, 1995) and the erosional trends of the tidal flats (see also Section 3.1).

Sediment transport simulations provide a powerful tool to expert analysis models, as they provide 'backbone' information for the development of 'bottom-up' morphodynamic models. In the case of Southampton Water, such simulations are provided by the various sediment transport models constructed by the ABP Research over the area (see Price & Townend, 2000). Generally, these models show that: (i) the different sediment modes entering the estuary are characterised by differential net transport, with the fine-grained sediments moving upstream and the medium-grained sediments transported downstream; (ii) there is a re-circulation of the medium-sized sediments in the vicinity of the tidal inlet; (iii) the superimposition of waves may change considerably the energy and sediment transport (in terms of both magnitude and direction) along the coastal environments of the estuary. It has to be noted here that, although these models have not been validated as such, there is some morphological and sedimentological evidence to support their results. For example, the upstream net transport of the fine-grained sediments is supported by the general (accretional) trends in the upper estuary (downstream section of the Test River, see Price & Townend, 2000), whereas the downstream transport of sand and its re-circulation around the tidal ebb delta is supported by side-scan sonar observations (see above). On the other hand, the grain-size trend analysis carried out in the area (Algan, 1993) indicate opposite trends in the direction of net sediment transport in the upper section of the estuary (Figure 6). A re-examination of the Algan's (1993) trends undertaken during this investigation suggests, however, that these results may be suspect, as the spatial resolution of the original sediment samples and the indiscriminate trend comparisons between different sedimentary

environments may have limited significantly their accuracy.

The field observations highlighted some particular limitations regarding the available sediment transport models, which may also compromise significantly the accuracy of sediment (bedload and resuspension) transport (and associated morphodynamic) predictions. The realistic calibration of such models requires good (in terms of spatial resolution) information on the bed (surficial) sediments; this is not the case in Southampton Water (see above). Moreover, the side-scan sonar information showed that most of the estuarine bed is artificially scoured (Figure 5). It has to be noted here, that these limitations are not unique to the Southampton Water models, as good sedimentological information (such as full-coverage side-scan sonar information) is rarely available. As, however, intensive bed usage is likely in most industrialised estuaries, particular caution must be taken when bed friction factors in sediment transport models are set.

3.4. Water Quality and Biology

As space constraints do not allow the, in depth, discussion of the substantial information available for the area, only a brief summary will be presented here. Generally, Southampton Water can not be regarded as a eutrophic environment according to the criteria set in the European Directive on Urban Wastewater Treatment; nutrient inputs are generally moderate and phytoplankton blooms tend to be short-lived. In addition, no excessive growth of pollution related macroalgae (e.g. *Enteromorpha* spp. and *Ulva* spp) is observed, in contrast to other estuaries of the area (i.e Langstone Harbour, see Montgomery *et al.*, 1985). The riverine nutrient discharges to the estuary are dominated by (agricultural) nitrate (NO_3), the concentration of which has increased by 25% in the last two decades (Hydes & Wright 1999). In contrast, phosphate (PO_4) levels have declined since their peak in the late 1980s and Ammonia (NH_3) and nitrite (NO_2) levels are generally low. Nutrient behaviour in Southampton Water itself is conservative, although summer nutrient depletion occurs near the inlet in response to increased biological production in this area. In terms of oxygen concentration: (a) levels are greater in winter (~6-8 ml/l) and minimum in summer (4.5-5.5 ml/l); (b) there is a general seaward increase; and (c) the estuary is well-stratified, although

differential water column saturation has been lately observed in the upper estuary during red tides.

Estuarine turbidity is higher during the autumn/winter season, increasing in an offshore direction (Hirst, 1996). However, significant (but brief) turbidity increases occur also during the summer in the mid- and upper-estuary, due to dense blooms (red tides) of the phototrophic ciliate *Mesodinium rubrum* (Crawford *et al.* 1997). During these periods, Chl-*a* concentrations may reach 300 mg/m^3 , resulting in very rapid light attenuation in the water column (to <10% of the surface values at 1 m below the surface), progressive decline of the oxygen levels in the water column and severe NH_3 depletion. Regarding the impact on the biological community, the accompanying increases in bacterioplankton biomass may provoke immunological responses in the molluscan populations. Generally, biological production in Southampton Water appears to be controlled by the hydrodynamic energy. Spring-neap variability in the water column stability determines the evolution of phytoplankton blooms; these occur mostly during periods of neap tides (Hydes & Wright, 1999). Shorter period variability in Chl-*a* concentrations have been also observed, due probably, to: (i) vertical diurnal migrations of certain species; (ii) *in situ* growth; and (iii) resuspension of benthic microalgae during the energetic part of the semi-diurnal tidal flow (Lauria *et al.*, 1999). The average annual primary production has been estimated as $25.4 \text{ mg C/m}^3/\text{yr}$ and $12.8 \text{ mg C/m}^3/\text{yr}$ at the estuarine mouth and $62.0 \text{ mg C/m}^3/\text{yr}$ and $31.2 \text{ mg C/m}^3/\text{yr}$ in the mid-estuary region for the coarse (>10 μm) and fine (<10 μm) size fractions, respectively. An interesting feature is the upstream increase in mesozooplankton abundance; this may be related to the larger benthic populations in the upper estuary associated with the presence of numerous man-made structures suitable for epifaunal growth.

Finally, although there have been no detailed studies relating to the biological controls on the geomorphological development of Southampton Water, there is some evidence that these might be significant. For example, some recent studies (e.g. Darnsfeld, 2000) have demonstrated that the (spatial and temporal) variability of diatom (and other) benthic communities present on the Hythe

tidal flats may affect significantly the surficial sediment cohesion (and, thus, erodibility). These effects might explain the increased resistance to surficial sediment erosion observed during the tidal flat monitoring (see Section 3.3). However, more information is required in order to assess these effects.

4. SYNTHESIS AND CONCLUSIONS

In this Section, the results of the study are summarised; particular reference is also made to the limitations of the analytical techniques used. As these limitations are thought not to be unique to the studied estuary, they should be taken into consideration when such analysis is used to identify characteristics and predict trends in the morphological estuarine development.

Although Southampton Water is a channel-like ria, is characterised by asymmetric (in terms of lateral extent and thickness) fringing sedimentary environments (i.e. tidal flats and saltmarshes), with the western side of the estuary being the locus of estuarine deposition during most of the Holocene. This differential sedimentation suggests that hydro- and sediment dynamic gradients were introduced during the 'roll-over' estuarine phase. The possible presence of such gradients should be taken into consideration, when 'top-down' models are used to study estuarine evolution as they may introduce further constraints (in addition to those set by the antecedent morphology) to the models.

The analysis of the historical morphological evidence showed that the tidal flats of the estuary are under erosion; this may be in response to changes in the supply of sediments into the estuary, or changes in the hydrodynamic regime and corresponding dynamic distribution of sediments. Both changes might be related to either: (i) anthropogenic influences, such as changes in the land usage in the riverine catchments, abstraction of fine-grained sediments from the deeper estuarine environments during navigational dredging and increased wave activity due to high tonnage shipping through the estuarine channel; and/or (ii) 'natural', large-scale changes in the hydrodynamic regime in the recent decades (e.g. increase of the wind-wave activity due to North Atlantic Oscillation?). In contrast, the Southampton Water saltmarshes can be characterised as 'healthy', as their accretion rates appear to exceed (or, at least, keep pace with) the relative sea-level rise in the area. This

may be related to the particular sediment transport patterns identified over the estuarine fringing environments (i.e. the onshore currents during the young flood coincide with the greater SPM concentrations resulting in net onshore fluxes of SPM).

Comparison of the morphological changes identified using historical bathymetric data sets with the remainder of the available information (Section 3.1) highlighted some of this technique's limitations; these are related to: (i) the quality/resolution of the available information; and (ii) the accuracy of the data interpolation methods used prior the comparison. It appears that although the 'chart differencing' technique can be a powerful (and sometimes the only available) diagnostic/predictive tool for the establishment of long-term trends in estuarine development (and morphological model validation), it should be used with caution.

Sediment transport simulations are basic components of bottom-up and 'hybrid' morphological models. However, these simulations require rigorous calibration and validation, in order to model realistically the sediment fluxes within and in and out of the estuaries. The present study highlighted some of the calibration difficulties, which are associated with the limited availability of information on the textural characteristics and sedimentary morphology of the estuarine bed. For example, a full-coverage side-scan sonar survey of the mid- and upper section of Southampton Water showed that the present sedimentary morphology of the sub-tidal areas has been extensively influenced by human activities. This not only suggests that the natural (bed) sedimentary processes of this particular estuary can hardly keep pace with human-induced 'scouring', but also that particular caution should be taken when the magnitude and distribution of bed friction factors are set in sediment transport models of industrialised estuaries.

Finally, the study showed that strong relationships exist between water quality/biology and hydrodynamics in Southampton Water. There is also evidence to suggest strong interactions between biological factors and sedimentary processes, particularly over the fringing environments of the estuary; these are currently under investigation.

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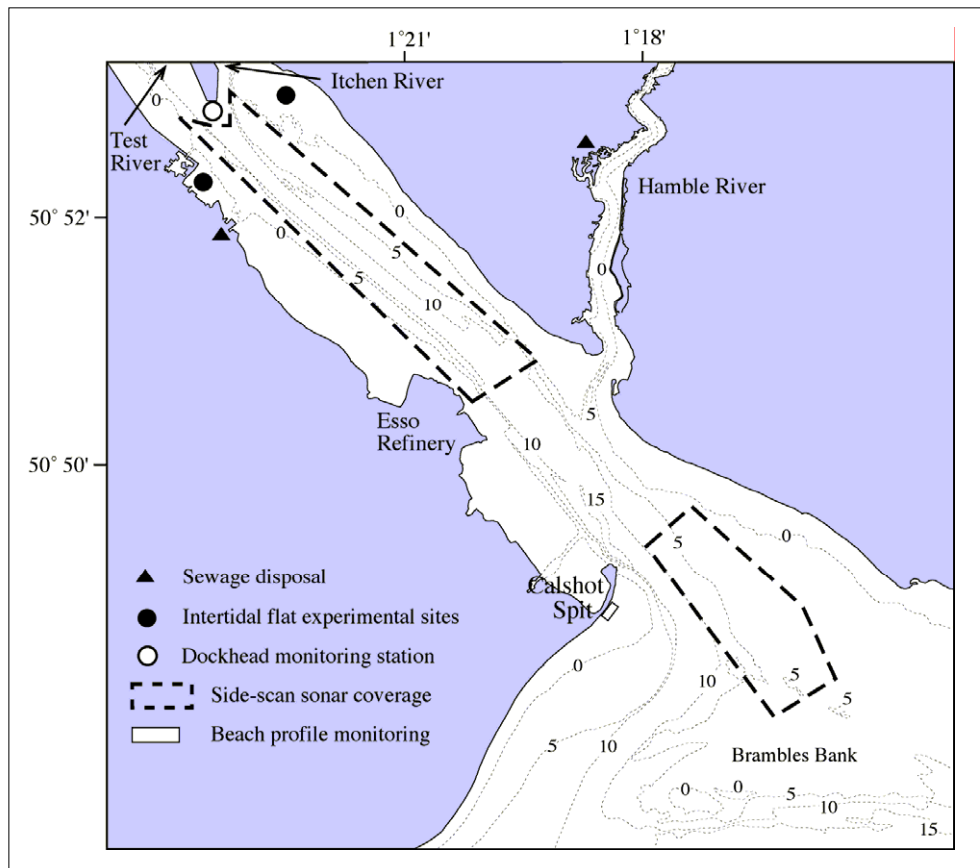


Figure 1 Location map of Southampton Water, showing the reclaimed areas and the experimental sites. The bathymetry is based on a compilation of bathymetric data from the EMPHASYS 1996 data set (for the inshore areas) and the most recent Admiralty Chart for the area around the tidal inlet.

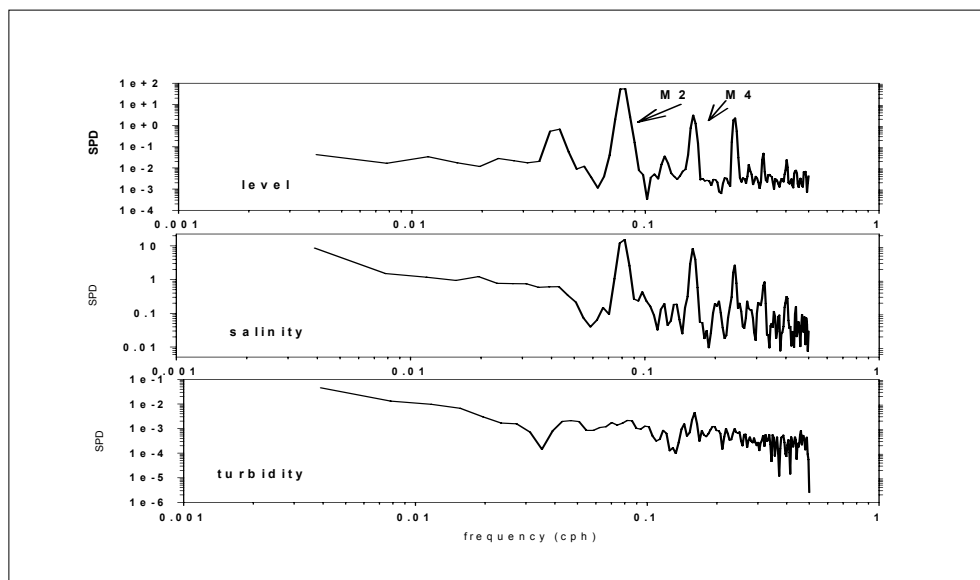


Figure 2 Tidal elevation, salinity and suspended sediment concentration (in standardised engineering units) spectra from the Dockhead monitoring station. Note the (significant) spectral peak of the turbidity associated with the M4 constituent. Harmonic analysis (using the Bell *et al*, 1999 software) of month-long sections of a 6-month time-series from the Dockhead monitoring station showed that the tides are coherent. The mean amplitudes and phases of the dominant constituents were estimated as: M2, 1.32 m and 326°; S2, 0.4 and 12°; K1 0.09 m and 116°; O1, 0.03 and 318°; M4, 0.25 m 18°; and M6, 0.20 and 141°.

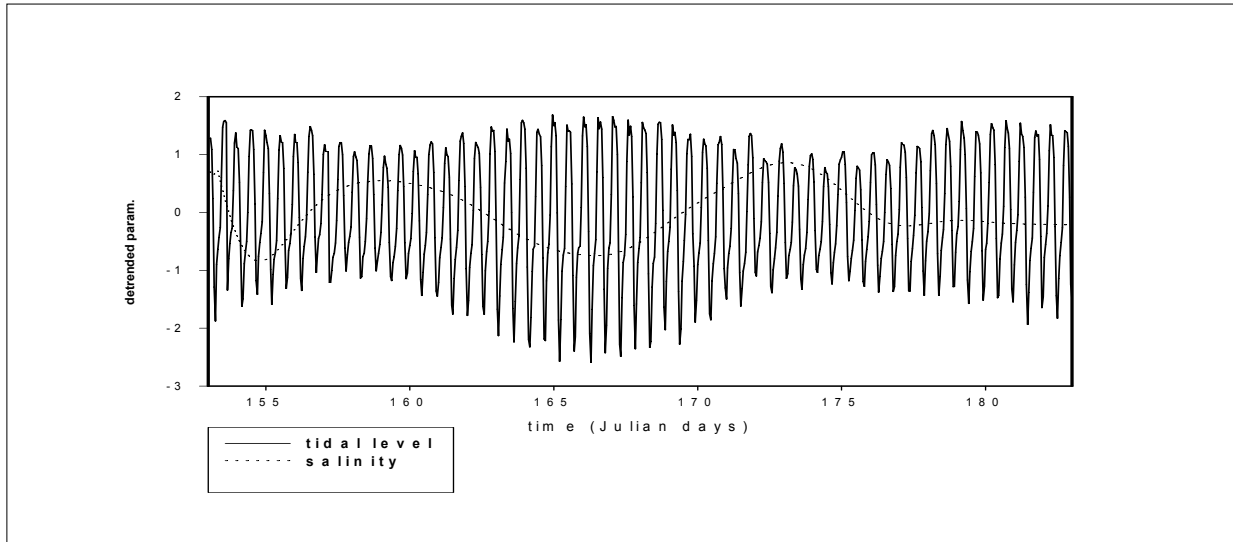


Figure 3 Water levels and corresponding salinity (filtered with a low-pass filter) at Dockhead, in June 1999. Note the asymmetry between the flood and ebb phases of the tide (the ebb being much shorter), the presence of double high waters and young flood stands. Note also the inverse relationship between tidal range and salinity, which is due probably to the higher mixing of the water column during the more energetic spring tides.

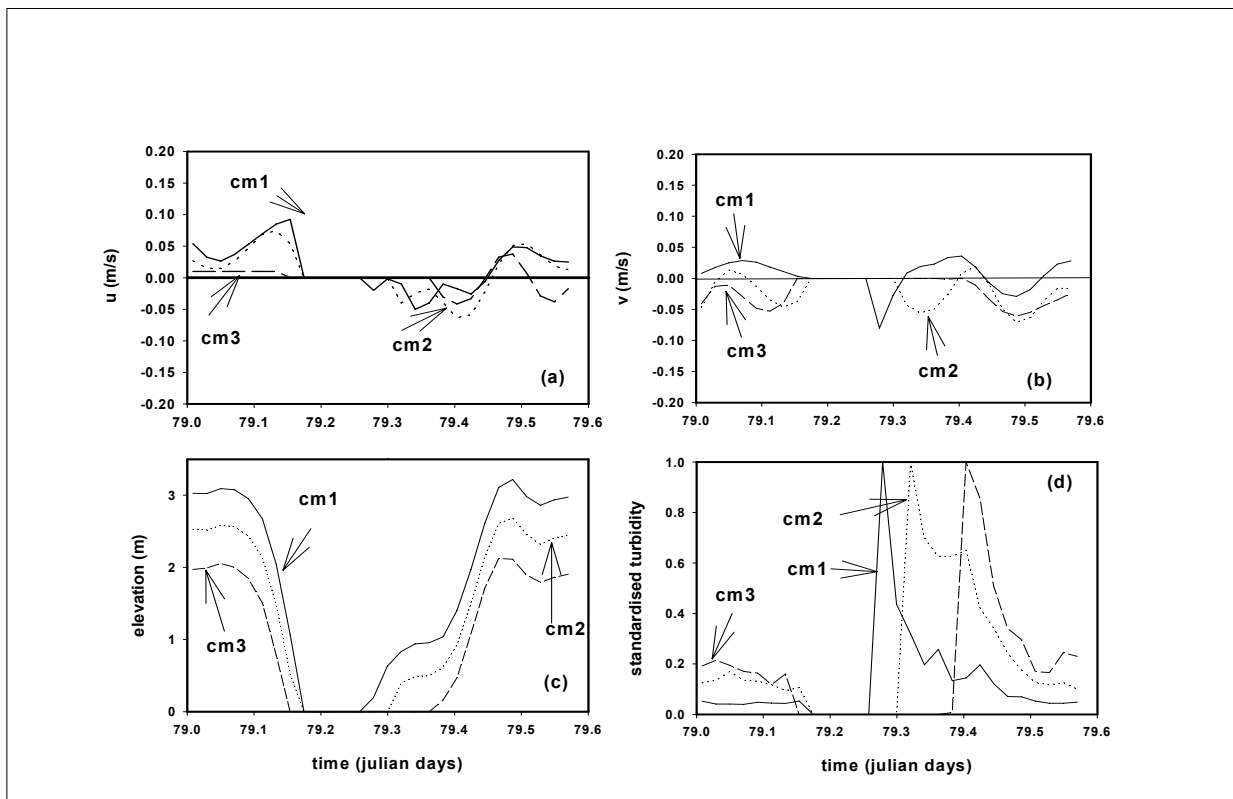


Figure 4 Flow and suspended sediment characteristics along a transect across the Hythe tidal flat: (a) cross-estuary currents at 15 cm above the bed (u positive towards the estuarine channel); (b) currents along the estuary at 15 cm above the bed (v positive towards the head of the estuary) (c) water level; and (d) standardised turbidity 20 cm above the bed. Key: cm1, lower flat; cm2, middle flat; cm3, upper flat. Note the offshore direction of the currents during the young flood, the horizontal flow shear between the lower and middle flat during the same period and the high turbidity associated with the early flood.

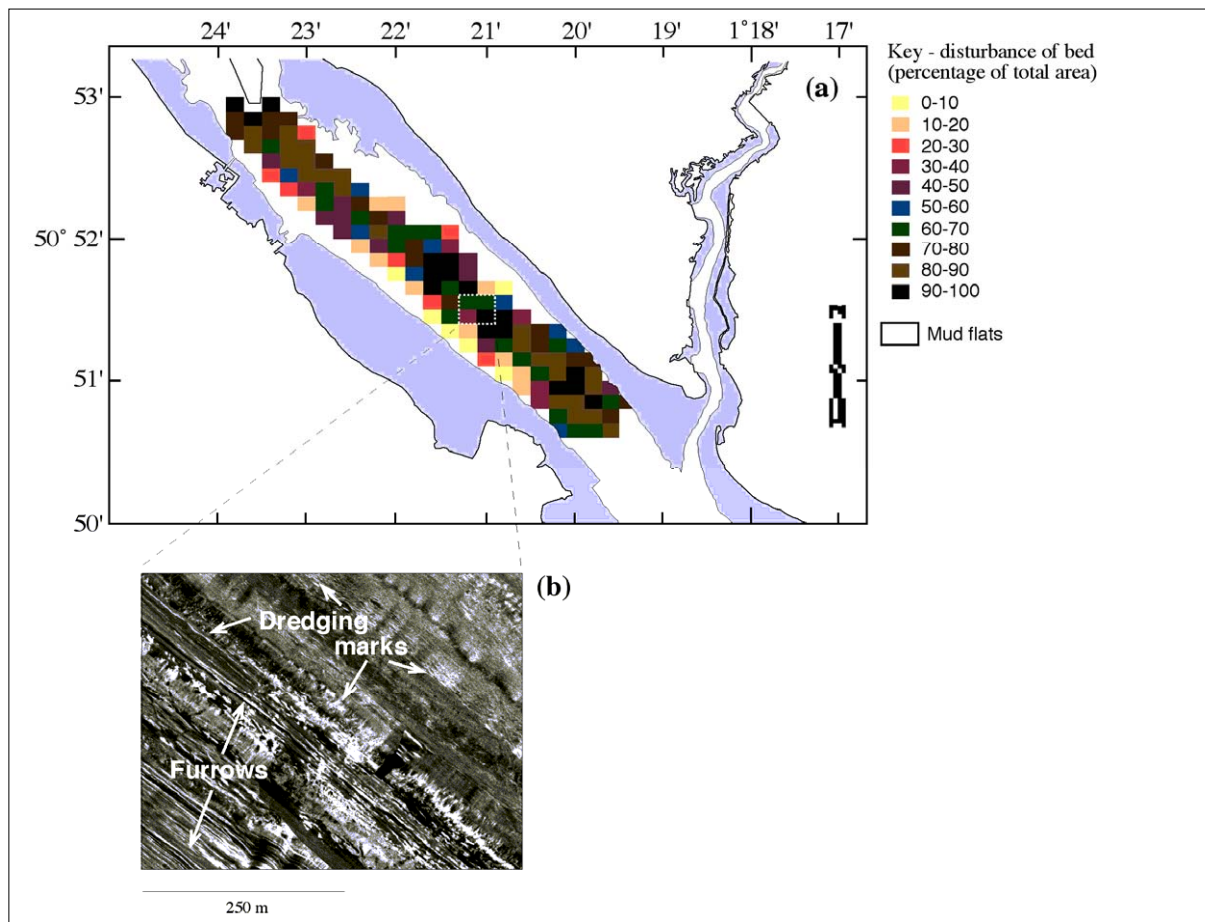


Figure 5 (a) Distribution of artificial disturbance on the sub-tidal areas of the upper section of Southampton Water, expressed as percentage of the total area. The map is based on a full coverage side-scan sonar survey (courtesy of the Challenger Division, SOC). The relief of the scour marks ranges from 0.2 to more than 1 m. (b) sonograph detail of bed morphology.

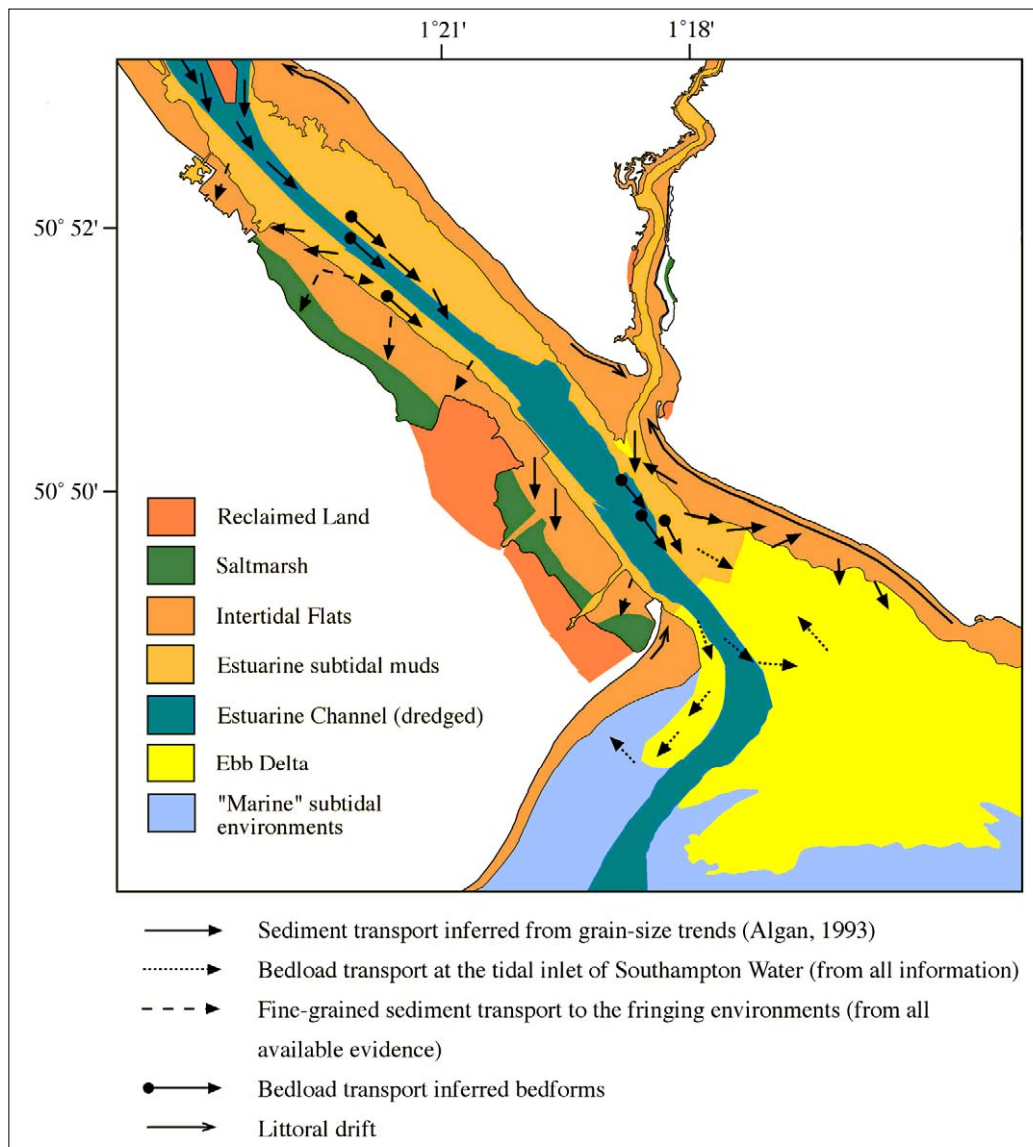


Figure 6 Sediment transport pathways in Southampton Water, based on a variety of sources and analytical methods.

SHAPE-SED

A MODEL LINKING ESTUARY VARIABLES WITH SEDIMENT COMPOSITION

John Goss-Custard

email: J.D.Goss-Custard@exeter.ac.uk

Centre For Ecology and Hydrology Dorset, Winfrith Technology Centre, Newburgh Road,
Dorchester, Dorset, DT2 8ZD, UK

1. OBJECTIVES AND APPROACH

The objectives of the research summarised here were to survey the intertidal sediment composition of a sample of contrasting British estuaries; quantify variables measuring the estuary size, shape, shore width and tidal range, together with position and exposure to gales of individual areas within each estuary; to develop equations which relate the sediment composition of an entire estuary, and areas within it, to these variables.

The motivation of the research, which was carried out under contract to the Energy Technology Support Unit in 1994-95, was to find ways of predicting the effect on the surface sediments of the construction of a tidal barrage. Reliable predictions of how tidal energy schemes might affect the sediment composition of the intertidal zone are difficult to obtain. The usual approach is to build bottom-up models for the particular estuary under consideration. Such models are necessarily quite simple and do not yet include the possibly highly significant influences of plants and fauna on sediments. Undoubtedly, these models will eventually improve and become more general in their implications. But, in the meantime, estimates of changes in sedimentation may still be required if we are to predict the effects of barrage construction on the ecology of an estuary, and particularly the habitats of shorebirds for which estuaries are of such importance. The essence of the approach used here is that it is empirical and measures directly the sediment composition of estuaries, and so automatically includes any effects of biotic factors.

2. METHODOLOGY

This study related the intertidal sediment composition of a sample of 25 contrasting estuaries to the environmental characteristics that were thought likely to determine sediment behaviour. These environmental variables include estuary size, and thus shore-width, exposure to gales and the tidal range. Within an estuary, sediment will additionally be influenced by shore-level and position up the estuary. All these variables were thought likely to directly or indirectly affect the rates of erosion and

deposition of sediment particles of different sizes. Because the effect of barrage construction on these environmental variables can be more easily foreseen, the results of the study were believed to allow their effects on the intertidal sediments, and thus habitat ecology, to be predicted.

The sediment composition of each of 22 estuaries was determined by analysis of airborne thematic mapper imagery acquired by NERC's aircraft for this project; that of three other larger estuaries was determined from LANDSAT satellite imagery held in archive. All imagery was acquired in cloud free conditions and within a period 2.5 hours either side of the time of low water to ensure that the intertidal areas were fully exposed. Each estuary was visited to locate and map uniform and representative areas of each sediment type. Samples of sediment were taken so that the sediment particle size distribution of each area could be accurately determined. These areas were used to determine the spectral signature of each sediment type within the imagery, from which the sediment composition of every count polygon could be determined. The overall accuracy of the sediment classification from the imagery was at least 90% for each sediment type. Areas classified as non-sediment, such as bare rock, shingle and especially saltmarsh, were excluded from all the analyses. The sediment area was classified into three major types according to the percentage of particles by dry weight which were less than 63 μm ; mud (>50%), sand (<20%) and muddy-sand (20-50%).

The environmental variables for each whole estuary were measured from Ordnance Survey maps and tidal range was extracted from published tables. Because the imagery provided the most up to date information on estuary topography, the count polygon outlines were superimposed on the imagery and the polygon-specific environmental variables were measured directly from the imagery.

Correlation and multiple regression statistical analyses were used to assess and quantify the relationships between the environmental features and the proportion of sediment area which was mud

or which was sand. Separate analyses identified the factors associated with whole-estuary sediment composition and those associated with variation in sediment type within each estuary. The findings were then integrated to derive predictive equations for the amount of mud and sand in any intertidal area of any estuary.

3. RESULTS

The main findings of the research were :

- Estuaries on the east and south coast of Britain (Ythan - Tamar) are, in general, much muddier over their whole intertidal sediment area (average 66% mud, 9% muddy-sand, 25% sand) than estuaries on the west coast, which are predominantly sandy (average 8% mud, 10% muddy-sand, 82% sand).
- The best simple correlate of whole-estuary sediment composition for all estuaries, independent of geographic region, was estuary shape (ESHAPE1), defined as estuary length divided by maximum width of the estuary. Estuary shape was correlated with mean shore width which itself was also a good predictor of sediment composition. Although estuaries on the west coast had some tendency to be relatively wider in shape and had, on average, shores twice as wide as elsewhere, both estuary shape and shore width were even more highly correlated with sediment composition within the east and south coast estuaries alone.
- Lack of variation in whole-estuary sediment composition on the west coast estuaries made it more difficult to identify any environmental correlates for the west coast.
- Mean spring tidal range (ETRANGE) was higher on the west coast, where intertidal sediments were sandier. Moreover, on the east and south coast estuaries, there was both less mud and more sand on the estuaries with the highest tidal ranges. Allowing for the influence of either estuary shape or shore width on these estuaries, there was still some suggestion of a correlation of whole-estuary sediment composition with tidal range. The variable ESHAPE1T, defined as ESHAPE1 divided by ETRANGE, gave the best relationships with whole-estuary sediment composition (Figure 1).
- Within several individual estuaries, sediments were shown to be sandier, and conversely less muddy, further down the estuary, further down the shore and in area exposed to long wave

fetches. Unsurprisingly fetch was higher nearer the mouth of estuaries.

- Median fetch tended to be higher for west coast estuaries. Because fetch is correlated with estuary shape and shore width, increased fetch may be one of the underlying factors causing the relationship between sediment and these two factors. Median fetch is a good predictor of whole-estuary sediment composition. Fetch appears to have no increased effect above about 10km.

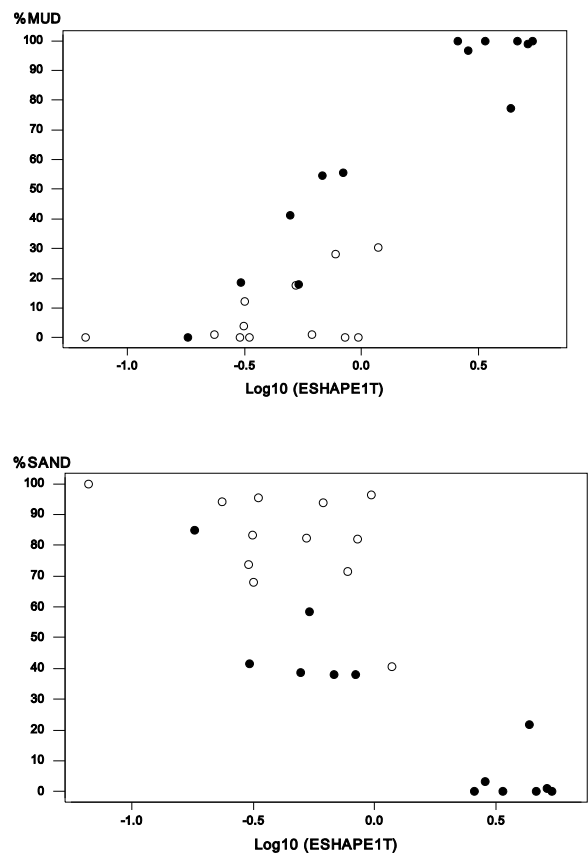


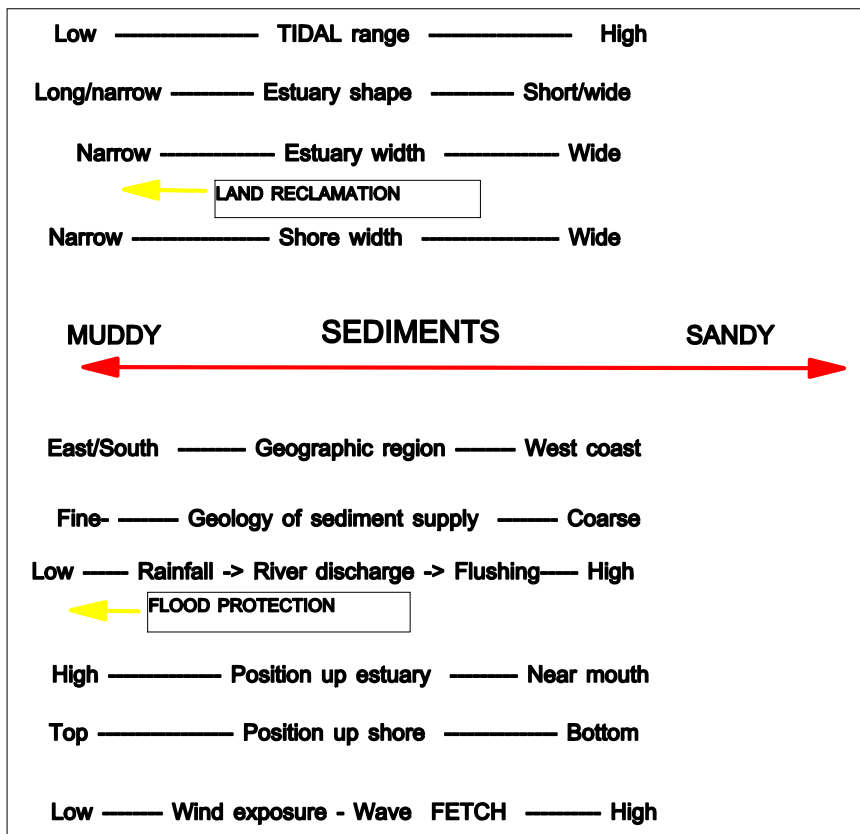
Figure 1 Plot of the percentage intertidal sediment area in each estuary which is mud (%MUD) or sand (%SAND) against the logarithm of ESHAPE1T; where ESHAPE1T is estuary shape divided by mean spring tidal range (m).

● and ○ denote the 13 east/south coast and the 12 west coast estuaries respectively.

4. CONCLUSIONS

The main conclusions from this study are that the overall sediment composition for whole estuaries, in terms of the proportional cover of mud and sand, appears to be predicted reasonably well from simple measures of the estuary shape, average shore width and tidal range. Estuary shape and shore width are both correlated with wave fetch and tidal range, which we believe represent the major influences

operating within estuaries. There are strong regional differences in intertidal sediment composition, with far less mud on west coast estuaries, which may be partly due to unmeasured differences in sediment geology and catchment discharge. Position up the estuary, distance down the shore and wave fetch can influence the pattern of sediments within estuaries. These relationships are summarised in the box below:



To predict the effects of building a tidal energy barrage, it is necessary to estimate how the values of these environmental variables will be changed by the barrage. Separate modified values are likely to be needed for upstream and downstream of the barrage. It not clear how to measure the new estuary length involved in the shape variable for this type of analysis. It was therefore suggested that separate predictive equations involving mean shore width and tidal range be used for whole-estuary predictions in each geographic region. For within-estuary predictions, these variables should be used in conjunction with position up the estuary, distance down the shore and fetch. Similar decisions and judgements would have to be made were this approach to be used to predict the intertidal habitat consequences of changes in estuary morphology brought by means other than barrage construction.

INTER-RELATIONSHIPS BETWEEN TIDAL DYNAMICS, SEDIMENT AND SALINITY REGIMES AND BATHYMETRY IN ESTUARIES

David Prandle

email: dp@pol.ac.uk

Proudman Oceanographic Laboratory, Bidston Observatory, CH43 7RA, UK

ABSTRACT

Generalised solutions are derived to indicate values, over a range of tidal elevation amplitudes $\hat{\zeta}$ and water depths D , pertaining at any section of an estuary, for: tidal current amplitude \hat{u} ; ratio of friction to inertial terms; slope of the estuarine bed; estuarine length; rate of energy dissipation and phase difference between $\hat{\zeta}$ and \hat{u} . These results provide reference frames that can be used to estimate likely sensitivities of conditions in any specific estuary. The solutions indicate the range of parameters consistent with quasi-equilibria of bathymetries in dynamic sedimentary regimes.

Sensitivity of the solutions to changes in: bed friction coefficient, mean sea level, localised water depth and coastal forcing conditions are examined. These analyses indicate the nature of changes in the shape and size of an estuary that might follow from variations in the prevailing tidal and sedimentary regimes.

Maximum tidal current amplitudes are shown to seldom exceed $1\text{--}2\text{ m s}^{-1}$, effectively controlled by bottom friction in water depths of less than about 10 m. Spatial uniformity of tidal current amplitudes is shown to be consistent with bathymetric stability.

The expression for estuarine length is sensitive to the specification of the bed friction coefficient. Calculated lengths are consistent with a range of observed values. Moreover the scatter of these observed values can be related to the influence of their prevailing sediment regimes on their respective bed friction coefficients.

Compared with fine sediments, the maximum (depth-averaged) concentrations of coarser sediments are smaller and more sensitive to both tidal range (order third power) and bed friction factor (squared).

Indications are given of the maximum, time and depth-averaged, suspended sediment concentrations as a function of sediment size and tidal velocity. These enable estimates to be made of the degree to which conditions in any estuary are 'supply limited'. Likewise the corresponding values of half-lives of individual particles in suspension are shown – these values indicate the likely impact on both light occlusion (limiting primary production) and transport of adsorbed contaminants. Combining these with typical tidal velocities indicates the likely scales of their impacts on bathymetric stability – typically a few kilometres for coarser sediments and greater than 10 km for fine material.

Energy considerations can be used to show that estuaries must, in general, be much smaller than the Bristol Channel, which dissipates $\sim 10\%$ of the net tidal dissipation of the North West Shelf Seas.

A subsequent study will consider the likely rates of temporal adjustments in bathymetry suggested by these sensitivity analyses. This latter point reflects the notion that the bathymetry of many estuaries represents a quasi-equilibrium with the existing dynamics, i.e. an approximate balance in sediment movements existent over the tidal, spring-neap or even seasonal cycles, co-existent with slower longer-term adjustment to climate change (glacial over-deepening) or reconfiguring following extreme event (fluvial, storm surge, tsunami etc).

1. INTRODUCTION

The aim here is to complement the wide-ranging model evaluation programme, carried out by partners within the EMPHASYS consortium, by providing broad-scale descriptions of dynamics, transport and mixing (of sediments and related ‘tracers’) within estuaries. The goal is to encapsulate these descriptions within frameworks that characterise the relative importance of differing processes within any specific estuary – thereby enabling end-users to interpret the assessment of existing models carried out in the EMPHASYS programme in terms of applicability to the estuary in question. Likewise, related sensitivity analyses indicate which parameters need to be considered most carefully.

Section 2 outlines the range of tidal dynamics and associated sediment regimes to be anticipated at any single point within an estuary – based on ‘analytical’ theory. Section 3 relates these ‘point values’ to conditions found over a range of estuaries – based on numerical simulations over a wide range of estuarine shapes and sizes and tidal regimes. Section 4 considers sensitivities of these results to changes in various external forcing, internal conditions and model parameterisations. Section 5 evaluates these new results against conditions in 25 UK estuaries.

2. TIDAL DYNAMICS AND SEDIMENT REGIMES

The tidal dynamics of estuaries can be readily explained from analytical solutions (Prandle and Rahman, 1980) and accurately simulated using 1-, 2- or 3-D numerical models. These dynamics are determined by estuarine bathymetry, the converse question of the dependency of bathymetry on tidal forcing is considered here.

The analytical solutions, derived here, assume tidal forcing predominates and can be approximated by a single semi-diurnal tidal constituent. Moreover we are especially concerned with shallow frictional-dominated estuaries. (Recent studies of UK estuaries predicted that the analytical solutions derived by Prandle and Rahman (1980) to interpret the tidal response of many (long) estuaries worldwide, may be inapplicable to these shallower estuaries).

2.1. Dynamics

Omitting the convective term from the momentum equation, we can describe tidal propagation in an estuary by:

$$\frac{\partial u}{\partial t} + g \frac{\partial \zeta}{\partial x} + k \frac{u|u|}{H} = 0 \quad (1)$$

$$B \frac{\partial \zeta}{\partial t} + \frac{\partial Au}{\partial x} = 0 \quad (2)$$

Prandle (2001) derived the following relationships for the propagation of the predominant (M_2) tidal constituent in an estuary with steadily varying bathymetry:

current amplitude	$\hat{u} = \hat{\zeta} (1 + F^2 / \omega^2)^{-1/2} \sqrt{2g} / D$
friction to inertia	$F / \omega = 1.46k\hat{u} / D$
sea bed slope	$S = F\hat{u} / \sqrt{2g} / D$
estuarine length	$L = \sum_{x=1,L} D_x - S_x dx$
net energy propagation	$POW = \rho g D \hat{\zeta} \hat{u} \cos \theta$
phase lag of \hat{u} to $\hat{\zeta}$	$\theta = \tan^{-1} F / \omega$

where:

\hat{u} is the amplitude of cross-sectionally averaged velocity in the axial direction x ,

$\hat{\zeta}$ is the amplitude of water level relative to a horizontal datum approximating mean sea level, D is the water depth relative to the same datum, H is the total water depth ($H = D + \zeta$)

k is the bed friction coefficient (≈ 0.0025), g gravitational acceleration,

B is the channel breadth,

t time,

$F = 8(e - 1)k\hat{u} / (3\pi D)$ (Proudman, 1923; §3.2.1), e is 2.718,

ω is tidal frequency.

The dependency of F on \hat{u} in the above equation is solved by successive iteration. The numerical solution for estuarine length, L , assumes \hat{u} remains constant and the summation continues until $D_x < 0$.

2.2. Parameter ranges in tidal estuaries

Figures 1(a–f) illustrate these relationships over a range of elevation amplitudes $\hat{\zeta}$ and water depths D . The ranges selected for $\hat{\zeta}$ (0 to 4 km) and D (0 to 40 m) represent all but the deepest of estuaries.

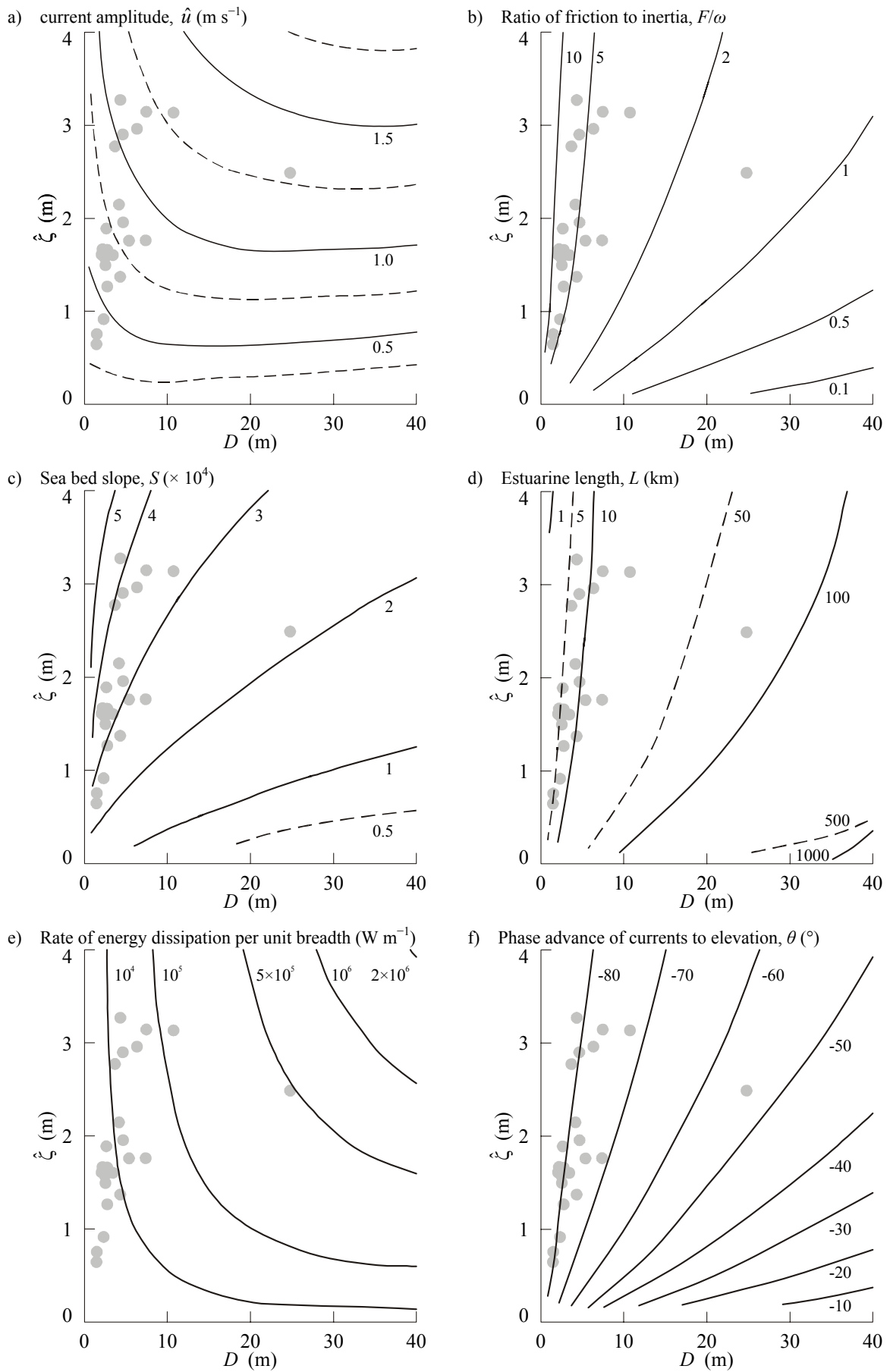


Figure 1. Relationships for M_2 tidal propagation as functions of water depth, D and tidal elevation amplitude, $\hat{\zeta}$. \bullet observations from Table 5

Figure 1(a) shows that the range of current amplitudes extends to 1.5 m s^{-1} . For $\hat{\zeta} \gg D/10$, this current range might increase or decrease by a factor of two over the extreme range of bed friction coefficient βk . This range of \hat{u} accords with general experience. The reduction of $\hat{u}/\hat{\zeta}$ for increasing $\hat{\zeta}$, via bed friction, indicates why, across estuaries in general, the observed range of \hat{u} is smaller than that of $\hat{\zeta}$.

The contours show that maximum value of \hat{u} occur at approximately $D = 5 + 10 \hat{\zeta}$ (m), however, these are not pronounced maxima. Figure 1(b) is discussed in Section 4.1. Figure 1(c) indicates sea bed slopes S up to 5×10^{-4} , corresponding to a minimum estuarine length of L (km) = $2D$ (m). In Figure 1(d), utilising the values of S in Figure 1(c), the length L of an estuary is calculated by successively updating S as D reduced along the estuary (assuming a constant value of \hat{u}).

By assuming $F \gg \omega$, an equivalent simple analytical solution can be determined:

$$D = \left(\frac{3}{2} k \frac{\hat{u}}{\sqrt{2g}} \right)^{\frac{2}{3}} x^{\frac{2}{3}} \quad (3)$$

$$\begin{aligned} \text{or } L &= \frac{D_L^{\frac{5}{4}} \cdot 120}{\hat{\zeta}_L^{\frac{1}{2}} k^{\frac{1}{2}}} \\ &\approx 1960 \frac{D_L^{\frac{5}{4}}}{\hat{\zeta}_L^{\frac{1}{2}}} \text{ for } k = 0.0025 \end{aligned} \quad (4)$$

A similar calculation can be made assuming $\hat{\zeta}$ remains constant,

$$D = \left(\frac{5}{4} \frac{(\hat{\zeta} k \omega)^{\frac{1}{2}}}{(2g)^{\frac{1}{4}}} \right)^{\frac{4}{5}} x^{\frac{4}{5}} \quad (5)$$

$$\begin{aligned} \text{or } L &= \frac{D_L^{\frac{5}{4}} \cdot 4 (2g)^{\frac{1}{4}}}{\hat{\zeta}_L^{\frac{1}{2}} \cdot 5 (k\omega)^{\frac{1}{2}}} \\ &\approx 2350 \frac{D_L^{\frac{5}{4}}}{\hat{\zeta}_L^{\frac{1}{2}}} \text{ for } k = 0.0025 \end{aligned} \quad (6)$$

(units in metres, subscript L denotes values at the mouth). Note that the estuarine shapes (Equations 3 and 5) correspond to values of ν (Prandle and Rahman, 1980) of 1.25 and 1.5 respectively, i.e. in the centre of the range shown of $0.5 < \nu < 3.0$.

The dependency on $D_L^{\frac{5}{4}}/\hat{\zeta}_L^{\frac{1}{2}}$ in (4) and (6) explains the distributions shown in Figure 1(d) with estuarine lengths significantly more sensitive to D than to $\hat{\zeta}$.

Figure 1(e) illustrates the net energy propagation (or net upstream dissipation rate) per unit estuarine width. By way of illustration, the net dissipation in the British Channel is of the order $20 \times 10^9 \text{ W}$, i.e. 10% of the net tidal energy dissipation in the entire NW European Shelf Seas (Flather, 1976). Thus for most of the several hundred estuaries in such seas, a net dissipation of less than 1 GW (10^9 W) is expected. Noting that the cross sectional slope in UK estuaries (Yates et al., 1996) corresponds to $0.005 < \tan \varepsilon < 0.05$, the $2 \times 10^5 \text{ W}$ contour represents an effective maximum likely value.

Figure 1(f) shows the phase lag of tidal currents \hat{u} relative to elevation. For large bed slopes, reflection occurs and $\sin \theta \rightarrow -1$ or $\theta \rightarrow -90^\circ$, i.e. a standing wave. Conversely for a flat bed $\cos \theta \rightarrow 1$, or $\theta \rightarrow 0^\circ$, i.e. a progressive wave.

2.3. Sediment regimes

A first order indication of the likely type (coarse to fine) and extent (supply limited) of sediments in any estuary can be obtained from SPM time-series.

Prandle (1997) (see Section 3.2) showed that the amplitude of the various tidal constituents in the suspended sediment time series corresponds to

$$C_i = \frac{\gamma k \rho |u^n|^i}{D(\omega^2 + \alpha^2)^{\frac{1}{2}}} \quad (7)$$

(See section 3.2.3. for notation, etc.) Thus when $\omega \gg \alpha$, the amplitude of the constituent is independent of α (and hence w_s) and the amplitude of the 15 day constituent C_{Msf} is up to 60 times larger than the quarter diurnal constituent C_{M4} . Conversely for $\alpha \gg \omega$, the amplitude of the constituents is independent of ω and hence the magnitude of C_{M4} approximates that of C_{Msf} . In practice, a range of sediment types are generally present with the resulting concentration time series indicating pronounced quarter diurnal variability mainly associated with coarse particles and a large fortnightly signal associated with finer particles. The effect of advection also introduces, typically, semi-diurnal signals.

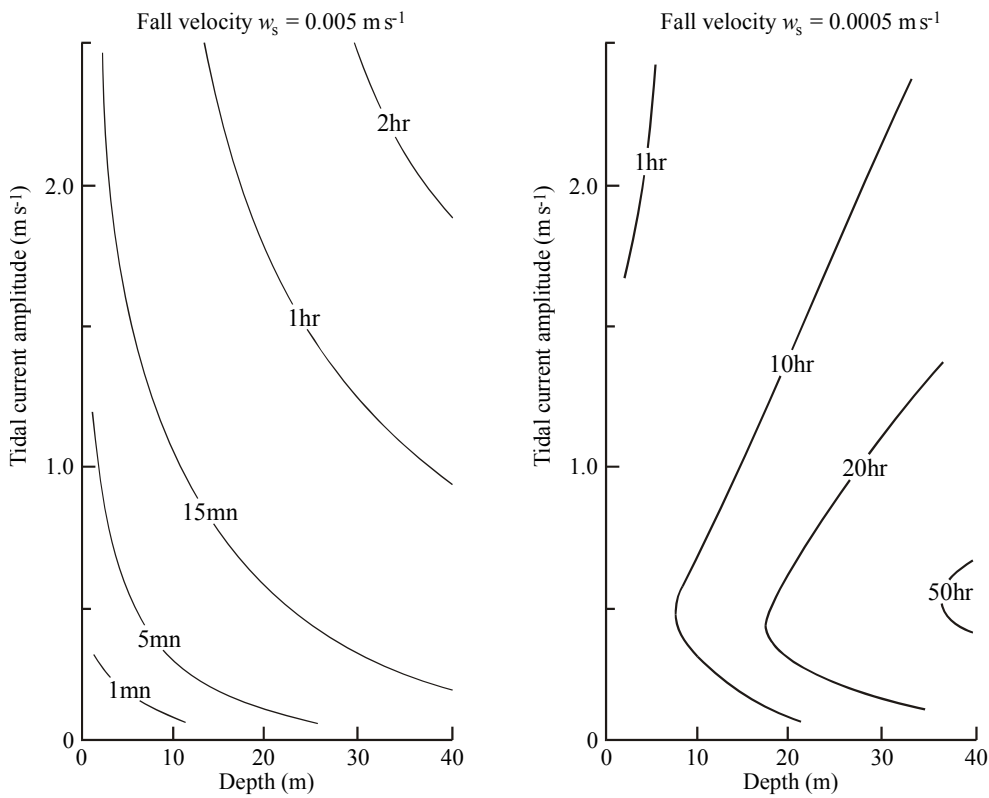


Figure 2 Half-lives ($0.693/\alpha$) of sediments in suspension for a range of water depths D , tidal current amplitudes \hat{u} and settling velocities w_s .

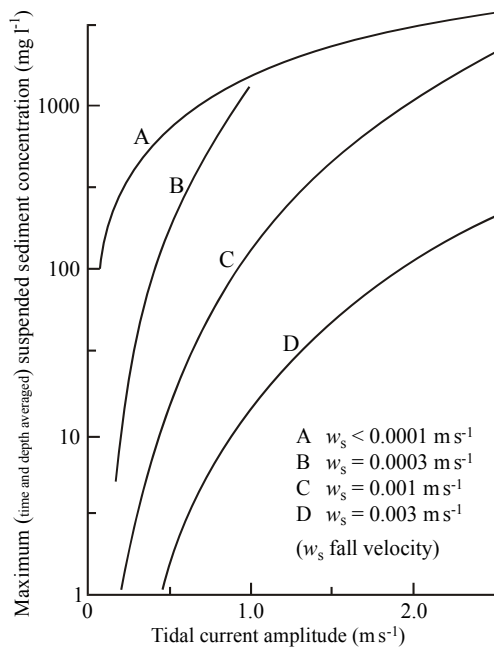


Figure 3 Maximum (assuming full availability) time and depth-averaged sediment concentrations for a range of tidal velocity amplitudes \hat{u} and settling velocity w_s .

From (7) the mean concentration ($\omega \rightarrow 0$) is given by

$$C_0 = 1500\hat{u} \text{ for } w_s D < 0.4 \text{ s}^{-1} \quad (8)$$

$$\text{or } 1.33 \times 10^{-3} \hat{u}^3 / w_s^2 \text{ for } w_s D > 0.4 \text{ s}^{-1} \quad (9)$$

(C_0 in mg l^{-1} , \hat{u} and w_s in m s^{-1}). Both expressions indicate depth-averaged mean concentrations independent of depth. This result indicates that wherever \hat{u} is spatially uniform, relative stability of bathymetry might be expected. For (8), appropriate to finer particles C_0 is independent of the bed roughness k . Conversely for (9), appropriate to coarse particles, C_0 is proportional to k^2 .

Figure 2 indicates typical values of the half-life, $0.693/\alpha$, for a range of water depths, and tidal velocities for two settling velocities $w_s = 0.005$ and 0.0005 m s^{-1} indicative of coarse and fine sediments.

Figure 3 indicates these mean concentrations as a function of u and w_s . We see that mean concentrations for fine particles (where these are available for erosion) generally exceed by orders

of magnitude the concentrations for coarser particles. Moreover the finer concentrations increase linearly with tidal velocity amplitude, \hat{u} whereas the coarser particles increase much more dramatically with both the third power of \hat{u} and the square of k . These greater concentrations of fine particles combined with their much greater half-lives in suspension (Figure 3) suggest that any erratic deepening in part of an estuary is likely to be filled by such mobile, available sediments. Conversely, the limited availability and much shorter half-lives of coarse sediments suggests associated bathymetric impacts are on much more limited localised scales.

3. SIMULATIONS OVER A RANGE OF ESTUARINE SHAPES, SIZES AND TIDAL REGIMES

New frameworks are assembled characterising the range of tidal dynamics, saline and marine sediment intrusions into short and shallow estuaries – typical of UK conditions. These characteristics are derived from 1-D numerical simulations of simplified (cross-sectionally averaged and triangular shaped) estuarine bathymetries.

3.1. Range of UK estuarine conditions

3.1.1. Size and shape

A simple triangular cross-section was adopted. The gradient of the side slope, $\tan \varepsilon$, is assumed constant, the first-order dynamics are unaffected by the value of this gradient. The breadths and (thereby for a constant side-slope) the depths were assumed to vary by some power, n , of axial distance along the estuary. On the basis of Prandle and Rahman (1980), it can be shown that adoption of $n = \frac{1}{2}$, 1 and 2 represent a wide range of shapes (see Figure 4). Moreover an analysis of data pertaining to 25 UK estuaries (Yates et al., 1996) confirms this range of n . Further analysis of this same data set indicates values of $\tan \varepsilon$ varying from 0.005 to 0.05 with a mean of 0.02. Henceforth the value $\tan \varepsilon = 0.01$ is adopted.

Noting from Prandle and Rahman (1980) that few estuaries exceed in length one quarter wavelength, $\lambda/4$, of the predominant M_2 tidal constituent and that few UK estuaries exceed 100 km in length, we adopt lengths, L , of 100,

50 and 25 km with depths, D_0 , at the mouth to correspond to $\lambda/4$ based on

$$L = \frac{2}{n+2} \frac{P}{4} g^{\frac{1}{2}} D_0^{\frac{1}{2}} \quad (10)$$

i.e. wave propagation at \sqrt{gD} and M_2 period, P .

Table 1 indicates the corresponding range of values of D_0 , and of B_0 for $\tan \varepsilon = 0.01$ together with other bathymetric statistics.

Many UK estuaries are much shorter than $\lambda/4$ (the phase difference between M_2 tidal elevation at the mouth and head indicate what proportion of 90° for $\lambda/4$ applies) and their response reflects a shorter portion (from the head) of results shown.

3.1.2. Boundary conditions

Although neap-spring variability in tides may be a significant factor in estuarine bathymetry, for present purposes only the predominant M_2 tidal constituent is considered. The values of river flow, (shown in Table 1) Q_f in $m^3 s^{-1}$, adopted correspond to the estuarine surface area (at mwl) divided by 10^6 – this provides a correspondence with catchment area.

Salinity at the mouth is specified as 35 psu. Here only the influence of sediments of marine origin are considered, the concentrations are prescribed from Equation (7).

3.2. Estuarine simulations

The range of simulations is summarised in Table 1, details of the associated models are summarised below.

3.2.1. Dynamics

The numerical model involved a finite difference solution to Equations (1) and (2) i.e. the cross-sectionally averaged momentum and continuity equations.

The friction term is written as $(e-1)ku|u|/D$ to account for the average value of $1/D$ with D the maximum depth of the cross-section. Generally, river flow has little influence on the first-order tidal dynamics away from the tidal limit. Some examples of tidal current and elevation distributions, for a range of prescribed tidal amplitudes z_M at the mouths, are shown in Figure 4.

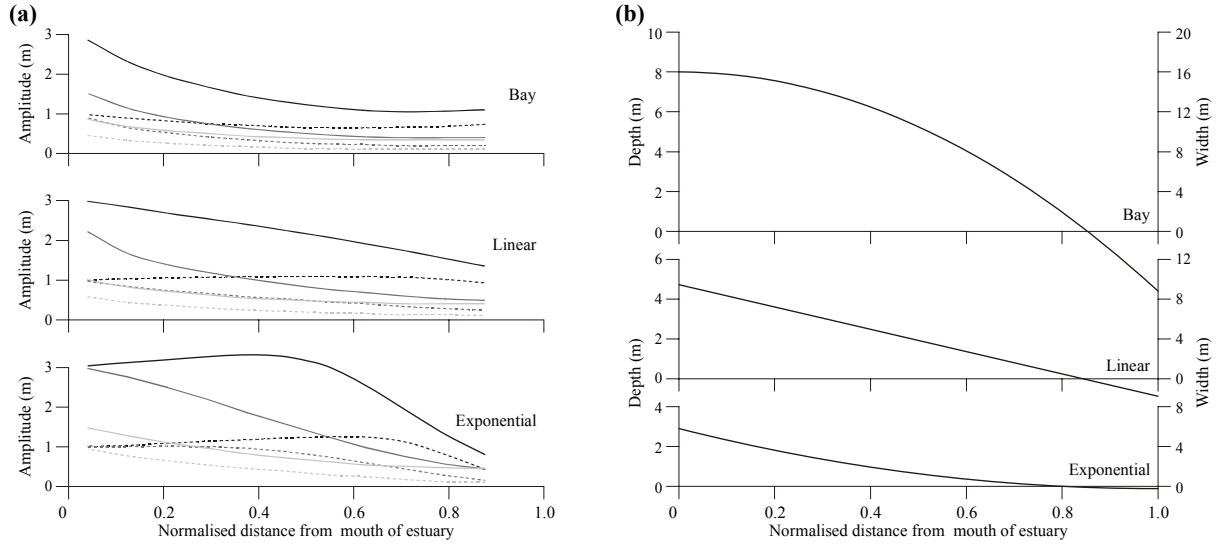


Figure 4 (a) Tidal amplitudes of the M_2 constituent of elevations for the (b) range of estuarine shapes adopted; lengths 100 (black), 50 (dark grey) and 25 km (light grey), depths and widths proportional to $x^{1/2}$, x and x^2 . Tidal amplitude at mouth, $z_M = 3$ m (solid line) and 1 m (dashed line)

The numerical scheme used a grid (ΔX) of 1/60 of the estuarine length with additional sections at the upstream end to allow for variations in tidal intrusion for varying river flows. A time step of 1/1000 of the 12.42 hour M_2 tidal period was used.

3.2.2. Salinity Intrusion

Solutions for the saline intrusion, s , involved introduction of the cross-sectionally averaged conservation of mass equation:

$$\frac{\partial As}{\partial t} + \frac{\partial Aus}{\partial x} = \frac{\partial}{\partial x} AK_{xx} \frac{\partial s}{\partial x} \quad (11)$$

where A is the cross-sectional area and K_{xx} is the longitudinal dispersion coefficient.

K_{xx} is essentially an empirical coefficient which accounts for axial dispersion not described by

the convective term. In stratified estuaries, varying concentration and velocities in different layers can generate appreciable longitudinal mixing. There are many formulations for K_{xx} (especially in tidally-averaged formulations of (11), here we assume

$$K_{xx} \text{ (m s}^{-2}\text{)} = 10D \text{ (m)} \quad (12)$$

or 10 m s^{-2} where $D < 1$ m.

3.2.3. Marine sediments

Solutions for the sedimentary processes of erosion, transport and deposition are also based on Equation (11) but with the incorporation of

$$\text{Erosion } ER = \gamma k \rho u^n \quad (13)$$

where γ is an empirical constant, k the bed stress coefficient, ρ density, u tidal velocity.

The value of n may vary considerably (with corresponding adjustment to γ), here we consider the case of $n = 2$, for which a value of $\gamma = 0.0003$ is found appropriate.

$$\text{Deposition } DP = -\alpha C \quad (14)$$

where C is the concentration and $0.693/\alpha$ is the half-life of sediments in suspension. Prandle (1997) showed that values of α can be approximated by the greater of

$$0.1E/D^2 \quad (15)$$

$$\text{or } 0.7w_s^2/E \quad (16)$$

where E , the eddy diffusivity, can be approximated, in shallow tidal waters, by $k\hat{u}D$ and w_s is the settling velocity. Here we adopt two sediment sizes with $w_s = 0.005 \text{ m s}^{-1}$ and 0.0005 m s^{-1} as indicative of coarse and fine sediments respectively.

Table 1
Ranges of estuarine geometries and river flows adopted.

Shape		Length (km)		
		25	50	100
$n = \frac{1}{2}$	D_0 (m)	0.79	3.15	12.5
	B_0 (km)	0.16	0.63	2.5
	Volume (10^6 m ³)	0.79	25.2	805
	Q_f (m ³ s ⁻¹)	2.6	21.2	170
$n = 1$	D_0 (m)	1.13	4.53	18.1
	B_0 (km)	0.23	0.92	3.6
	Volume (10^6 m ³)	1.10	35.1	1120
	Q_f (m ³ s ⁻¹)	2.9	23.0	184
$n = 2$	D_0 (m)	2.01	8.0	32.2
	B_0 (km)	0.40	1.61	6.4
	Volume (10^6 m ³)	2.11	67.5	2160
	Q_f (m ³ s ⁻¹)	3.4	27.5	220

D_0 depth, B_0 width at the mouth, Q_f surface area/ 10^6

3.3. Results

3.3.1. Dynamic response

A progressive wave propagating in a uniform canal with negligible friction has velocity

$$u = z \cdot \sqrt{g/D} \quad (17)$$

where z is the water level displacement and D water depth. However bottom friction, τ , generally expressed as quadratic in velocity.

$$\tau = \rho k u^2 \quad (18)$$

where $k \approx 0.0025$, severely limits velocities.

Referring to Equation (1), the general solution for a single harmonic constituent, ω is $z = \hat{z} \cos(\omega t - kx)$ and $u = \hat{u} \cos(\omega t - kx)$, requiring

$$\hat{u}(-\omega + \frac{8k|\hat{u}|}{3\pi D}) = -gk\hat{z} \quad (19)$$

where the linearisation of the friction term is based on conserving energy dissipation (proportional to \hat{u}^3).

The contours in Figure 5 show: (a) currents calculated in tidal simulations of the estuaries described in Section 3.2, (b) currents calculated from assuming $g \partial z / \partial x = -k u |u| / D$, (c) the relative magnitude of the friction term to the surface gradient in Equation (1).

3.3.2. Salinity intrusion

Table 2 indicates a wide range of flushing times (F_t) varying from 2 hours to over 2 years. For the latter case, encountered for reduced river flows ($Q_f/10$), effective flushing of tracers introduced from adjacent seas is

Table 2

Flushing times for salinity intrusion for a range of estuary shapes in days. Central F_t is for river flow as Table 1. Values to the left are for $z_M = 1$ m, the centre $z_M = 2$ m, and to the right for $z_M = 4$ m. Values above are for $Q_f/10$, and below for $10Q_f$.

Shape	Length (km)								
	25			50			100		
$n = \frac{1}{2}$	863.			326.			445.		
	21.5	75.7	253.	13.9	22.4	55.1	28.9	33.0	39.4
	2.8			0.4			0.7		
$n = 1$	370.			176.			325.		
	8.5	29.3	106.	9.8	11.8	21.7	22.6	24.2	25.4
	0.8			0.3			0.8		
$n = 2$	9.3			101.			222.		
	3.2	5.8	23.0	7.4	7.7	8.2	15.6	16.9	18.0
	0.1			0.4			0.7		

likely to be via horizontal and vertical circulations, i.e. not directly dependent on river flows. The proportional changes in F_t with river flow always exceed that corresponding (factor of 10) change in Q_f . For the longest (100 km) estuaries, changing tidal elevation amplitudes has relatively little effect. Whilst for the shortest estuaries, the proportional change in F_t exceeds that (factor of 2) in tidal amplitude \hat{z} . Since semi-diurnal tidal elevations can increase by up to 50% on spring tides and decrease by up to 50% on neap tides (relative to mean values), we expect much longer residence times on spring tides in short estuaries. Varying the value of K_{xx} by a factor of 10 and 0.1 showed changes in F_t of typically less than +10% and -10%.

3.3.3. Sediment regimes

Tables 3(a), 4(a) show that estuarine mean concentrations (average of axial profile, not cross-sectionally weighted) are little influenced by river flow. However, the extents of the sediment intrusion are highly sensitive to river flow with the results for the fine sediment closely resembling those for salinity.

By contrast the estuary-mean sediment concentrations are highly sensitive to prescribed tidal range \hat{z} . This proportionality is close to a power of 3 for coarse sediments and 1 for fine, as suggested by Equations (8) and (9) the concentration of fine sediments is an order of magnitude larger than that for coarse sediments. However, for the largest \hat{z} and the smaller estuaries this factor is reduced to a factor of 2–3. The latter result follows

from the corresponding larger values of \hat{u} which lead to distributions dependent on (8) rather than (9) even for the coarser sediment.

Table 3
Computed regime for coarse ($w_s = 0.005 \text{ m s}^{-1}$) marine sediments.

(a) estuarine mean concentrations (mg l^{-1})

Shape	Length (km)								
	25			50			100		
$n = \frac{1}{2}$	113.	427.	1890.	51.2	419.	2330.	28.3	133.	789.
		446.		468.		147.			
$n = 1$	130.	499.	2040.	30.3	288.	2190.	16.9	81.1	426.
		535.		267.		91.5			
$n = 2$	32.9	445.4	2080.	6.3	39.7	380.	1.4	9.6	63.3
		533.		44.1		8.9			

(b) time (years) to fill the estuary by deposition of entire flood tide sedimentary load. Table shows sensitivity to tidal amplitude and river flow as for Table 2.

Shape	Length (km)								
	25			50			100		
$n = \frac{1}{2}$	159.3	15.5	1.0	295.4	53.4	8.0	535.3	87.6	15.6
		16.2		64.4		113.8			
$n = 1$	130.	15.3	1.2	246.5	41.8	6.8	657.	91.3	13.9
		16.8		52.7		118.5			
$n = 2$	166.3	21.1	2.1	841.1	88.7	11.0	11600	898.2	73.2
		26.0		136.4		2250.			

Mean concentrations are smallest in the longest and broadest (bay shaped) estuary and largest in the shortest (irrespective of shape).

Table 4
Computed regime for fine ($w_s = 0.0005 \text{ m s}^{-1}$) marine sediments.

(a) estuarine mean concentrations (mg l^{-1})

Shape	Length (km)								
	25			50			100		
$n = \frac{1}{2}$	2370.	3900.	6480.	1830.	3680.	6630.	1480.	2660.	4790.
		3950.		3780.		2720.			
$n = 1$	2390.	4010.	6560.	1530.	3070.	6310.	1180.	2240.	3990.
		4090.		3180.		2300.			
$n = 2$	1460.	3640.	6360.	626.	1710.	3690.	136.	876.	2050.
		3790.		1740.		770.			

(b) time (years) to fill the estuary by deposition of entire flood tide sedimentary load. Table shows sensitivity to tidal amplitude and river flow as for Table 2.

Shape	Length (km)								
	25			50			100		
$n = \frac{1}{2}$	1.6	0.3	0.0	4.3	1.5	0.5	9.2	3.4	1.3
		0.3		1.7		3.4			
$n = 1$	1.4	0.3	0.1	3.5	1.2	0.4	8.8	3.0	1.1
		0.3		1.4		3.5			
$n = 2$	1.6	0.4	0.1	8.4	1.6	0.5	115.7	8.8	2.1
		0.5		2.1		22.5			

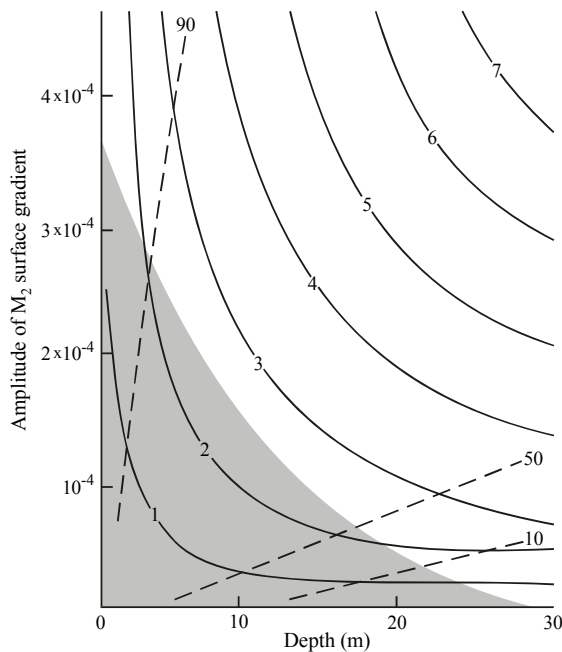


Figure 5 Tidal current amplitudes (M_2) from a balance of frictional to surface gradient terms. Dashed line shows ratio of frictional term to surface gradient term in equation (12). Shaded area indicates range of values from simulations described in Section 3.

Tables 3(b) and 4(b) show times (in years) for integrated volumes of net influx of sediments at the mouth over the flood tide to equal the estuarine volume (Table 1), i.e. the time taken to fill the estuary if all inflowing sediments were deposited.

Studies of the Dee (Hutchinson and Prandle, 1994) indicate that approximately 2.5% of the net sediment flux is deposited. Since the Dee is accreting rapidly, relative to most UK estuaries, we might adopt a value of 1% as appropriate to consider those estuaries that might be subject to serious siltation. Hence we see from Table 3(b) that for coarse sediments only the shortest estuaries combined with the highest tides are likely to lead to significant siltation over time scales of decades. Conversely, for fine sediments only the longer estuaries combined with small tides are likely to be unaffected by siltation over such time scales.

The results shown are effectively linear in terms of prescribed concentrations at the mouth. Thus where supply at the mouth reduces mean concentrations below those indicated by Figure 3, concentrations and 'infill' times would be reduced accordingly. Likewise, where some mixed source of fine and coarse sediments is available, the net results would correspond to the respective additions of the separate simulations. (Behaviours such as cohesive binding, consolidation, sheltering and flocculation are not considered).

Thus we might deduce that where there is plentiful marine supply of fine material at the estuarine mouth we might expect long estuaries and, moreover, such estuaries may only remain stable in areas of low tidal amplitude. Conversely, a plentiful supply of coarse marine material can co-exist with the full range of estuaries considered with only the shortest estuaries combined with the highest tides likely to produce significant siltation.

4. SENSITIVITY OF ESTUARINE CONDITIONS TO: EXTERNAL FORCING AND MODEL PARAMETERISATIONS

Here we seek to interpret the nature and sensitivity of the parameter distributions described in Sections 2 and 3 in terms of the implications for stability of estuarine bathymetry. In particular we consider the likely response to changes in: bed roughness, tidal elevation, mean sea level, storminess and sediment regime.

4.1. Sensitivity to bed friction coefficient

As indicated in Section 2.1, the sensitivities of the six parameters considered to the value of the bed friction coefficient k relate directly to F/ω . Figure 1(b) illustrates that F/ω is approximately equal to unity for $\hat{\zeta} = D/10$. For values of $\hat{\zeta} \gg D/10$, tidal dynamics become frictionally dominated, whereas for $\hat{\zeta} \ll D/10$ friction becomes insignificant. The consequent ratio of the modified parameters in Figures 1(a) to (f) corresponding to a changed bed friction coefficient, βk , the sensitivities can then be conveniently summarised as follows:

Parameter		Proportional $F/\omega \gg 1$ or $\hat{\zeta} \gg D/10$	Change $F/\omega \ll 1$ or $\hat{\zeta} \ll D/10$
1. current amplitude	\hat{u}	$\beta^{-1/2}$	1
3. sea bed slope	S	$\beta^{1/2}$	β
4. estuarine length	L	$\beta^{-1/2}$	β^{-1}
5. net energy propagation POW		β	1

Wolf and Prandle (1999) showed how tidal currents can be reduced by up to 70% due to added bed friction associated with wave-current interaction, this corresponds to $\beta \approx 2$. The likely extreme range of β is $0.2 < \beta < 5$.

4.2. Sensitivity to tidal elevations

At the mouth of almost all estuaries, away from large scale engineering works, the tidal elevation amplitudes remain extremely stable over centuries. However, over the familiar M₂-S₂, spring-neap, cycle the effective amplitude

of the semi-diurnal tide can vary by up to $\pm 50\%$.

One weakness of the results shown in Figures 1(a) to (f) is the adoption of $\hat{\zeta}$ and D as ‘independent’ axes. In most estuaries $\hat{\zeta}$, at the month, is determined by the prevailing coastal amphidromic system and D effectively adjusts according to $\hat{\zeta}$ and to the alluvium, river flows, wave regime etc.

Thus in considering how an estuary attempts to adjust to the effective variation in $\hat{\zeta}$ over a spring-neap cycle we may consider Figure 1(c). Then, if the larger scale bathymetry (i.e. bed slope S) remains constant, the changes in $\hat{\zeta}$ would require approximately linear (and in the same sense) changes in D . Whilst the temporal scales of any such adjustments are incompatible, we might expect some tendency to increased depths on spring tide and vice versa.

4.3. Sensitivity to changes in mean sea level

Tidal records over the last two centuries show that small long-term changes in mean sea level seldom produce significant changes in $\hat{\zeta}$ at the coast. Thence a small rise in sea level will produce a corresponding change in D , which for $\hat{\zeta}$ constant, will produce (Figure 1(c)) a decrease in bed slope S , i.e. an increase in estuarine length. More explicitly, an indication of this increased length can be obtained from Eqns. (4) and (6), i.e. $\delta L/L = 5/4\delta D/D$ or a greater relative impact in shallower water.

4.4. Sensitivity to Storminess

Storminess may include storm surges and wave activity – often concurrently. Moreover this concurrence may generate exceptional mobility of sediments – thence a rapid convergence towards an ‘immediate’ bathymetric equilibrium. Thus for storms of duration greater than the tidal cycle, the relationships indicated in Figures 1(a) to (f), which apply to the tidal conditions, might be superseded by the respective relationship for the prevailing ‘tide plus surge’ range. However, it seems more likely that exceptional dynamical conditions will yield exceptional bathymetric adjustments.

4.5. Sensitivity to Sediment Regime

The sensitivity to bottom friction coefficient, k , has been discussed in Section 4.1, likewise the relationship between k and sediment type is indicated in Figure 7 and Eqn. (20). The predominance of axial momentum in the tidal dynamics of most estuaries dictates that the magnitude of the axial sea surface gradient will remain constant laterally (some phase adjustment can exist). Thus maintenance of the equilibrium relationships derived here can accommodate lateral changes in water depth by appropriate adjustment of the effective bottom friction coefficient, i.e. smaller values (muddier) in deep water and larger (sandier) in shallow water. Channel sinuosity can also accommodate these relationships with deeper water and muddier sediments on the outside of beds and shallower sandier on the insides.

5. APPLICATION TO REAL ESTUARIES (UK)

A survey of the shapes and surficial sediments of 25 UK estuaries was made by Yates et al. (1996) – also see Paper 17 by Goss-Custard in this volume. Table 5 indicates the estuaries surveyed. Values of $\hat{\zeta}_L$ and D_L have been determined (indirectly) from these data, whilst values for L and percentage mud content are extracted directly. The distribution of these respective $\hat{\zeta}_L$ and D_L values are shown as circles in Figures 1(a) to (f). It should be recognised that these data were collected for purposes significantly different from their present usage and were derived from a diverse range of shapes and coastal sites. We note that (with one exception) all of these estuaries lie, as suggested, within the $POW = 2 \times 10^5 W$ contour in Figure 1(e) and within the $\hat{\zeta} > 30D$ contour in Figure 1(b), i.e. in frictionally dominated regimes.

Table 5
UK Estuaries surveyed (Yates et al., 1996)

1. Ythan	13. Hayle
2. Montrose	14. Swansea Bay
3. Eden	15. Dyfi
4. Tynninghame	16. Artro
5. Humber	17. Mawddach
6. Breydon	18. Glaslyn
7. Blyth	19. Foryd Bay
8. Alde	20. Dee
9. Swale	21. Lune
10. Pagham	22. Duddon
11. Tamar	23. Solway
12. Plym	24. Auchencairn

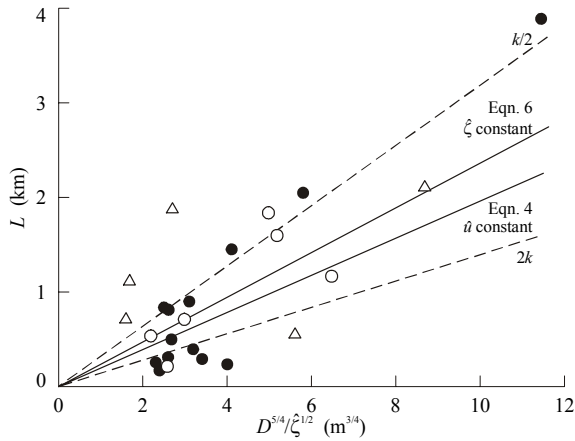


Figure 6 Observed and predicted estuarine lengths. Percentage mud content, M : ● < 30, 30 < ○ < 70, Δ > 70.

5.1. Estuarine lengths

Figure 6 shows the distribution of observed estuarine lengths versus the parameter $D_L^{5/4}/\hat{\zeta}_L^{1/2}$ (from (4) and (6)). Figure 6 also shows the lengths indicated by (4) and (6) together with a broader envelope corresponding to $k/2$ in (6) and $2k$ in (4). Whilst the Equations (4) and (6) lie close to the centre of the distribution of the observations, there is considerable scatter. However, this scatter generally lies within the anticipated range of variability of the bed friction coefficient k .

5.2. Bed friction factor as a function of mud content

This sensitivity of predicted estuarine length to the bed friction coefficient, k is further investigated by re-analysis of the data discussed in Section 5.1. In this case, the observed length is specified in Eqn. (4) and the requisite bed stress coefficient, k , determined. Figure 7 shows these values of k plotted against the percentage mud content. Although there is again significant scatter, there is a reasonable fit to a relationship,

$$k = 0.025/M \quad (20)$$

where M is the percentage mud content. This corresponds to $0.0005 < k < 0.005$ for $50\% > M > 5\%$.

5.3. Estuarine shape and size vs tidal range and sediments

Yates et al. (1996) derived the following schematic summarising estuarine characteristics:

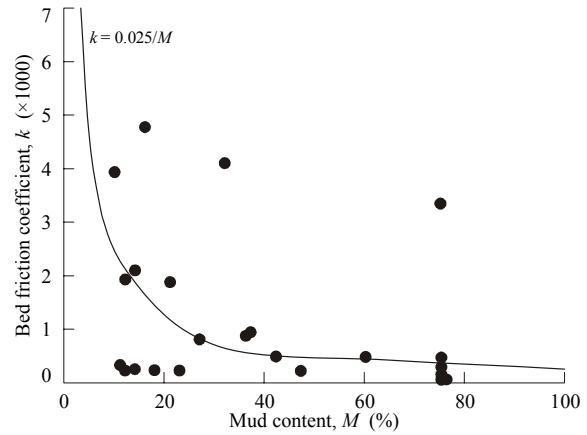


Figure 7 Sensitivity of bed friction coefficient, k to percentage mud content, M . ● observations from Table 5.

Low	Tidal range	High
Long	Estuarine length	Short
Narrow	Estuarine width	Wide
Muddy	Sediments	Sandy

Results shown in Figure 7 indicate that a four-fold increase in bottom friction coefficient may be commonly encountered between muddy and sandy beds with a consequent halving of estuarine lengths in shallow estuaries ($D \ll \hat{\zeta}/10$) or quartering in deep ($D \gg \hat{\zeta}/10$).

From earlier discussions (Section 2.2) of the value of maximum observed tidal currents and energy propagation, it was deduced that large tidal elevation amplitudes (≥ 3 m) will generally be confined to shallow water (≤ 15 m). Thence, from Figure 1(d), large tidal elevations will correspond to shorter estuaries and the attendant shallow water will reduce estuarine widths.

6. SUMMARY AND CONCLUSIONS

For a triangular cross section:

- i) the cross-sectional, time-averaged linearised friction coefficient $F = 8(e-1)k\hat{u}/(3\pi D)$.
- ii) the ratio of the friction to inertial terms F/ω , can be approximated by $10\hat{\zeta}/D$.
- iii) Assuming constant values of either \hat{u} or $\hat{\zeta}$, estuarine lengths may be approximated by $2200 D_L^{5/4}/\hat{\zeta}_L^{1/2}$ (with adjustment for variation in bed friction coefficient as indicated in Section 4.1).

- iv) Fitting observed estuarine lengths for 25 UK estuaries (short and shallow) to the above expression provided an estimate of $k = 0.025/M$ where M is the percentage mud content.

For the longest estuaries (~100 km), flushing times are in excess of the 15-day spring-neap tidal cycle and thus effectively average both the related tidal variation and that of river flow. For shorter estuaries (~25 km), flushing times can be O(hours) with consequent enhanced susceptibility to changes in both tidal range and river flow.

The intrusion of sediments of marine origin is sensitive to the extent and nature of supply, where available fine sediments produce significantly higher (depth-averaged) concentrations and extend farther upstream – often remaining more-or-less continuously in suspension.

Some indication of the likely relative stability of any estuary (due to the influence of marine sediments) can be obtained from comparing the net flux of sediments on the flood tide with the existing estuarine volume. By expressing this ratio in terms of the number of tides to ‘fill’ the estuary (assuming complete deposition) it may be deduced that the longer estuaries are more compatible with fine sediments and lower tides while shorter estuaries may reflect coarser sediments and higher tides. Such correspondence assumes plentiful sediment supply.

Shallow estuaries are likely to be most sensitive to changes in mean sea level.

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AN EVALUATION OF ESTENT ON SIX SELECTED ESTUARIES

Julie Gill, Darren Price, Natalie Edwards

email: dmp@research.abports.co.uk

ABP Research & Consultancy Ltd, Pathfinder House, Maritime Way, Southampton
SO14 3E, UK

1. INTRODUCTION

An evaluation of six estuaries was made in order to determine their energy distribution profile. This has allowed the hypothesis that natural systems evolve to do minimum work to be tested. If the hypothesis is correct, the rate of entropy production will move towards a minimum as it progresses towards its most probable state. The availability of data over more than one time span has also enabled energy distributions from some models to be examined over time (Southampton Water and Humber). In these cases, a more in depth picture of how these estuaries are moving towards their probable state can be determined.

2. HYPOTHESIS

For the evolution of an open system to its most probable state, the entropy production per unit volume will tend to evolve to a minimum compatible with the conditions imposed on the system (Prigogine, 1955). Therefore, for the case of an estuary, the system will tend to evolve in an attempt to achieve the most probable distribution of tidal energy. However, the time taken to evolve to this state will be dependent on constraints imposed upon the system (such as geological constraints and supply of sediments). Such constraints may be significant enough to prevent the evolution to the most probable state in which entropy is maximised, or may induce a switch to some other steady state.

The concept of minimum entropy production per unit discharge has been derived for the more general case of a bi-directional variable discharge along a channel reach. This suggests that the longitudinal energy distribution along an estuary may be represented as;

$$\rho g \int HQ dt = \exp(C.x + D)$$

where; C and D are constants, and $\rho g \int HQ dt$ is the sum of the energy passing through a cross section at a distance x from the mouth of the estuary over a complete tide. With ρ being the density of water, g the acceleration due to gravity, H is the specific energy head and Q is the discharge. The equation represents the most probable distribution of tidal energy within an estuary and suggests that the exponential decay of tidal energy as it traverses

upstream. This theory suggests that the estuary morphology will evolve to a point whereby it achieves a minimum production of entropy at a steady rate.

EstEnt (ABP Research's entropy model) has been applied to the six chosen estuaries for the Estuaries Research Programme Phase 1. The main aim is to test the general validity of the hypothesis on which EstEnt is based, namely that the most probable distribution of energy within an estuary (as a result of the tidal wave) will decay exponentially in an upstream direction. Numerical hydrodynamic models, either 1D or 2D, have been set-up for each of the estuaries, with at least two bathymetries, where data is available. Some estuaries have been tested for more than 2 bathymetries (Southampton Water and Humber).

3. RIBBLE ESTUARY

The Ribble estuary was set up as a two-dimensional model and run for both a spring and neap tide. The results show that the distribution of energy under both spring and neap conditions varies exponentially along the full length of the system.

The estuary is some way from its most probable state (as indicated on figure 1 as 'Theoretical') but with only one data set it is impossible to establish the direction of change.

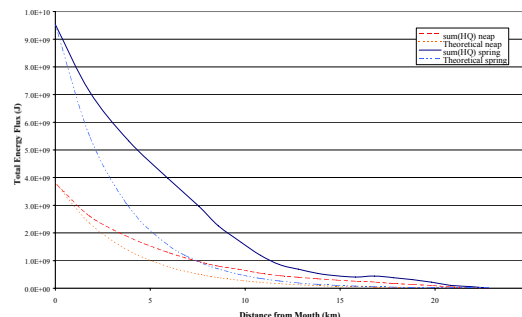


Figure 1 Distribution of energy in the Ribble estuary.

Unfortunately, there was not any bathymetric data available to run the model prior to any anthropogenic alterations to the estuary. This

would have been useful as a comparison could have been made pre and post the changes.

The percentage difference from the most probable indicates that the neap tide is however, marginally closer to the most probable (Figure 2).

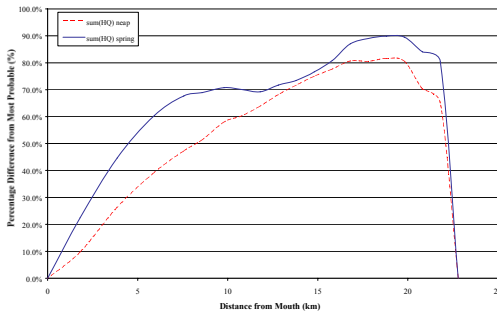


Figure 2 Percentage difference from most probable state

4. BLACKWATER AND TOLLESBURY CREEK

Results from a two-dimensional model of the Blackwater estuary were obtained from HR Wallingford. The Blackwater results indicate an almost linear variation in total energy distribution (figure 3) along the length of the estuary (the magnitude of the energy distribution presented in figure 3 is lower due to the model being run to Chart Datum rather than ODN). The linear trend line applied to the energy curve has an R^2 value of 0.99, which represents a strong fit. The percentage difference from the most probable distribution is up to 90 percent at a distance of 12km from the mouth.

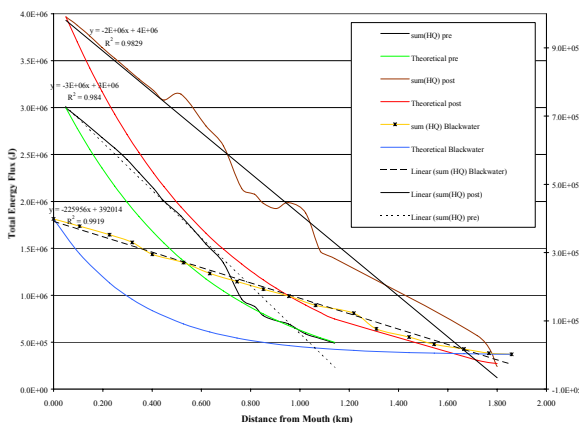


Figure 3 Distribution of energy at Blackwater and Tollesbury Creek.

A one-dimensional flow model of Tollesbury Creek was also obtained from HR Wallingford and run for pre and post breach scenarios. In Tollesbury Creek, both the existing and post-breach scenarios indicated a linear variation in energy

along the Creek (figure 3). The linear trends give R^2 values of 0.984 and 0.983 respectively.

However, the percentage difference from the most probable (Figure 4) indicates that the pre-breach case is closer to the most probable than the post-breach case. This is as expected, as the estuary might be expected to be closer to greater equilibrium before breaching than after. After breaching, the estuary would be expected to exhibit lesser amounts of entropy. Hence, in the short-term, the breach has moved the estuary further away from the equilibrium. The difference between pre and post breach is approximately 25 percent from the most probable for the existing case and up to 50 percent for the post-breach case.

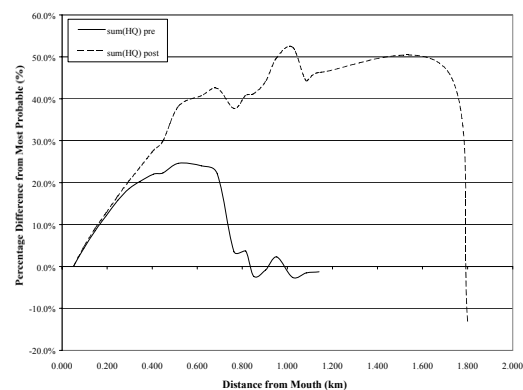


Figure 4 Percentage distribution of energy for Blackwater

5. MERSEY

A 2D flow model was set up for the Mersey and the energy results showed an unusual distribution along the estuary. The Mersey has a highly constrained system at the mouth at the Narrows, which then widens into a more 'ideal' estuary shape. As a result, the energy distribution obtained is linear from the mouth up to 10km inside the estuary and exponential thereafter (figure 5). The linear distribution is thought to have occurred because the water is being forced through geological constraints. Therefore the energy level remains lower due to the capacity for energy transmission at this point being constrained and higher energy losses are occurring to increased turbulence etc. If the mouth of the Mersey were not constricted, the level of energy at the Narrows would be expected to be significantly higher. Figure 5 also shows that the energy distribution would be much closer to the most probable if the constriction were not occurring. This is shown by locating the start of the estuary 8 km from the Narrows.

The difference between the two time intervals suggests that the 1993 bathymetry is moving away from the most probable state although it could be oscillating around this point as it adjusts to changes in the estuary channel.

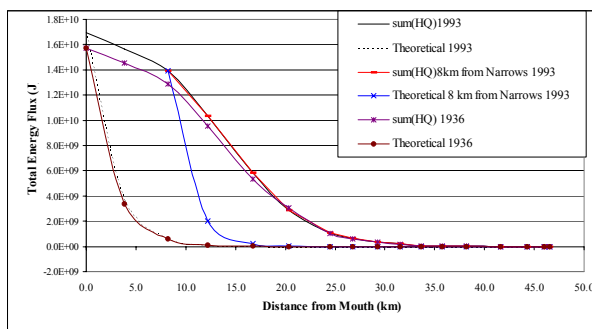


Figure 5 Distribution of energy in the Mersey

When the estuary was assessed 8km from the Narrows, a new energy distribution based on this new definition showed that it was closer to the most probable (figure 6). However, although high energy levels are present at the mouth, it only begins to significantly reduce at more than halfway up the estuary. Therefore it is possible that the estuary may be further constrained due to high levels of hard engineering around Birkenhead, Liverpool and Bootle, which are located along the outer margins of the estuary.

The percentage difference from the most probable is almost constant at 100 percent except in the far reaches of the estuary where the estuary is constrained by tight meanders in an intertidal area which are subject to drying out. Also the model's grid resolution in this part of the estuary is poor which could also affect the results. Because the energy levels are low in the upper reaches of the Mersey, the 250-300 percent move away from the most probable 45 km upstream from the estuary mouth is quite small in terms of the actual fluctuation in energy levels.

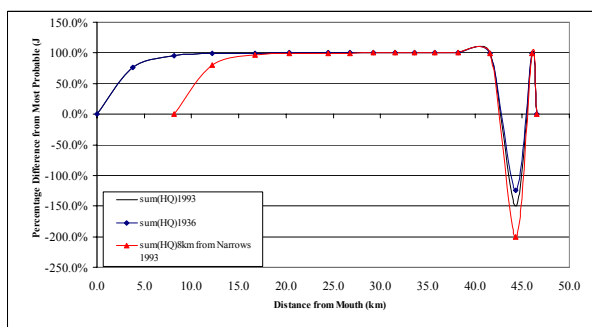


Figure 6 Percentage difference from most probable

6. SOUTHAMPTON WATER

Energy assessments were made for 4 different sets of bathymetry, which were for the years 1783, 1926, 1996 and 1998. The tidal energy distributions for all bathymetries were almost linear rather than exponential (figure 7). Although the 1996 and 1998 bathymetries appear closer to the most ideal. In addition, all reaches of the estuary had a higher magnitude of tidal energy passing through it than has been predicted by the most probable state (figure 8). There is also little variation in energy distribution over the time intervals.

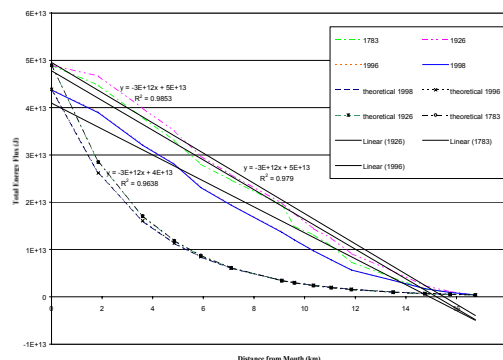


Figure 7 Distribution of energy in Southampton Water

The minimum entropy production argument suggests that a most probable state will be approached when the difference between the actual and most probable energy distributions is minimised. In order for the system to move towards the most probable state, then the energy distribution needs either to reduce over extensive lengths, or increase through the mouth. This might suggest that the system could accrete within the estuary or widen at the mouth to enable it to move towards the most probable state.

However, it is possible that future changes to boundary conditions, such as increased rates of sea level rise together with the influence of the deep dredged channels, may mean that the sediment demand required to maintain the position of the estuary form cannot be met. If this sediment demand is not met, it may result in a lowering of the intertidal relative to the tidal frame. If this happens, the estuary may take longer to reach the most probable state, or may even seek a different state.

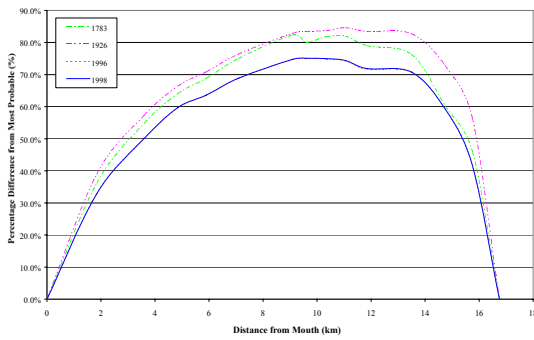


Figure 8 Percentage difference from most probable

7. HUMBER ESTUARY

Due to the availability of existing data, the Humber estuary model was run for 14 sets of bathymetry. Bathymetric data sets from 1851, 1875, 1900, 1910, 1925, 1936, 1946, 1956, 1966, 1976, 1986, 1993, 1997 and 1998 were used to extract cross-sectional data for a one-dimensional model of the Humber.

Each year modelled showed an overall exponential energy distribution along the length of the estuary. However, none matched the most probable case completely. From the plot of total energy distribution (figure 9), there is no evidence of any uniform movement either towards or away from the most probable over time given the constraints on the systems. In examining the central section of the estuary, (20-50km), the 1851 curve is furthest from the most probable and the 1998 curve is the closest. The curves in the river are too closely grouped to assess the differences. However, it is

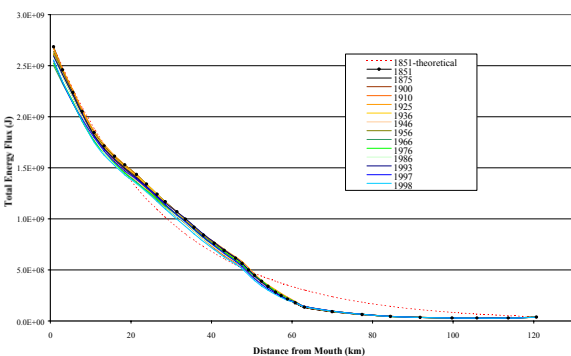


Figure 9 Distribution of energy in the Humber

interesting to note that the rate of energy loss falls below the most probable state about 50km upstream from the mouth. At this point, the estuary splits into the rivers Trent and Ouse where the energy dips below the most probable. This may be a consequence of the erection of flood defences, which constrain the banks of both rivers.

As a percentage difference (figure 10), the variations are clearer, especially in the rivers. At a distance of 20km upstream from Trent Falls, 1851 is furthest from the most probable and the existing case is closer to the most probable. There is a general movement towards the most probable in this area over time and the curves are grouped so that 1851 and 1875 stand out below the rest. 1900 to 1956 appear in a cluster and 1966 to 1998 are closer to the most probable, but are again grouped in a cluster. However, the biggest percentage changes occur in the rivers.

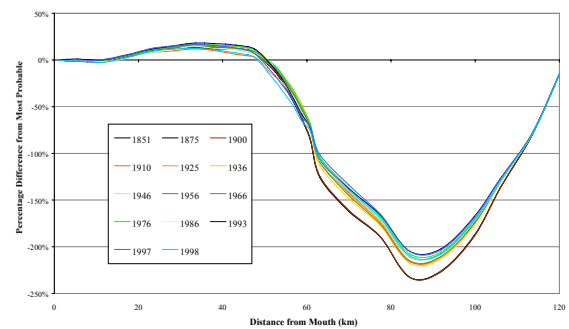


Figure 10 Percentage difference from most probable state

The concept of minimum entropy can also be examined in 2D. This is shown for the Humber in figure 11, where deviations from a constant value indicate the extent of deviation from the rate of doing work being uniform across the estuary as a whole. This highlights the fact that most of the areas with a higher rate of doing work are in the intertidal and shallow subtidal zones, where frictional losses are likely to dominate. This may also be a useful indication of the degree of 'stress' in the estuary.

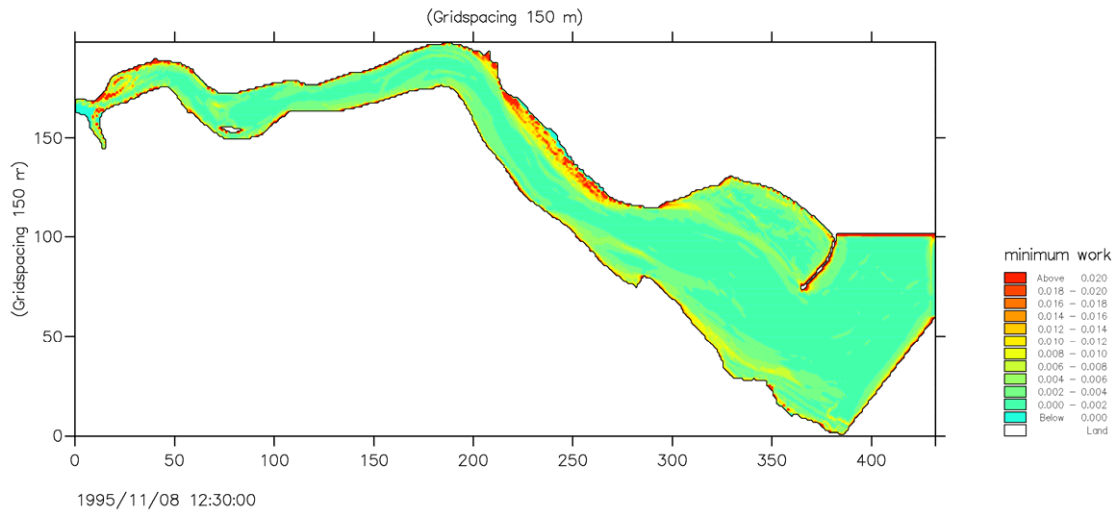


Figure 11 Plan View of energy distribution

8. TAMAR ESTUARY

A 2D model was set up for the Tamar estuary and the energy results obtained show that the decrease in energy is linear/convex from the mouth of the estuary and up to 5 km along the estuary where it becomes convex and then exponential from 10 km (figure 12).

Initially, the tidal flow is constricted around the estuary mouth at the Narrows. This keeps the energy loss high and a uniform rate of energy loss occurs. Although, 4 km from the mouth, the energy levels rapidly drop. This can be attributed to the hydraulic flow dissipating into St John’s Lake, which is a large intertidal area. However, further upstream, around 5 km from the estuary mouth, the rate of energy loss noticeably increases. This is where the hydraulic flow passes a constricted area at Torpoint which is an area built out into the estuary to avoid the intertidal area due to chain ferries operating at this point. In addition, the hydraulic flow is constricted by the hard engineering of the Navel dockyards at Devonport which are located along the eastern side of the estuary up to 10 km upstream. Along this point, the depths are regularly maintained and are therefore considerably deeper than they would normally be. This could account for the rate of energy loss being kept exceptionally lower along this length.

However, where the estuary meets the rivers Tavy and Lynher (13 km from the mouth), the rate of energy dissipation begins to reduce exponentially and falls below the most

probable. This is similar to the energy dissipation in the Humber, which also fell below the most probable state where the estuary divided into two independent rivers.

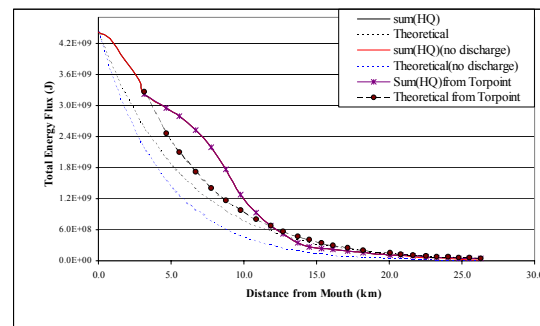


Figure 12 Distribution of energy in the Tamar

The energy distribution was obtained from a high water to high water simulation. However, in order to provide a comparison of energy results, a new scenario was run with the river discharge turned off at the head of the estuary. This scenario is compared with the previously obtained result. The results are almost identical to the previous energy results except for the reduced energy levels at the head of the estuary. Although this accounts for the lack of river discharge, the overall results show that the Tamar estuary is tidally dominant and the river discharge makes little difference to the way the energy distribution changes in the estuary. This is demonstrated on figure 12 where ‘sum(HQ)’ is hidden by ‘sum(HQ) without discharge’ and hence cannot be seen. Although it is interesting to note that the estuary is closer to the most probable when

there is a high discharge from the river (figure 13).

Nonetheless, the estuary operates within a seasonal system as the bathymetry significantly alters during the summer months when unconsolidated bed source sediment up to 1 meter thick moves into the upper reaches of the estuary during the summer months (HR Wallingford, April 1999). However figure 13 shows the estuary is in greater equilibrium when there is a high river discharge in place at the head of the estuary. Ideally, a comparison with a low discharge simulation with lowered bathymetry in the upper estuary could have been performed but there was no data available to do this analysis.

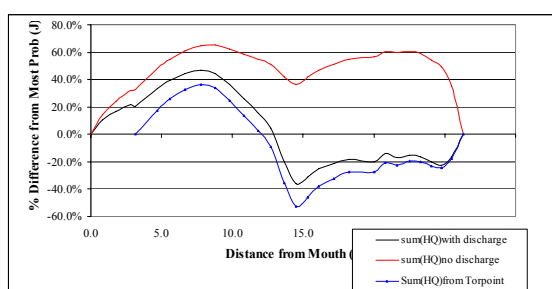


Figure 13 Percentage difference from most probable

9. CONCLUSION

The results obtained demonstrate that each estuary reveals different patterns of energy distribution and energy dissipation. The results also highlight some of the key estuarine constraints attributing to some of the energy distribution patterns. An interesting aspect has also been observed between those estuaries with a predominant linear distribution of energy and those with a predominant exponential distribution. Although only six estuaries have been compared, the emergent distributions may be a result of each estuaries plan shape. In these examples, a funnel shaped estuary, which is normally a macrotidal estuary such as the Mersey, Humber, Tamar and Ribble, appears to exhibit exponential decay whilst a canal shaped estuary, which is normally a mesotidal estuary such as Southampton Water and Blackwater, exhibits linear decay. However, further analysis on other estuaries would need to be performed to qualify whether this trend is consistent. In addition, analysis needs to be undertaken on estuaries whose plan shape is more unusual such as Poole and Chichester Harbours to

establish what type of energy distribution they exhibit.

The results obtained from each of these modelling exercises demonstrate that each estuary is constrained by its geology and fluvial inputs. Further to this, the rate of work performed by an estuary, is also a function of its these constraints. This gives rise to each of the models being interpreted differently.

It is also important to stress that the six estuaries modelled show only one representation of how each estuary is moving towards its most probable state. However, when these results are taken in conjunction with other modelling processes being carried out, a rounded picture can be established from each estuary. Although the two types of process models used can marginally affect the outcome of the results. One-dimensional models cannot account for energy losses on bends, whilst two-dimensional models are poor at simulating the hydraulic flow in upper reaches of estuaries due to the low resolution that occurs when the grid spacing becomes more dense.

There is also the issue of where the system's boundaries lie within an estuary and whether wider system parameters such as wind and wave conditions are also significantly affecting the results. In addition, determining where an estuary starts and ends is also difficult. In these examples the tidal limits and what was generally accepted as the mouth of each estuary determined the location of each system's boundaries. However, the ability of other parameters to affect the system may go far wider than this. For example, the inclusion of Plymouth Sound and the elimination/inclusion of the artificial breakwater within the Tamar estuary may affect the predicted distribution of energy and move it towards or away from the most probable state.

Nonetheless, one of the benefits of the results obtained is that they are simple to interpret and are not overcomplicated by the introduction of sediment transport or off-shore wave regimes etc. Although there are a number of other means of entropy production not accounted for in the method, such as 3D effects, turbulence, secondary circulation, density gradients, sediment and turbidity influences and related sources of lost work. In addition, the effects of

saltmarsh development and vegetation are also not fully explored. Availability and use of this information may indicate that the system is already closer to the most probable state than predicted by the current methodology.

However, by eliminating these characteristics in the estuarine system, we have to accept that the degree of completeness in the results obtained is reduced. Although it is important to realise that despite operating the models with just the tide and fluvial inputs, a significant amount of information has already been drawn out from each model. Therefore, if EstEnt were developed to allow further information to be input into the model, thus further refining the modelling process, each additional level of information could help to build up a profile of what is happening in the estuaries by individually examining every additional input.

Although the EstEnt model is diagnostic rather than a predictive tool, it can be predictive in as much that in many of the estuary examples used, the mouth of the estuary is constrained by its geomorphology and anthropogenic influences. Where this occurs, we can assume that this part of the estuary is unlikely to reach a steady state due to these constraints. However, the upper parts of these estuary's are more likely to reach their steady state due to their ability to continue to evolve in these areas. Therefore, by altering parameters in the lower estuary, we can observe how the energy distribution changes in the upper estuary, thereby giving EstEnt its predictive capacity. In addition, knowledge of the local geology can also help to determine how quickly an estuaries response time is in terms of its ability to evolve towards the most probable state. For example, the Ribble estuary consists mainly of mud and sands and is subject to greater rates of erosion and accretion, therefore evolving more quickly. Whilst the Tamar estuary's response time will be longer as it has been carved through Devonian limestone during the pre-holocene period. Further to this, the availability of historic bathymetric data can provide information on whether an estuary is moving towards or away from its most probable state or oscillating about a given point by examining the general trend. (This has been true for Southampton Water and the Humber).

EstEnt is a modelling tool that helps to provide a picture of the stability of an estuary. It is effective for determining how constraints and changes in parameters will effect an estuary's equilibrium and once a model has been set up, it can achieve this function fairly rapidly. As previously discussed, although each EstEnt model is currently only driven by the tidal wave, the potential for the amount of information to be extracted is significant and clearly the more bathymetric data sets available, the greater the diagnostic and interpretative potential of the approach.

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11. GLOSSARY

Entropy - An estuary is continually evolving over time. In order to do this its uses the available energy from the tidal wave and river discharges within the estuary. This energy is able to evolve the estuary by scouring the sides and estuary bed. The energy used in this process is doing work and the level of entropy production, which is the rate of increasing disorder within the system, will be minimised. However, when the estuary bed is close to being fully evolved, the energy required for

this process is substantially reduced. Therefore the work required is also substantially reduced. Because the work performed in an estuary is an irreversible process, it will naturally evolve towards a state whereby entropy is at a maximum unless geomorphological or anthropogenic influences restrict this process. In the absence of these factors, an estuary will evolve towards its most probable state where work is minimised and entropy is maximised.

Probable State – The system is searching for the lowest point in an estuarine valley. The lowest point may be a function of an estuary's preceding geology and sea level rise or the attainment of the lowest point can be constrained by fluvial inputs and hydraulic flow. Both geological and anthropogenic constraints can also prevent an estuary from achieving its most probable state. In such circumstances the estuary may seek a new state through the effects of erosion and accretion or may breach and create a new course for itself.

FLUXES OF SUSPENDED SEDIMENT IN ESTUARIES, AND THEIR RELATIONSHIP TO EQUILIBRIUM MORPHOLOGY

Keith Dyer

email: keith-r-dyer@supanet.com

Norton Hayes, Bradford-on-Tone, Taunton, Somerset, TA4 1HP, UK

ABSTRACT

Measurements of suspended sediment fluxes obtained in the Humber estuary have been analysed as a series of components to assess the contributions made to the transport by various processes. It is apparent that the mean seawards flux on the river flow is counteracted by an inwards flux due to asymmetry of the tidal currents. Additionally, the effect of stratified flow and vertical gradients of concentration generate appreciable landward fluxes. Further important contributions appear from lags in the response of the sediment to the flow.

An exploratory modelling approach is proposed in which the contributions to the suspended sediment fluxes are represented by harmonic terms both in time during the tidal cycle, and along the estuary. The proposal is for the bathymetry to be adjusted to explore the situation in which the estuary is in equilibrium with no net sediment transport.

1. INTRODUCTION

Changes in the morphology of estuaries are created by spatial variation in the transport of suspended sediment when averaged over a realistic period. Thus a positive or negative gradient (divergence) in the transport rate leads to erosion or a deposition of sediment on the bed. The change in bathymetry affects the current strength, with erosion causing a decrease in current, and an increase in bed level an increase in current. The concept is that an equilibrium situation will be created where the erosion or deposition becomes reduced by the change in the currents. Initially the transport has to be averaged over a tidal cycle, and then integrated over longer periods to encompass, the lunar cycle, the cycles of weather induced change, and seasonal effects.

To estimate the tidally averaged transport from measurements, a number of components can be

separated that represent the different active processes. This has been done for a number of estuaries by Dyer (1978, 1988), Uncles et al (1984, 1985) and Su and Wang (1986). In contrast to the transport of salt, the studies have shown that there are important contributions to suspended sediment transport from lags in the sediment response to the asymmetrical tidal currents, and due to stratification of the water column, both in terms of water density and suspended sediment concentration. Not all of the components are well represented in regime models. The purpose of this paper is to review those results in the context of the EMPHASYS study, and to present new results for the Humber Estuary.

2. METHOD

The instantaneous flux of suspended sediment through an element of the estuary is:

$$F = \int_0^h ucdz \quad (1)$$

Averaging a number of equally spaced measurements over the tide, and defining tidally averaged, tidal oscillatory and deviation components of velocity and concentration as $u = \bar{u} + U + u_d$ and $c = \bar{c} + C + c_d$, and depth as $d = \bar{h} + H$, then the tidally averaged flux:

$$\begin{aligned} \bar{F} = & \bar{h}\langle\bar{u}\rangle\langle\bar{c}\rangle + \overline{H\langle U\rangle\langle\bar{c}\rangle} + \overline{H\langle C\rangle\langle\bar{u}\rangle} + \\ & \overline{h\langle U\rangle\langle C\rangle} + \overline{\langle HUC\rangle} + \overline{h\langle\bar{u}_d\bar{c}_d\rangle} + \overline{h\langle U_dC_d\rangle} \end{aligned} \quad (2)$$

1 2 3
4 5 6 7

where angle brackets signify mean values over depth, and overbars signify tidal averages. Where data from a number of stations on a cross section are available, summation of the

values multiplied by their respective section areas can be made to obtain the complete integrated cross sectional flux.

The first two terms on the right hand side of Eqn. 2 are the advection terms. The first is the flux on the non-tidal drift, and the second is the Stokes drift flux. The latter is caused by phase differences in the relationship between depth and velocity due to asymmetry in the tide, and drives more water landwards at high tide because of the larger area, than moves seawards around low tide when the cross sectional area is smaller. The water moved by Stokes Drift towards the head of the estuary is released as part of the mean flow and causes the non-tidal drift \bar{u} to exceed the river flow. Thus,

$$R = \bar{h}\bar{u} - H\langle U \rangle \quad (3)$$

Terms 3, 4 and 5 in Eqn. 2 are the ‘tidal pumping’ terms produced by phase lags in the sediment response to the flow. These arise mainly because the suspended sediment concentration variation during the tide is not well correlated with the flow velocity, due to the delay in the movement of sediment caused by presence of a threshold of erosion, and the delay caused by settling of the sediment (Dyer 1997). These delays are only significant when the tidal currents are asymmetrical. Term 6 is associated with the occurrence of vertical gradients in concentration correlated with those in the mean currents arising from salinity stratification and vertical gravitational circulation. Term 7 is again due to sediment induced lags which create tidally time varying profiles of velocity and suspended sediment. Terms 6 and 7 are known as shear terms. The relative importance of the various terms is likely to vary along an estuary, and between estuaries, as a consequence of differences in estuary form, tidal asymmetry and sediment characteristics.

Data is available for a number of positions in the Humber Estuary (BTDB, 1980) at spring and neap tides. Inspection of the data has revealed that only those taken at Halton Middle Bank are sufficiently complete for analysis. The measured suspended sediment concentrations were separated into fine and coarse fractions at 40 microns, and consideration of both fractions allows

comparison of the movement of mud and sand, and assessment of the relative importance of the various processes.

3. RESULTS

The calculated values for the various terms are shown in Table 1. Positive values indicate a flux towards the head of the estuary, and negative values fluxes towards the mouth. It is apparent that the greatest transport is for the fine fraction, as one would expect.

The total transport suggests that the coarse fraction is more or less in equilibrium over both spring and neap tides, whereas, for fine sediment an overall export of sediment is indicated. For fine sediment the ebb tide dominance of the advective term is reduced by the contributions of the other terms, more at neap tides than at springs. This indicates that there is a feedback between the response of the sediment to the flow that tends to reduce the tendency for sediment to be flushed out of the estuary by the mean flow on the non-tidal drift. However, it is probably unrealistic to consider the totals from only a few tides as being representative. On the other hand, consideration of the relative magnitudes of the various terms is likely to be rather more significant.

The mean advection of sediment (Term1) is negative for both tides, as is expected from the river discharge. From Eqn. 3, the river discharge was calculated at neaps as $1.23 \text{ m}^2\text{s}^{-1}$ per m width, and at spring tides $0.98 \text{ m}^2\text{s}^{-1}$ per m width, both of which appear reasonable for a position in the main channel. The suspended sediment transport was greater for the coarse fraction on spring tides than on neaps. That for the fine sediment was about on both springs and neaps, suggesting that the fine sediment concentrations do not vary as much as they could and the fine sediment supply might be limited in availability at that position at spring tides.

The Stokes drift term indicated a landward flux for both coarse and fine sediment. The greater values at spring tides being caused by the greater asymmetry at spring tides. The tidal pumping Term3 may be negligible. However, Term 4 changes direction, being downstream at spring tides, and upstream at neaps. It is more important at spring tides for both coarse

and fine sediment, and increases with tidal range for fine sediment. The changes in Term 5 may be considered negligible. The shear terms 6 and 7 are only important at neap tides, suggesting that at spring tides higher flow speeds keep the fine sediment in suspension and with homogeneous vertical profiles for greater proportions of the tide. Term 6 shows that vertical gravitational circulation is important for fines at neap tides. This suggests that the vertical stratification effect of salinity needs to be included in models for accurate simulation of the transport of fines at neap tides. The movement of fine sediment is also enhanced at neap tides by the tidally varying relationships of profiles of current velocity and concentration shown in Term 7.

4. DISCUSSION

Comparison of the Humber data with that from other systems show that there are a number of general similarities, with explicable differences. Dyer (1978) has presented the results of a similar approach for the Thames Estuary. Stokes drift was relatively more important than in the Humber. Also Term 4 was relatively larger, possibly as the result of differences in the settling velocity of the sediment. The vertical gravitational circulation term was important, despite the estuary being comparatively well mixed, and Term 6 was large, relating to relatively high concentrations.

Uncles et al (1984) have examined data for the Tamar have shown (Table 2) that the rates of transport due to vertical shear were negligible due to low and fairly uniform concentration at neap tides. At spring tides there was higher concentration variation, but the temporal correlation with flood and ebb currents were small because the highest concentrations appeared at highest currents. Up estuary pumping was due to enhanced suspension of sediment particularly during the dominant flood currents. Uncles et al (1985) showed that the tidal pumping was up estuary at spring tides near the head of the estuary, but down estuary elsewhere, and was larger than the mean flow and the shear effect.

Both Dyer (1978) and Uncles et al (1984) have shown that there are large lateral variations in the tidal pumping, and in the Tamar it was directed down estuary in the deeper part of the cross-section. This suggests that models need

to have a good representation of the time varying vertical profiles of both velocity and concentration.

5. CONCLUSIONS

Based on the analysis of the Humber estuary measurements, and comparison with other estuaries, it is apparent that Eqn. 2 can effectively be reduced to 5 terms. The important terms are those representing the non-tidal drift (term 1), the Stokes drift (term 2), the tidal pumping term 4, and the two shear terms, 6 and 7. Regime theories generally assume relationships between the bathymetric change and the currents, and do not specifically account for the lags involved in sediment movement. Additionally, most simple mathematical 1D models do not include density effects, or the vertical profiles. The implications are that models need to include accurate representation of the tidal asymmetry, as well as asymmetry in the concentrations, together with vertical profiles of both flow and concentration. Ideally 3-D modelling is required.

6. A ZERO NET FLUX MORPHOLOGICAL MODEL

For morphological equilibrium in an estuary there must be zero net flux of sediment at all positions, otherwise the gradient of transport rate would require either erosion or deposition. It is assumed that the equilibrium-state is one to which every estuary will progress as sediment transport modifies the morphology. In that situation, though there may be active transport within the tide, there is as much sediment carried landwards on the flood as is carried seawards on the ebb tide. Though estuaries with exponential outlines are commonly considered to be equilibrium, it is not necessary that other forms may not also be in equilibrium. The aim, then, of a model to examine the morphological situations in which the balance of flux terms will lead to a constant flux along the estuary, and how that relates to the classical ideas of an equilibrium estuary having an exponential form.

The method is to represent the constituents of the terms in the flux equation (Eqn. 2) by a set of harmonic relationships. These will need to account for the tidal variations in current velocity, suspended sediment concentration and cross sectional area, all of which will also

be functions of position along the estuary. The equation can then be explored by iterative techniques by varying the topography, and such factors as the threshold of sediment and availability of sediment, to determine the conditions that provide the zero net fluxes. The main difficulty is that net erosion and deposition is the sum of small differences between large terms of opposite sign, so that errors in the formulation may become predominant. But this is a problem with all morphological calculations.

There are two possible candidate estuaries where there is enough information to carry out a preliminary study, the Humber and the Tamar estuaries. The former is close to the exponential form already.

6.1 Humber

For the Humber, the depth $\bar{h} = 0.55\exp(3x/L)$. The tidal oscillation in water depth can be defined as

$$H = a_{M2}\cos(\omega t - \Theta_{M2}) + a_{M4}\cos(2\omega t - \Theta_{M4}).$$

Within the Humber, $a_{M4} = 0.003M_2$ and $(2\omega t - \Theta_{M4}) = 223$ at the mouth,

and $a_{M4} = 0.25M_2$ and $(2\omega t - \Theta_{M4}) = 52$ at Burton Stather.

The mean velocity $\bar{u} = \left(R + \overline{H\langle U \rangle}\right) / \bar{h}$, and the river flow R can be obtained from gauged values.

The oscillatory velocity tidal $U = u_{M2}\cos(\omega t - \varphi_{M2}) + u_{M4}\cos(2\omega t - \varphi_{M4})$.

The relative amplitudes and phases of the currents (u_{M2} , u_{M4} and φ_{M2} , φ_{M4}), and how they change along the estuary would need to be estimated from data.

Similarly the amplitude and phase relationships for C along the channel need to be specified, as well as the distribution of mean concentration \bar{c} . C will have its maximum at low tide near the mouth, and maximum at high tide at the head. Thus the phase relationships with the current are likely to be widely varying. The other information should be available from the LOIS data set. This should also provide information on the vertical profiles of \bar{c} and C .

6.2 Tamar

For the Tamar, Uncles and Stephens (1993) has given information on the variation in the mean advection, tidal pumping and shear terms along the estuary (Table 2). These show that the shear term is only significant near the head of the salt intrusion, but may be neglected elsewhere. The other necessary data should be available from the Tamar data base.

The resulting analysis would provide a valuable adjunct to other models relating to estuarine equilibrium, and should assist in widening them to include otherwise neglected processes.

7. REFERENCES

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Table 1 Flux terms at Hatton Middle Bank, Humber Estuary

TERM	Springs		$\text{gm}^{-1}\text{s}^{-1}$	Neaps	
	Coarse	Fine		Coarse	Fine
1	-311	-605		-67	-617
2	134	261		13	118
3	17	36		0	-3
4	52	-198		-38	58
5	50	44		26	10
6	24	17		-13	100
7	43	-16		50	108
total	9	-461		-29	-226

Table 2 Flux terms; Tamar Estuary

Distance km	Advection	Tidal pumping ppmms-1	Shear
3.0	-90.3	143.3	-3.7
3.7	-115.7	125.9	-0.5
4.5	-358.1	443.8	-69.8
5.6	-225.6	137	-19.0
7.0	-26.6	92.2	-2.8
8.5	8.3	16.2	0.6
8.5	1	17.5	-0.3
19.8	-0.4	-0.2	0
22.7	0.5	-0.2	-0.1
26.8	0.1	-0.2	-0.2

A SIMULATION OF TIDAL CREEK RESPONSE TO MANAGED RETREAT USING A HYBRID REGIME MODEL

Jeremy Spearman

email: jez@hrwallingford.co.uk

HR Wallingford, Howbery Park, Wallingford, Oxon, OX10 8BA, UK

1 INTRODUCTION

1.1 Background

As part of the EMPHASYS project a hybrid morphological modelling tool, HYMORPH, was used to simulate the morphological evolution of a tidal creek in response to managed retreat. The tidal creek investigated was part of Tollesbury Fleet, a tributary of the River Blackwater in Essex, UK. This creek is currently part of an ongoing MAFF study into the effects of coastal realignment and a farmers field, located at the head of the creek was deliberately breached in 1995 to create setback.

1.2 The hybrid model approach

Hybrid models utilise both top-down and bottom-up approaches, in this case combining regime theory with a 1D flow model. A calibrated 1D model of the tidal creek was developed based on field measurements, bathymetric survey data and 2D modelling work. This 1D model was used to develop regime relationships for cross-sectional area, width and depth based on a power law dependence on discharge. After deriving the regime relationships the 1D model was re-run with the breach in place and the corresponding pattern of discharge and cross-sectional area was used as input to the regime relationships to establish a new bathymetry corresponding to a time in the future. The 1D model was re-run with this new bathymetry to gain the next set of discharge/area data, and so on, iteratively, simulating the evolution of the morphology over time. This type of procedure reproduces the estuary-wide evolution of sediment transport in muddy estuaries over time, (Spearman et al, 1998).

1.3 Tollesbury Creek

Tollesbury Creek itself is just over 1km in length (Figure 1). Mean spring tidal range within the estuary is of the order of 4m. The intertidal area of the creek is composed of a complex network of saltmarsh cliffs and small-

scale creeks and most of the creek dries out at low water. Peak currents are of the order of 0.3-0.5m/s and wave heights are small, the annual wave height being of the order of 0.3m (H_s).

The breach occurred in 1995, allowing the inundation of a 21 hectare area. The ongoing study into the impact of the breach includes regular bathymetric and biological field surveys. As part of the study 2D flow modelling of the scenarios before and after the breach and a series of bathymetric surveys from before the breach in 1994 and annual surveys after the breach in 1996, 1997, 1998 and 1999.

2 HYDRODYNAMIC MODELLING

2.1 Introduction

Tollesbury Creek exhibits some significant 2D flow characteristics which reduce the ability of a 1D model to describe the hydrodynamic behaviour of the creek in an accurate manner. The results of the 2D modelling undertaken as part of the MAFF study (Chesher et al, 1995) identified the following features:

- The level and flow through the salt marsh level is poorly defined.
- The catchment boundary of Tollesbury Creek is poorly defined.
- The creek system experiences two phase flow with the direction of flow changing significantly near HW.
- There are significant differences in the directions of the flow before and after the breach in the vicinity of the breach itself. This feature is most prevalent near HW, when the water level has risen above the level of the salt marsh.

These features affect the prediction of cross-section area and discharge by the 1D flow model and therefore the regime relationships and predicted creek evolution of the hybrid morphological model. While the 1D model

would have to represent the salt marsh surface and cliff as a constant solid boundary, in reality there is considerable flow through the salt marsh creeks.

The scenario of managed setback therefore presents a difficult test for the hybrid approach used and this type of approach is open to criticism for this reason. However, it is hoped that this study will highlight the various practical problems involved with predicting morphological change resulting from setback schemes and will provide an indication of the degree of accuracy which can be expected to be achieved with good practice.

2.2 1D flow model

- The model used for the 1D flow modelling was the HR/Halcrow ISIS model. The bathymetric data from the 1994 pre breach survey was processed augmented using data from the TELEMAC-2D model bathymetry used in Chesher et al (1995) and from further field surveys and aerial photograph analysis presented in the same study and in Spearman and Chesher (1997). The downstream tidal boundary condition was taken from field measurements undertaken near the mouth of the creek (Chesher et al, 1995) and the upstream discharge boundary conditions imposed were all of zero flux. Further field measurements given in Chesher et al (1995), consisting of water level measurements and fixed point measurements of current speed were used as calibration data. However, no measurements of water level or current speed were available from the setback field itself. The results of the calibration exercise can be summarised as follows:
- The tidal variation within the creek was well reproduced by the flow model but current speeds were not reproduced as accurately.
- The 1D flow model predicts that peak velocity (on both ebb and flood tides) occurs at a higher water levels than the observations. This will be returned to later.
- Although the 1D model did not reproduce the (modified) observed current speeds well, the results are similar to the results gained by the 2D models in Chesher et al

(1995), in particular the tidal prism throughout the creek matched those of the 2D model results very closely.

- Furthermore, changing the calibration parameters did not change the essential behaviour of the model.

It was considered that any deficiencies in the 1D model were either a result of processes also not reproduced in the 2D modelling, and therefore beyond the scope of this study to consider further, or possibly a result of uncertainty arising from field measurements.

3 MORPHOLOGICAL MODELLING

3.1 Choice of regime relationship

As a first step towards simulating the evolution of the creek over time, the calibrated 1D model discussed above was used to derive the regime relationship. A large number of different discharge/area parameters have been used in literature, of which relationships between peak discharge and area at peak discharge, and tidal prism and area at mean water level, are the most common. However, for this study these relationships were rejected for the following reasons:

- A relationship based on tidal prism would have been too susceptible to uncertainty in the representation of flow over and through the saltmarsh and the poorly defined water shed of the creek.
- The relationship based on peak discharge was found to be too responsive to effects other than the effect of the breach. This may be due to sudden large changes in the cross-section area at peak discharge as the water level at which peak discharge occurred crept above or below the defined salt marsh storage level.
- Previous morphological studies reproducing evolution of the Lune Estuary as a response to training wall construction (Spearman et al, 1998) found that relationships based on peak discharge cause changes in the estuary at higher water levels thus causing large changes at the channel margins which were not observed to occur.

For these reasons a relationship between discharge at peak velocity and area at peak velocity was chosen. This relationship was best able to describe changes in the LW

channel and was found to respond well to the forcing effect of the breach.

3.2 Initial conditions for evolution

In deriving the regime relationship it should be recognised that the relationship chosen is a best fit relationship through a fair degree of point scatter and that, without in some way accounting for the discrepancy between the scatter and the best fit relationship, evolution will occur as a result of the initial “less than perfect” regime state of the initial estuary bathymetry rather than the scheme being considered. There are two possible ways in which evolution resulting from the initial state can be eliminated:

- The first is to store the discrepancies, consider them to be constant throughout the evolution and to take these discrepancies into account whenever the regime algorithm is utilised. This procedure was used in some initial runs but it was considered that this method did not completely remove spurious evolution caused by the initial state of the model. In particular, as discharges and cross-sections change over the evolution, each cross-section will change in the degree to which it differs from the regime state.
- The second way to remove spurious evolution is to “smooth” the estuary bathymetry by evolving the estuary to a steady state (subject to some sensible tolerance), rederiving the regime relationship on each iteration. This method has the benefit of allowing morphological simulation to commence with a (nearly) perfectly in-regime estuary. However, it is advised that some care should be taken to achieve a calibrated model that is reasonably close to regime before smoothing is undertaken as extensive smoothing could change the nature of the estuary being simulated, which would itself create spurious evolution.

In this type of modelling the experience of the author is that both the initial smoothing and the simulation of evolution benefit from reducing the magnitude of bathymetric change on each iteration – a process analogous to using a shorter time step in hydrodynamic modelling. This is because bathymetric changes resulting

from large local impacts can sometimes respond in oscillatory behaviour, or even show signs of instability. For this reason, throughout this study, iterations take the form of “half-steps”.

The smoothing process undertaken consisted of 5 half-steps, being terminated when the average discrepancy of cross-sectional discharge at peak velocity, $Q_{V_{max}}$, from the regime value was less than 1% and the maximum discrepancy was less than 5%. The resultant regime relationship took the form, $Q_{V_{max}} = 0.4194 A_{V_{max}}^{0.9516}$, where $A_{V_{max}}$ is the cross-sectional area at the time of peak velocity.

It was considered that the initial evolution of the creek in the vicinity of the breach (cross-sections 29, 20 and 30a) would not be well reproduced by the regime method and so bathymetric data for the scenario just after the breach was used for these sections.

3.3 Time scale of encroachment by saltmarsh

The procedure of finding the regime relationship for the estuary highlighted the fact that the section of the channel leading to the breach – cross sections 29, 30 and 30a (See Figure 1) -was not “in regime” with the rest of the estuary. The pre-breach current speeds through this section were much reduced, (for both the 1D and 2D models) even though the sea wall protecting the farmers field had been in place for approximately 30 years. This result suggest that this part of the creek is sediment supply limited or at least that the time scale for encroachment by saltmarsh is very long. It is also apparent from anecdotal observations that there has been no noticeable erosion of the salt marsh cliffs. For this reason the evolution of the channel in the simulations described below was constrained to below 1.5mOD which was considered to be a reasonable estimate of the level at which saltmarsh cliffing would occur.

3.4 Algorithm used to change bathymetry

The relationships for width, W , and depth, H , were derived from the final smoothed estuary state and took the following form, $W \propto Q^{0.4749}$ and $H \propto Q^{0.6271}$. Note that the dependence on depth is much greater than normally found in estuaries. Usually estuary width will change

more dramatically along its length than estuary depth. This may be a result of the slower time-scale of evolution resulting from the salt marsh margins of the creek channel, which largely controls the variation in channel width.

The flow model was used to derive the value of $Q_{V_{max}}$ and $A_{V_{max}}$ and the regime relationship was used to derive the regime value of discharge, Q_{reg} for the given cross-section area. The width and depth were then changed as follows:

$$W \rightarrow W \left(\frac{Q_{V_{max}}}{Q_{reg}} \right)^{0.4749} \quad H \rightarrow H \left(\frac{Q_{V_{max}}}{Q_{reg}} \right)^{0.6271}$$

The width and depth were specified as those corresponding to the water level at which peak velocity occurred, but the bathymetry was not changed above the level of 1.5mOD for the reasons specified in Section 3.3.

3.5 Time scale of evolution

The time scale corresponding to each iteration was estimated by running a simple calculation of the total net erosion occurring for a single (spring) tide and comparing this total with the total net erosion predicted by the regime model. The ratio between these totals represented the number of spring tides simulated by each iteration of the regime model. The sediment transport calculation used constant but representative values for settling velocity, and suspended sediment concentration and deposition threshold. However, the net erosion within the creek was dominated by the parameters of erosion threshold and erosion rate constant. The field measurements of erosion threshold suggested a value of $3N/m^2$ was representative for the erosion threshold, which is high but not unrepresentative of consolidated intertidal mud. The erosion rate constant used was $0.0002kg/NS$ which is a value corresponding to the lower limit of the range of values from analysis of different mud types by HR. It was assumed that the net erosion resulting from neap tides was small compared with that of spring tides. In some ways this manner of calculating the time-scale of the corresponding evolution is unsatisfactory since the range of erosion rates produced by the possible range of all the relevant parameters is at least an order of magnitude and thus the time scale can be

“legitimately” adjusted to almost any value required.

4 RESULTS

The results of the second simulation were compared to the surveyed bathymetry for the end of 1999, some 4 years after the breach. Figures 3 to 9 show the comparison as cross-sections 3, 9, 13, 16, 19, 29 and 30. It can be seen that although the prediction of evolution of the sections near the breach, is plausible (though no data is available at present to validate the model in this area), the model predicts significantly more erosion as a result of the breach than has been observed at sections 3, 13 and 16. The observations show that cross-section 19, in the main channel upstream of the breach, does not significantly experience any changes as a result of the breach (see Figure 7). The model predicts a small amount of accretion which is predicted to disappear with further evolution over time.

The results also present the predicted final regime state of the creek which corresponds to a time approximately 20 years after the breach occurred.

Sensitivity tests were carried out to observe the sensitivity of the results to the representation of flow in the setback field and the sensitivity of the results to allowing the breach itself to evolve. The results showed that the evolution of the creek was relatively insensitive to both these changes.

5 DISCUSSION OF RESULTS

The predictions of the hybrid method indicate that a reasonable assessment of future evolution can be achieved although the accuracy of predictions can be best described as qualitative rather than quantitative. However, the short description of the study included here masks the considerable number of trial runs and the extensive examination of results which were undertaken to achieve these results. Furthermore, this study has benefited from hindsight in being able to make judgements about the manner in which evolution occurred, and in being able to use bathymetric data from just after the breach to eliminate further error that would result from trying to reproduce the rapid evolution occurring for the period immediately after breaching. Essentially the hybrid model has

been “calibrated” to reproduce the observed evolution of the creek. Without the benefit of hindsight, and this “calibration” process the inaccuracy of predictions would have been considerably greater. It is possible, though, that experience gained as a result of the completion of a number of such modelling studies could provide some of the insights that hindsight has provided in this case.

The 2D features of the creek discussed in Section 2.1 do not appear to have caused too many problems for the method in this particular case because the 2D features are manifest near HW and the peak velocities driving the evolution of the creek occur sufficiently below this level as to be reasonably approximated by the 1D model. This would not be the case had a regime relationship based on tidal prism or peak discharge been used. The inability of the 1D model to produce the correct phasing for peak velocity may be partly attributable to 2D features, but it should be noted that 2D modelling work carried out for the same creek produced very similar results.

The over-prediction of erosion downstream of the breach could be partly due to the fact that the 1D flow model generally predicts peak velocity to occur at higher water levels than the observations and so any modification of bathymetry by the regime algorithm will predict greater amounts of erosion. If so it would appear that the accuracy of the 1D flow model, in particular the phasing of peak current speed, has a significant effect on the predicted evolution. This problem also affects regime relationships involving peak discharge, but does not affect regime relationships involving cross-section area parameters which operate at a fixed level such as cross-section area at mean water which is generally used in regime relationships with tidal prism.

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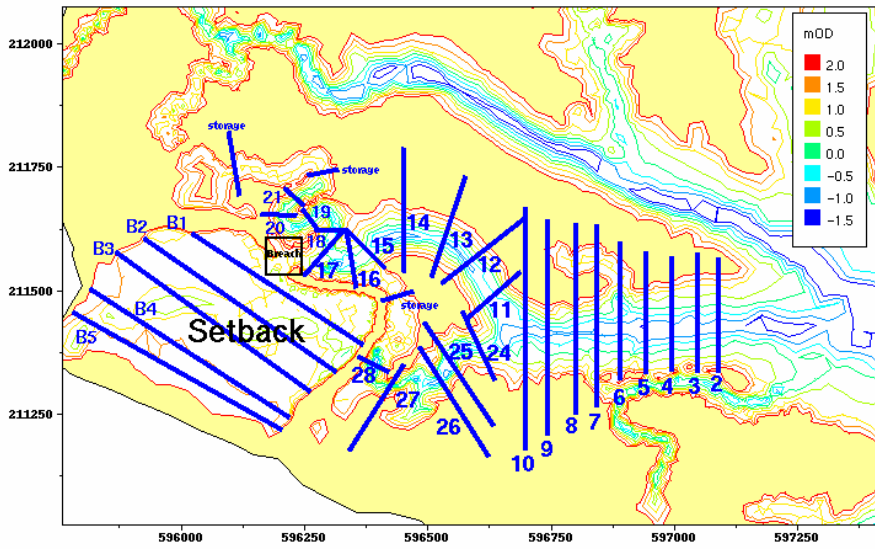


Figure 1 Tollesbury Creek and flow model cross-sections

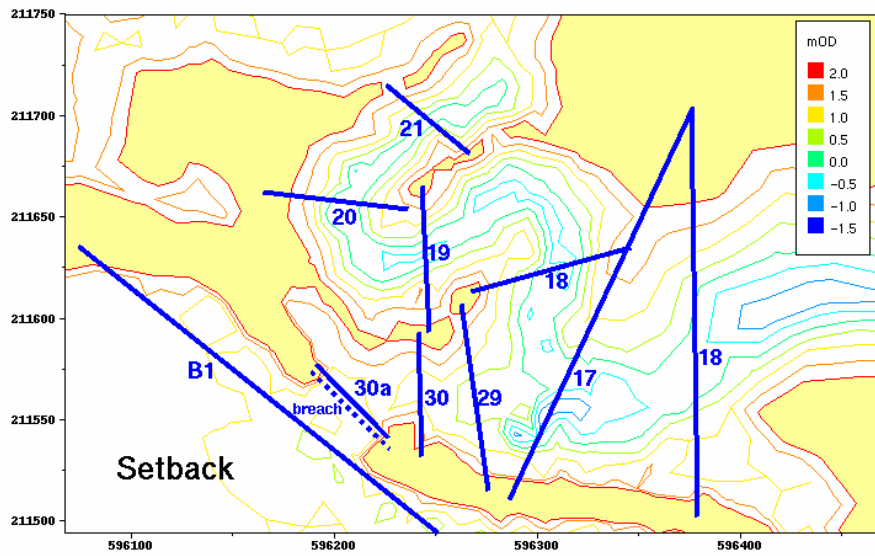


Figure 2 Tollesbury Creek in the vicinity of the breach

Figure 3 Predicted and observed changes at cross-section 3 (near mouth)

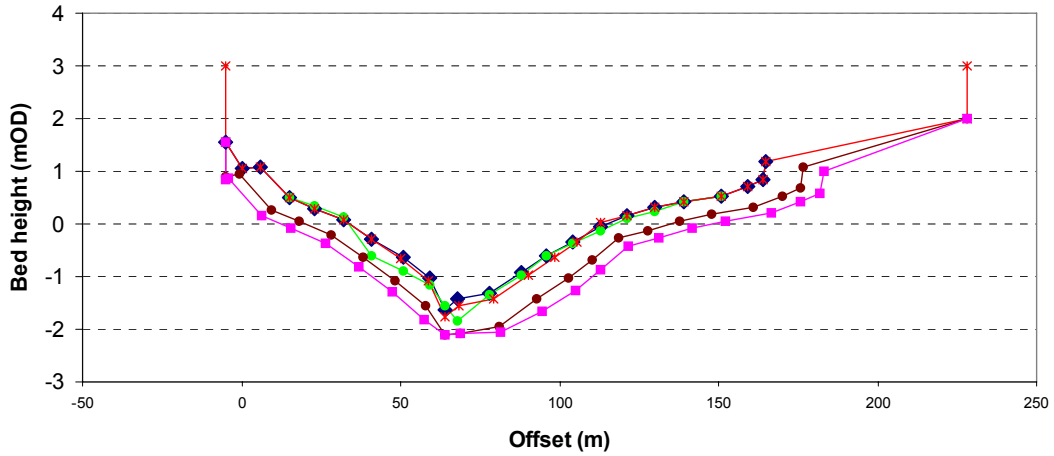


Figure 4 Predicted and observed changes at cross-section 9

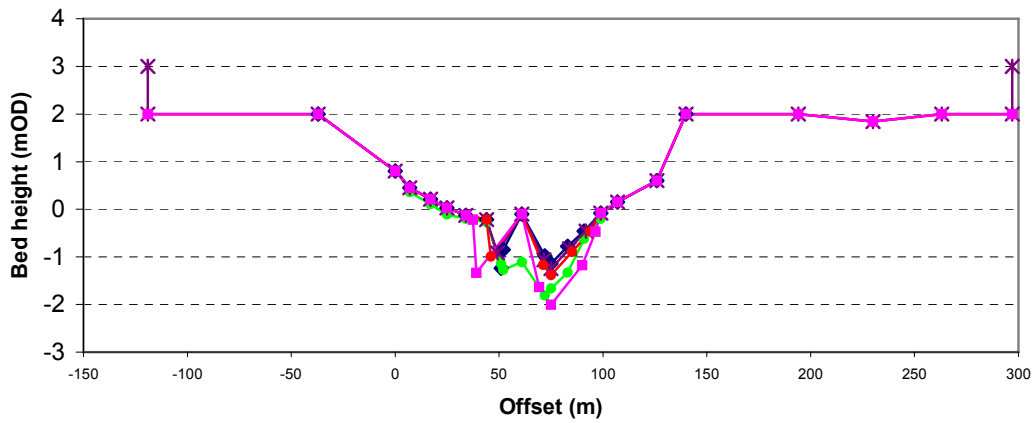


Figure 5 Predicted and observed changes at cross-section 13

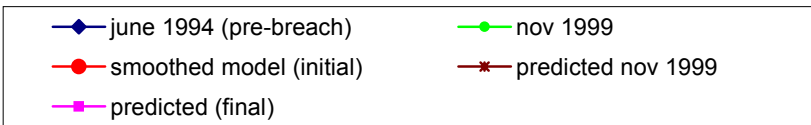
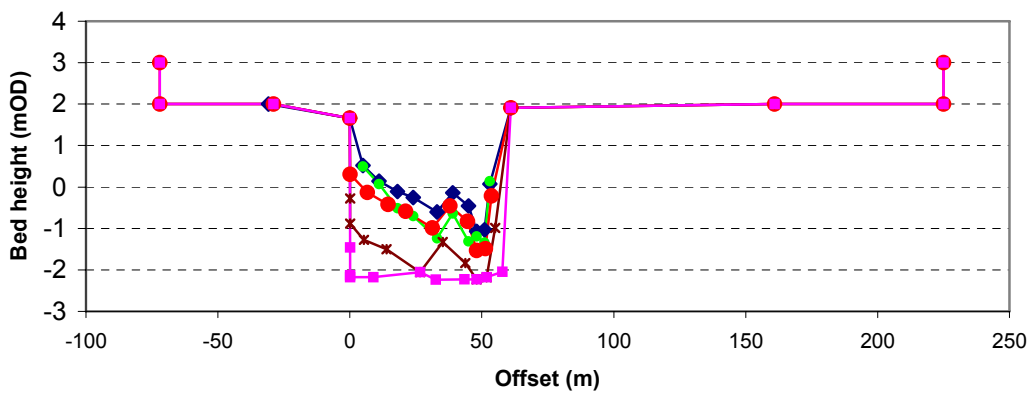


Figure 6 Predicted and observed changes at cross-section 16 (downstream of breach)

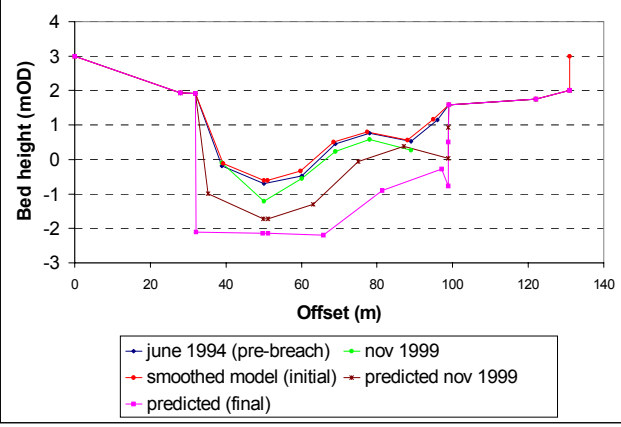


Figure 7 Predicted and observed changes at cross-section 19 (upstream of breach)

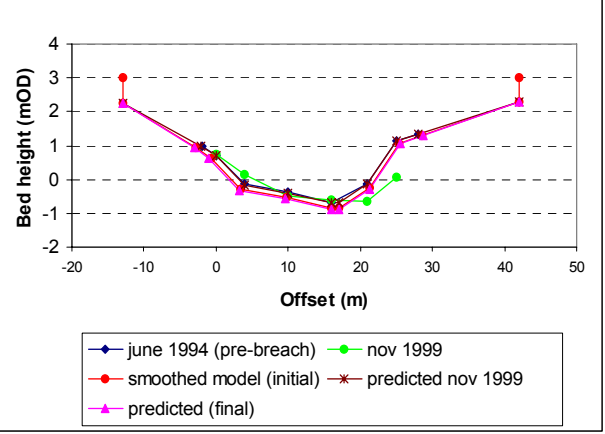


Figure 8 Predicted and observed changes at cross-section 29

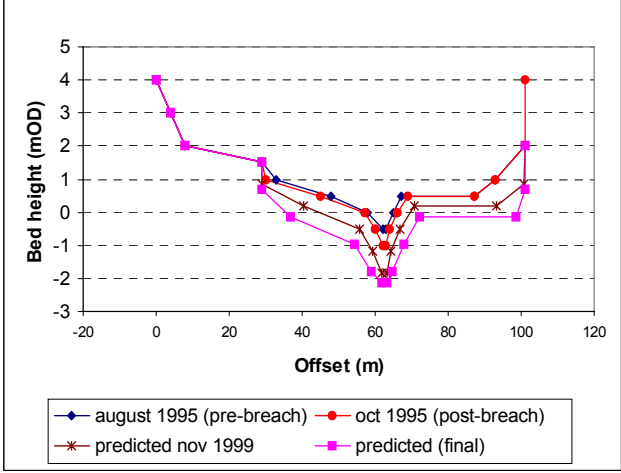
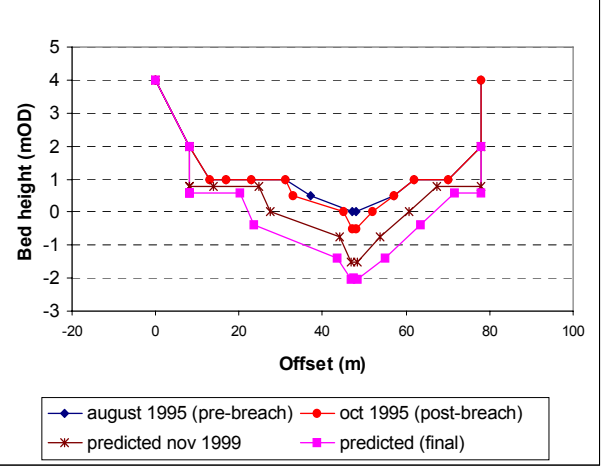


Figure 9 Predicted and observed changes at cross-section 30



ESTMORPH HUMBER ESTUARY MODEL AND HABITAT EVALUATION; MODELLING OF LONG-TERM MORPHOLOGICAL DEVELOPMENT OF HUMBER ESTUARY PLUS ECOLOGICAL ASSESSMENTS

Zheng Wang, Mindert de Vries and Andries Roelfzema

email: andries.roelfzema@wldelft.nl

WL I Delft Hydraulics, Marine and Coastal Management, PO Box 177, NL-2600 MH Delft, NL

In collaboration with

Andrew Kenny of ABP R & C and John Goss-Custard of CEH

1. INTRODUCTION

Within his task as a manager /regulator of an estuary, the responsible officer often has to ask himself how his estuary will look like in the future. How will it develop due to natural changes, such as sea-level rise or due to man made interventions such as harbour extensions, reclamation works etc., and how may these developments affect the variety of the estuarine functions? The hybrid long-term morphological model ESTMORF has been developed in particular to answer these questions. In combination with biological data and assessments the model can give insights in the overall biogeomorphological state of the estuary with time horizons ranging from decades until a few centuries. The present document aims at giving an overview of the major capabilities and potentials of this model system via an application to the Humber Estuary.

2. MORPHOLOGICAL MODELLING

Based on ESTMORF, a hybrid type long-term morphological model has been set up for the Humber estuary, see figure 2.1. The major purpose of this part of the study is to evaluate the ability of the ESTMORF model for studying morphological development in estuaries and to provide morphological data for ecological impact assessments. No detailed calibration of the model has been carried out. Nevertheless the behaviour of the model appears to be logical and the simulated morphological changes due to sea level rise at a rate of 0.2 m/century agree quite well with the observations.

As an example of human interference a not effected land reclamation project is considered. Sea level rise has been included with different

rates. In total 5 simulations of 50 years have been carried out for analysing the impact of the land reclamation project in combination with sea level rise. The results of a simulation with a sea level rise of 0.2 m/century are shown in Fig. 2.2. In this figure the change of the wet volume under +3.5 m is shown for the various parts (upper picture) of the estuary and for the estuary as a whole (bottom picture).

Under the influence of sea level rise sedimentation occurs in the estuary, as can be expected because sea level rise causes an over depth in the estuary. However, the over depth needs to be build up first before the morphological development will compensate it. This explains the increasing rate of sedimentation in all the parts in time. After a period of about 35 years a dynamic equilibrium situation is established, indicated by the fact that the sedimentation rate becomes constant. The total sedimentation rate at the end of the simulation is about 0.18 million m³/year. This is less than the volume increase by sea level rise (about 0.5 million m³). There are two reasons for this. First, sedimentation can only occur if there is an over depth in the estuary, so there is a lag of the morphological reaction to the sea level rise. The second reason is that the tidal volume increases due to the sea level rise. The flood volume at the mouth of the estuary is increased by about 1% at the end of the simulation. This increase is due to two reasons. First, the storage area becomes larger at higher water level and thereby increasing the tidal prism at the same tidal range. Second, the tidal range within the estuary increases due to sea level rise. As shown in the upper picture of Fig. 2.3, the low water at the upper end of the estuary rises less than the

sea level rise whereas the higher water slightly more, causing an increase of the tidal range. Note that there is also a third reason which is not taken into account in the present model, i.e. a possible increase of the tidal range at the mouth. The increased tidal volume means a larger equilibrium cross-sectional area, so the sediment demand caused by the sea level rise is less than the volume increase due to sea level rise. At the dynamic equilibrium state the sedimentation rate is equal to the sediment demand. In summary the following conclusions are drawn from this simulation:

- With a constant sea level rise a dynamic equilibrium situation establishes. The time scale for this development is about 35 years. At this dynamic equilibrium state the sedimentation rate is equal to the sediment demand caused by the sea level rise.
- The sediment demand caused by a sea level rise of 0.2 m/century is according to the model results about 0.18 million m³/year. This is in the same order of magnitude as the observed sedimentation rate in the estuary.
- The sediment demand is smaller than the volume increase due to the sea level rise. This agrees with observations. The reason of this is that the tidal volume increases as sea level rise occurs.
- The increase of tidal volume is caused by increase of storage area in the estuary in combination of increase of the tidal range.

Figure 2.4 shows a simulation without sea level rise and with a land reclamation. Note that the reclamation has not been effected in reality and the present simulation is only meant to demonstrate the ability of the model to simulate the impact of such a project.

The considered land reclamation causes a decrease of the tidal prism in the estuary. As the reclamation is located at the downstream part of the estuary, only for the few sections near the mouth a decrease of the tidal volume will occur. Further it also directly causes a decrease of the cross-sectional area of a number of sections, especially sections 2 and 3. This explains the simulated morphological development as shown in Fig. 2.4. In the upper picture the change of volumes at the sections 1 to 10 are shown and in the lower picture the volume change of the whole estuary. The largest changes occur in the vicinity of the land reclamation itself. Sedimentation

occurs at section 1 because at this section the tidal volume decrease is more important than the decrease of the cross-sectional area. Erosion occurs in sections 2, 3 and 4, where apparently the decrease of the cross-sectional area is the dominant disturbance. The morphological time scale is relatively small, only in the order of about 5 years. This is due to the fact that the length scale of the reclamation is relatively small and that the estuary is morphologically very active.

The volume change of the whole estuary shows also that after the first morphological reaction of the estuary to the disturbance caused by the reclamation with a time scale of about 5 year, morphological change (erosion) with a much larger time scale continues to occur. This can be understood by examining the morphological development in the estuary in more detail, as shown in Fig. 2.5. It can be observed from this figure that upstream of the land reclamation first sedimentation occurs and later erosion occurs. Sedimentation in the first phase is due to the deposition of the material eroded in the sections located at the reclamation. When the erosion at the reclamation stops it is also logical that the deposited material then starts to erode. However, the figure shows that the erosion continues further even after that the original state is established. This means that the land reclamation in combination with the induced morphological change have caused a change of the tidal volume further upstream. The total erosion in the whole estuary in 50 years simulation period is about 10 million m³.

The ability of the model to predict long-term morphological changes due to human interference as well as due to natural development such as sea level rise is well demonstrated by this pilot application. Due to the hybrid character (combining process modelling and empirical relations) of the model it supplies the information of long-term morphological development as well as changes of the hydrodynamic conditions, and takes into account the interaction between the two. For the morphological development the model gives not only the changes in the channel part of the estuary but also the changes of the intertidal areas. The changes can be expressed in changes of volumes as well as changes of horizontal areas under a certain (absolute or relative) level. These informations are required for e.g. sound

ecological assessments. The model can thus supply the large scale information (time and space) for required engineering as well as management purposes.

3. PHYSIOTOPES MODELLING

On the basis of work executed in the Netherlands for various estuaries and the Dutch Wadden Sea three physical factors have been selected that describe the characteristics of so called fysiotoxes. These physiotoxes are therefore defined as homogeneous areas where a certain combination of physical factors is found. Changes in physical conditions outside given boundaries will of course force the change of the physiotope identification for a given location both in time and space. Within the limitations of the present study and availability of parameters from the ESTMORF model, the following factors were used: Depth, Inundation time, Maximum current speed and Salinity. For each factor, classes were derived that indicate a certain range of values. Model results show that the area of brackish flats have been increasing due to the influence of sea level rise. Practically all other physiotoxes show no or little change at 20 cm/century. At 60 cm/century, changes are more severe, decreasing areas in the fresh fysiotoxes, increase in the brackish zone and a less severe decrease in the saline area. Scenario L00 (no sea level rise) illustrates that changes due to land reclamation can be severe for certain physiotoxes (for example, saline low flats sandy).

From an ecological point of view, these physiotoxes can be interpreted as having a certain habitat value to local species. For instance, certain types of benthos will be found on the silty lower flats. Birds will forage on the saline flats or fresh water subtidal areas, depending on the species. Changes in the area of these fysiotope due to land reclamation or sea level rise will therefore directly impact on benthos habitat availability and on bird feeding opportunities. In combination with the zoning found for zoobenthos in the Humber estuary (see work of A. Kenny), it is possible to generate so called 'ecotoxes' that relate the physical environment to distribution of zoobenthos. This will enable the modelling of species such as birds utilising the ecotoxes of the Humber for foraging (see work of J. Goss-Custard). Figure 3.1 shows the Physiotope Map, resulting from the described procedures, based on the morphological model results and 2D data.

4. BIOLOGICAL VALIDATION OF THE PHYSIOTOPE MODEL PREDICTIONS

4.1 Macrobenthic Data

The Environment Agency have collected intertidal core samples for macrobenthic analysis along the whole length of the Humber Estuary every year since the late 1970's. Data covering a period of 15 years from 1984 to 1998 for the north and south banks of the estuary have been analysed by ABP Research to evaluate the trends in the composition of the dominant macrobenthic assemblages along the entire length of the estuary. The location of Environment Agency sampling stations is shown in Figure 4.1.

Each of the 15 annual survey mid-shore station data sets were concatenated into a single sample/species matrix. Two matrices were created, namely; one for the north bank and the other for the south bank. The species abundance data was then double root transformed and sample similarities obtained by applying the Bray-Curtis similarity index. This produced a lower-triangular matrix of sample similarities which can be presented as a dendrogram using group-average linkage hierarchical cluster analysis or as an ordination using non-metric multidimensional scaling. The output from this analysis is presented as dendrograms in Figures 4.2 and 4.3, north and south banks, respectively.

It may be concluded from the cluster analysis that a number of spatially discrete assemblages occur along the entire length the Humber Estuary and that these remain relatively constant over time. However, it is still possible to identify temporal variation within each of the identified assemblages (clusters). For example, the south bank assemblages E and F presented in Figure 4.3 reveal that a transition in ecological state occurred sometime during 1989 with a cluster of years occurring between 1985 and 1988 showing a high degree of similarity then changing state fairly quickly (within one year) to a second cluster composed of years 1990 to 1996. This is further highlighted by performing a non-metric multi-dimensional scaling ordination of the average annual sample densities for assemblage E (Figure 4.4).

4.2 Comparison with the Predicted Physiotoxes

The model predictions of the present day distribution of intertidal physiotoxes (see section

3) identifies 4 sections of the estuary, namely; i. predominantly fresh water influenced tidal flats, ii. brackish water tidal flats, iii. saline muddy flats and, iv. saline sandy flats. Their distribution with the exception of fresh water influenced tidal flats corresponds well with the distribution of the predominant assemblages described above. The similarity is most striking at the transition between brackish water tidal flats (assemblages A & D) and the saline muddy flats (assemblages B1 & E) and the prediction of sandy flats in the Spurn bight area which corresponds well to assemblage B2 & F.

Overall there is a good fit between the predicted physiotores and the present day distribution of macrobenthic assemblages.

5. PREDICTING THE EFFECT OF CHANGES IN ESTUARY MORPHOLOGY ON THE ABUNDANCE OF WADING BIRDS AND WILDFOWL

One of the questions that is most frequently asked when the possible consequences of changes in estuarine morphology are being evaluated is: 'What effect will they have on the populations of migratory waders and wildfowl for which the estuaries of Europe are such important feeding areas during the non-breeding season'. Answering this question has been given special force by the numerous local, national and European instruments that have been set up to protect these birds because of the high conservation value they are accorded internationally. This section discusses and evaluates the two presently-available alternative modelling methods available for making predictions.

The NICHE model approach is conceptually identical to that used to predict how changes in estuary morphology will affect the species composition and biomass density of the benthos. In birds, the approach is based on the well-established finding that the density of intertidal birds is often strongly positively correlated with the density of their main prey organisms. Other factors, such as the risk of being attacked by birds of prey, may also have an influence, but usually this can also be taken into account. From field work, empirical relationships are established between an environmental predictor variable and either (i) the species community structure of the birds or (ii) the density, or number, of particular species. The predictor

variable can be the abundance of the food organisms themselves or an environmental variable, or combination of variables, that are themselves predictors of the species composition and biomass density of the benthos or vegetation on which the birds feed.

The advantage of these regression or correlative models is that they are simple in conception and relatively straightforward to parameterise. The main difficulty is that their predictions are limited in kind and very likely to be faulty.

One reason for this is illustrated in Figure 5.1. Imagine that a change in morphology is expected to reduce the area of mud by 25%. If bird density was at the absolute limit, or carrying capacity, at each point along the regression line, then the equation would probably hold in the new circumstances arising from a change in estuary morphology. But if bird density was not at capacity, bird density at a given value of the predictor variable, shown as y_1 in Figure 5.1, could increase up until, at the value of y_2 , capacity is reached. In this case, the present-day equation could give a very pessimistic prediction of what would happen to bird numbers locally. This happens because some 'compaction' of the birds is possible, allowing the same number to survive in an area of mud that has been much reduced.

There are now several good reasons for believing that capacity as defined above is not widely reached in the estuaries of Europe. The fundamental reason for this is that the supply of birds trying to occupy an estuary may normally fall well below the numbers required to compact the birds to the point at which capacity is reached (Goss-Custard 1993; Goss-Custard *et al.* 1996a). In these circumstances, the predictive model illustrated in Figure 5.1 is unreliable and pessimistic in its predictions. In the hypothetical example posed above, many more birds would remain after 25% of the mud was lost than this method would predict.

A particularly serious weakness with the attractively simple version of this approach that uses the area, or extent, of a simple habitat predictor, such the amount of mud, as the predictor variable is that it makes no allowance for changes in habitat quality. In terms of the quality of the food it provides the birds, one area of mud can be very different to another because

of differences in the species composition, energy-content and biomass density of the benthos. Predictions of the effects on birds of changes in estuary morphology which are likely to affect the benthos could be very unreliable if they rely solely on a physical predictor variable, such as mud area, and do not take changes in the quality of the food supply into account (Goss-Custard *et al.* 1996a). Predictions for the benthos itself are required first if reliable predictions for birds are to be obtained.

But even then, a fundamental problem remains with the attractively simple NICHE model approach. One might, for example, predict on the basis of the present-day predictor regression line shown in Figure 1 that a change in estuary morphology would reduce bird numbers by 1000. But it would be wholly incorrect to interpret this to mean that the population size, either locally on the estuary in question or more widely in the greater population to which the birds in that estuary belong, would therefore be reduced by 1000. Not only would compaction of birds enable more to remain than predicted, but several compensatory behavioural and population-level processes would also contribute to reducing the impact on population size.

It is often overlooked that the numbers of birds in any one estuary depends not only on the quality of that estuary relative to that of the others available but also depends on the size of the larger population to which the birds on that estuary belong. One must therefore predict the effect of changes in estuary morphology on mortality and reproductive rates, and not just the density of feeding birds on the mudflats that are directly affected. Because it cannot do this, the simple NICHE model approach, though entirely suitable for saltmarsh plants and benthos, will not perform well for the mobile and migratory populations for which estuaries are so important.

Behaviour-based individuals population models
CEH is developing a suite of models (BIRD-POP) that are designed to predict the effect of a wide range of environmental change, including changes in estuary morphology, on the survival rates of waders and wildfowl during the non-breeding season, and thus on the population size at both local and global scales. They have none of the limitations of the NICHE model approach. The models are very flexible and, due to the large amount of research conducted on these

species, many of the parameter values are available from the literature. They have many applications and can predict the effects on the birds of changes in the size and quality of feeding area as, as well as the amount of disturbance from people. So, if estuary morphologists and benthos experts predict that, for example, the biomass density of certain macro-invertebrates will change by a particular amount, BIRD-POP is designed to calculate the effect that such a change in the food supplies would have on bird body condition and survival over the non-breeding season and, from that, the effect on population size. The outputs of the behaviour-based model also enable one to predict the effect on the long-term population size, or the body condition of the birds at the end of the winter, for a particular scenario; the latter is important as birds must leave Europe in spring with enough fat reserves to reach their breeding areas. The effects that any predicted morphology-induced change in the mortality rate has on the abundance of birds, whether at the estuary scale or more widely, is calculated using a separate suite of demographic models that include population processes on the breeding grounds as well as those in the non-breeding season (Goss-Custard *et al.* 1995; 1996b).

In summary, the objective of this model development programme is to develop the scientific and technological basis and tools for understanding and predicting the effects on bird numbers and diversity of habitat loss and change and the many other human activities carried out on the coast. The research aims to provide policy makers with quantitative predictions as to the possible negative effects on bird diversity of a wide range of potentially conflicting human activities. Simultaneously, it aims to provide quantitative predictions as to the possible positive, or counter-acting, effects of mitigating measures, such as creating new flats by breaching sea walls. It aims therefore to be able to predict the net impact on bird numbers of the positive and negative effects that changes in estuary morphology can have on the food supplies of these birds.

5.1 CEH saltmarsh niche model

This simple 'top down' model is designed to predict the upshore and downshore limits of the distribution of the major saltmarsh plants.

The environmental variables selected as predictor variables were chosen on the basis of the known

ecology of the plants concerned and from multiple regression analyses carried out by ITE, now CEH. The model predicts the upshore and downshore limits of each species distribution, using different groups of variables for the different plant species. Depending on the saltmarsh species, and whether the upper or lower limit of distribution is being predicted:- the position of MHWN; estuary size; spring tide range; fetch along the direction of the transect; latitude; number of hours uncovered during daylight in autumn (September-November); annual number of hours submerged by more than 50cms of water. The model works at the scale of single estuaries. The model remains to be validated and only considers the west coast of the UK at present, although east coast versions are under development.

6. CONCLUSIONS AND RECOMMENDATIONS

The main results from the morphological modelling used for the biological analyses were developments in depths, inundation time, current speed and salinity (derived from existing data). Based on these parameters the biological analyses resulted in a mapping of physiotores. Comparison with the intertidal samples from the Environment Agency surveys shows good agreement.

In general we conclude that the present hybrid approach, using various data sources like 1D and 2D data, deterministic and empirical data, model data and field data, abiotic and biotic data, in combination with adequate expert judgements, results in an effective procedure to support the management of long-term, large scale estuarine developments.

Based on the present pilot application we conclude also that:

- improvement of this hybrid approach should be effected via analysis of available biological and physical data from the Humber estuary.
- the functionality of this tool allows for further improvement by inclusion of more detailed mathematical models (hydrodynamics, waves, sediment transport and water quality).

On birds it is concluded that behaviour based individual models, such as Bird-pop are highly suited to predict the effect of changes in estuary

morphology on the survival rates of waders and wildfowl during the non-breeding seasons, and thus on the population size at both local and global scales.

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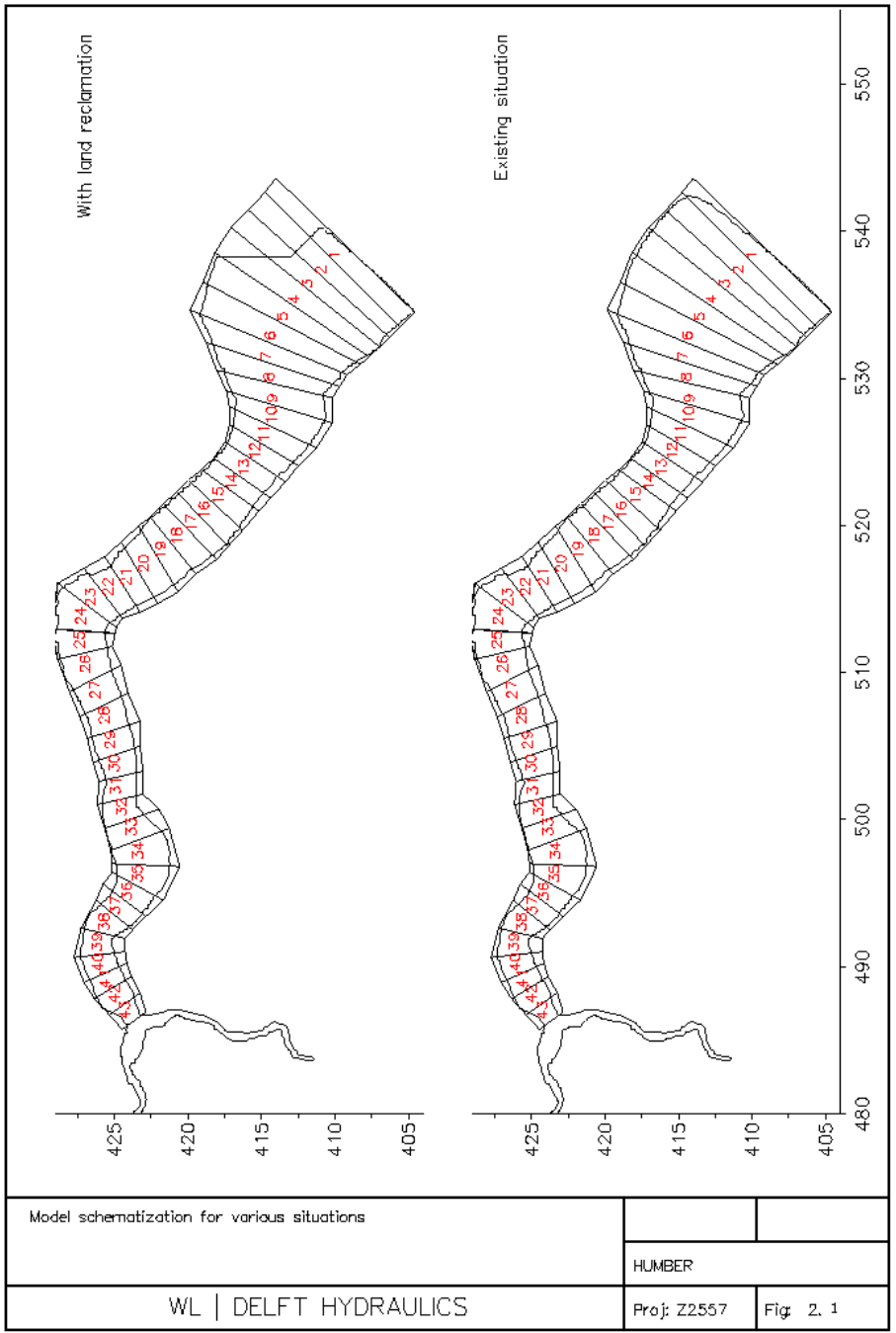
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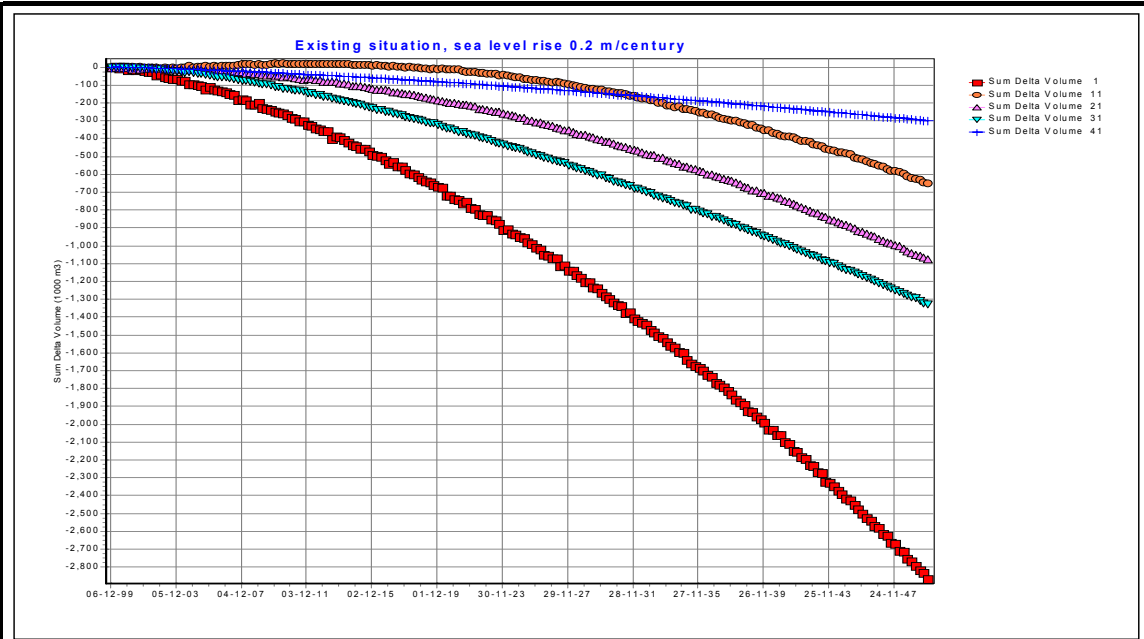
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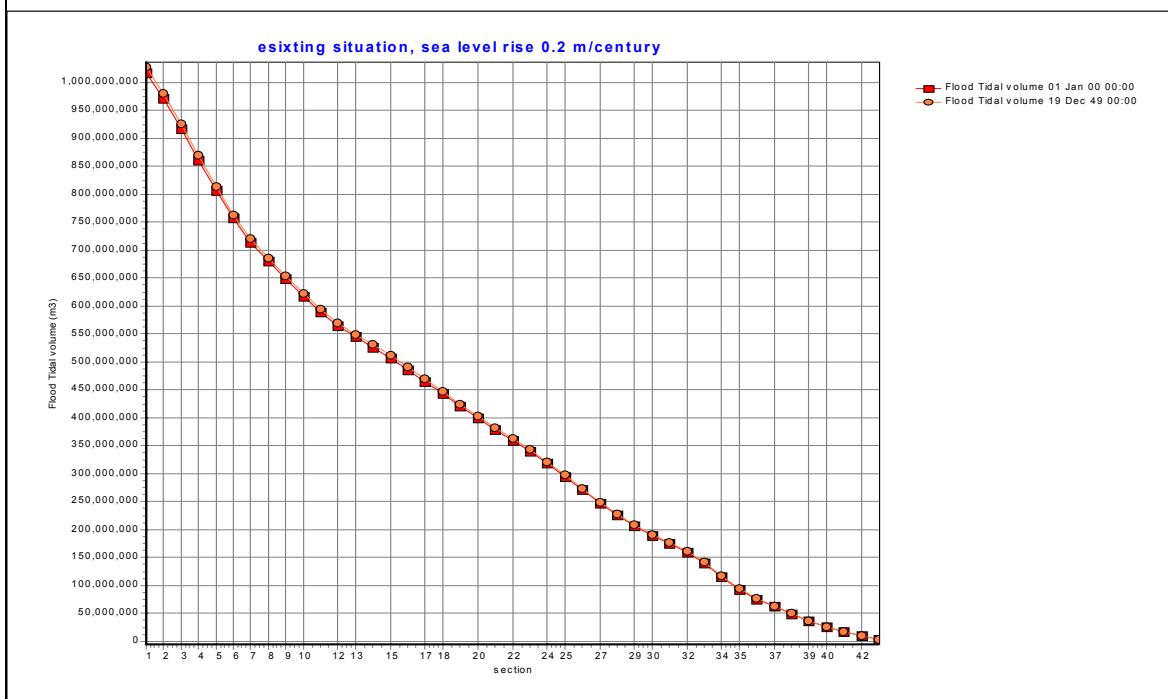
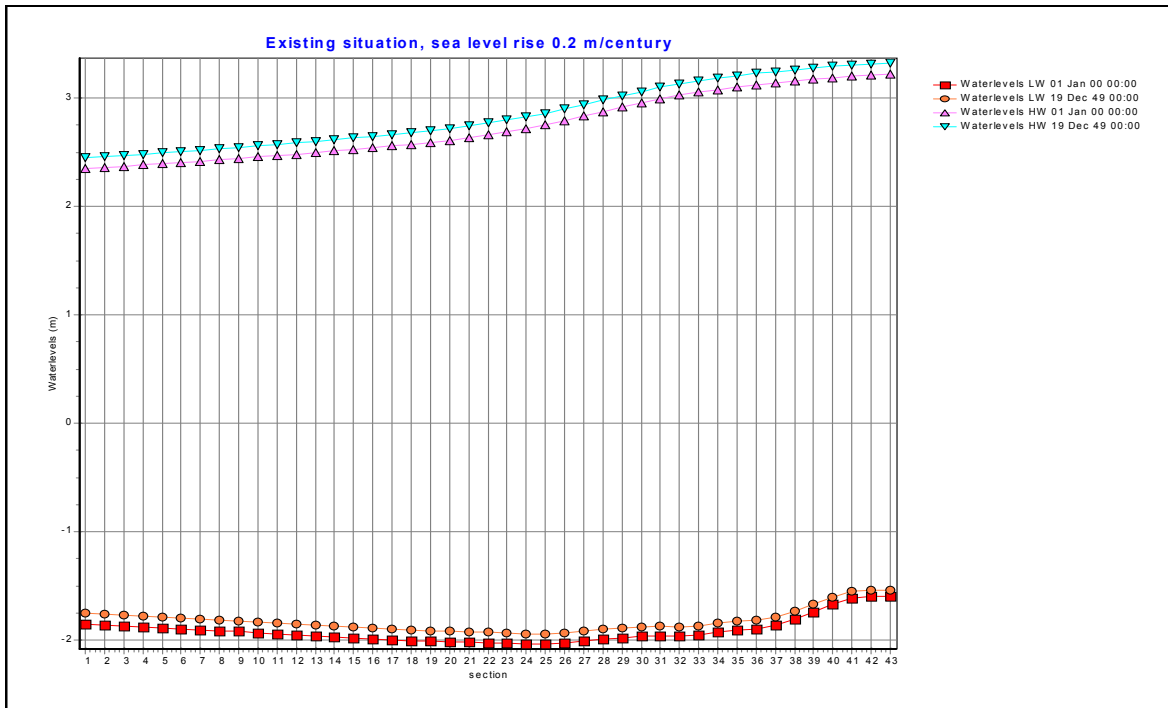
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Volume change under +3.5 m (+=erosion) Run 1: existing situation, sea level rise 0.2 m/century Top: various parts, Bottom: whole estuary	May 2000	EMPHASYS
	ESTMORF Humber	
WL DELFT HYDRAULICS	Z2557	Fig.2.2



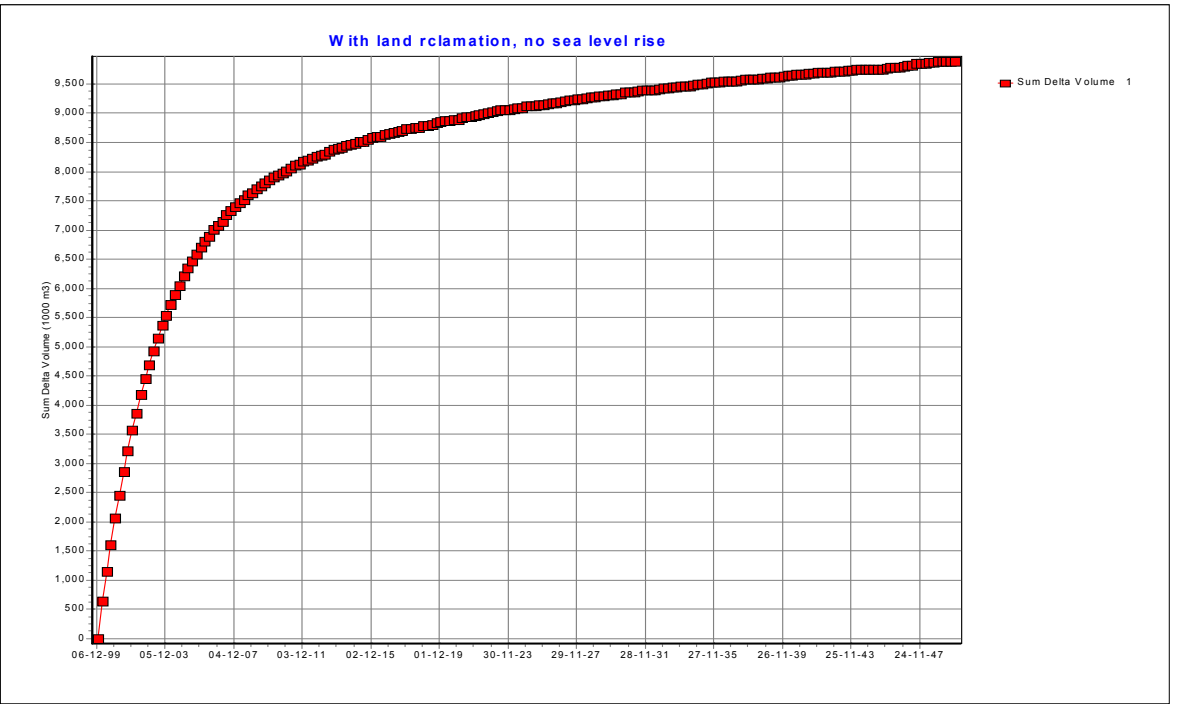
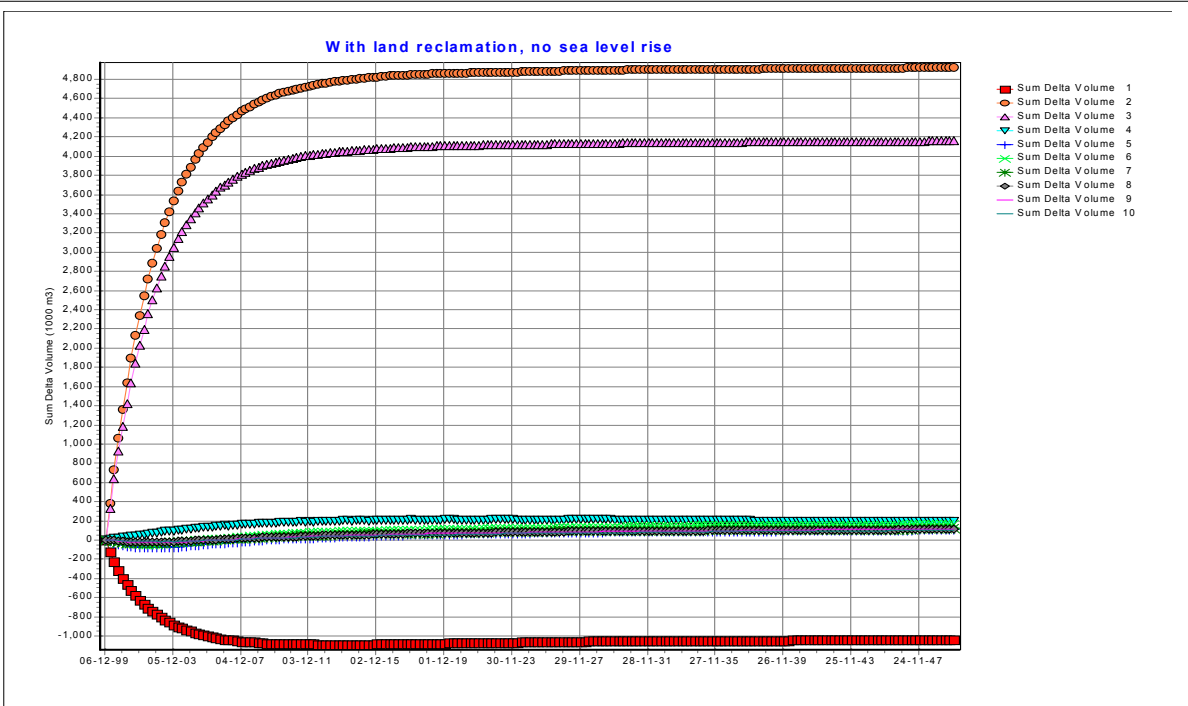
Change of hydrodynamic conditions
 Run 1
 Top: water levels, Bottom: flood volume

May 2000 EMPHASYS

ESTMORF Humber

WL | DELFT HYDRAULICS

Z2557 Fig.2.3



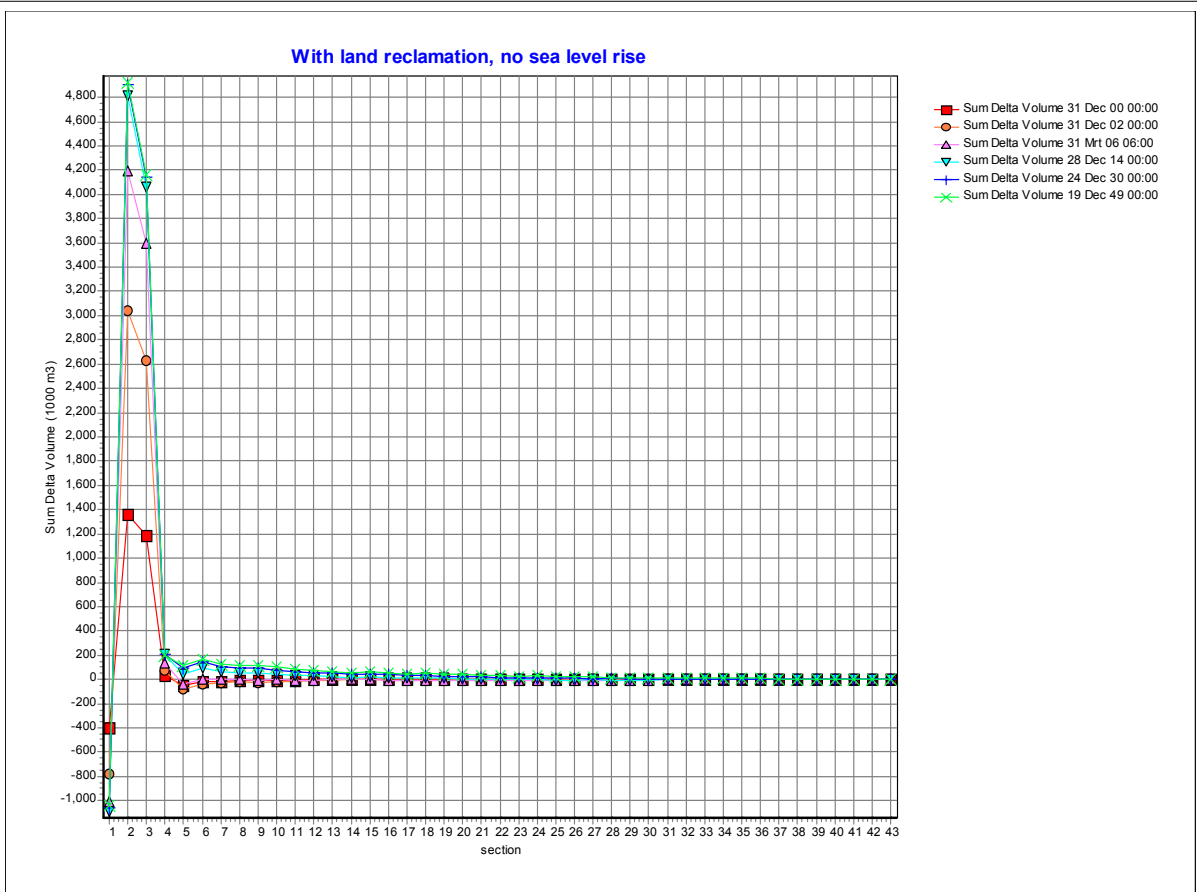
Volume change under + 3.5 m (+ = erosion)
 Run 3
 Top: various parts, Bottom: whole estuary

May 2000 EMPHASYS

ESTMORF Humber

WL | DELFT HYDRAULICS

Z2557 Fig.2.4



Morphological changes along the estuary
Run 3

May 2000 EMPHASYS

ESTMORF Humber

WL | DELFT HYDRAULICS

Z2557 Fig.2.5

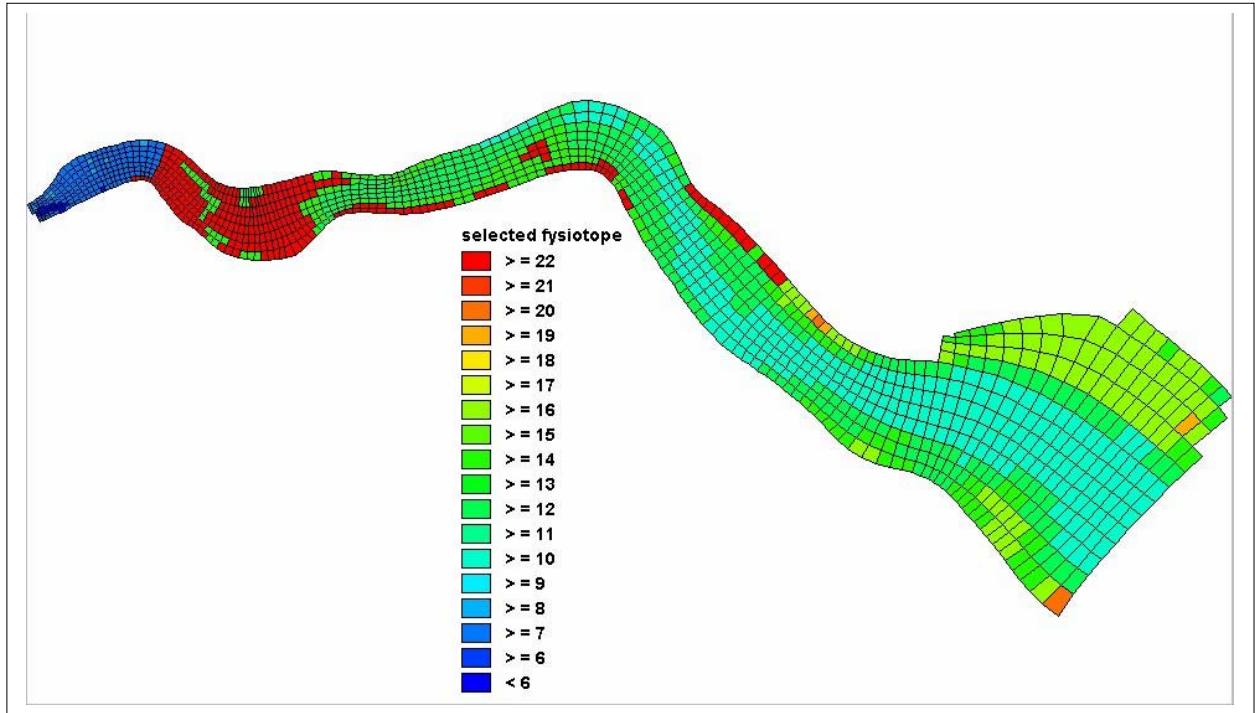


Figure 3.1 Physiotope map, based on selection of best match of physical requirements (present situation)

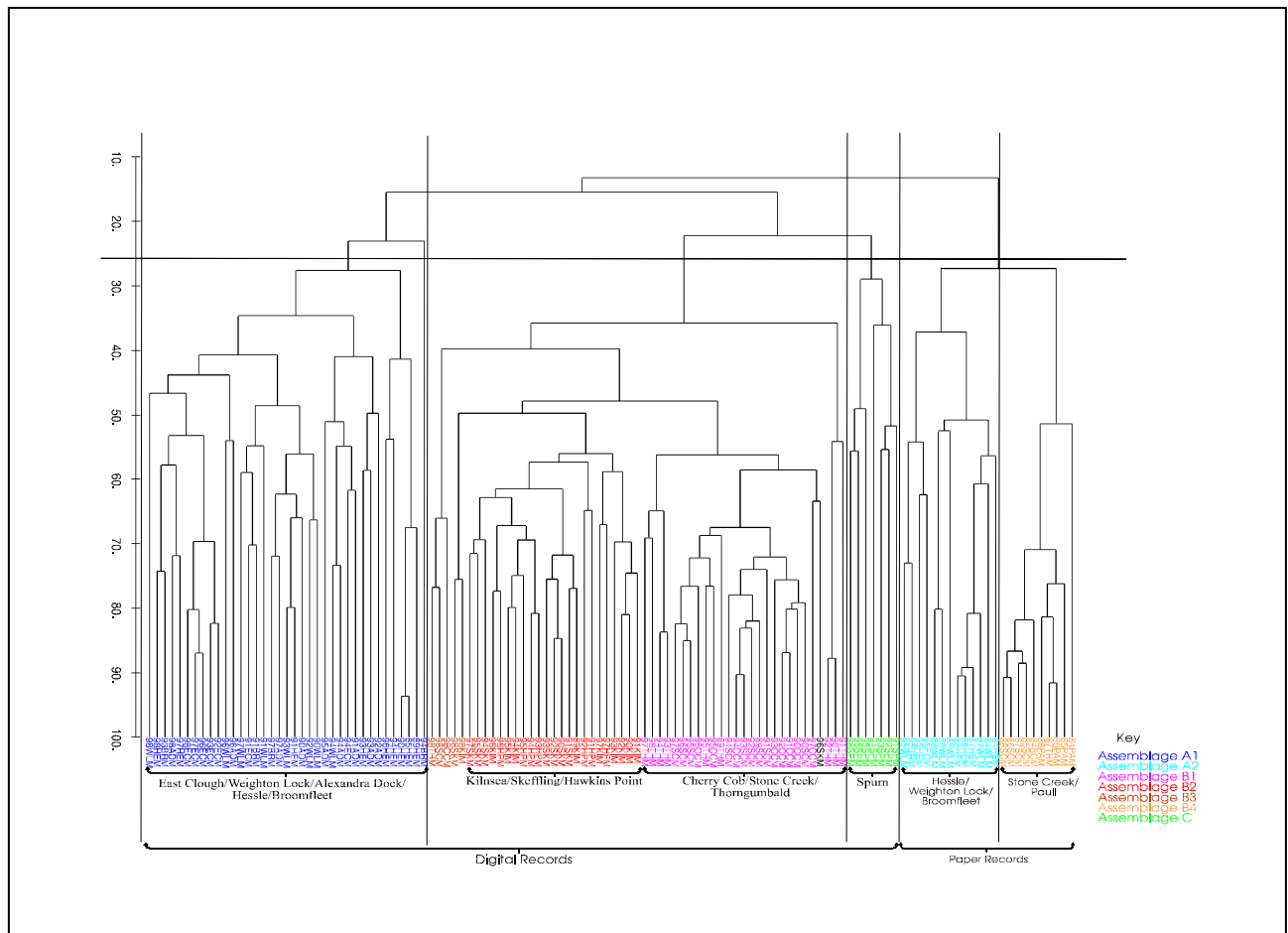
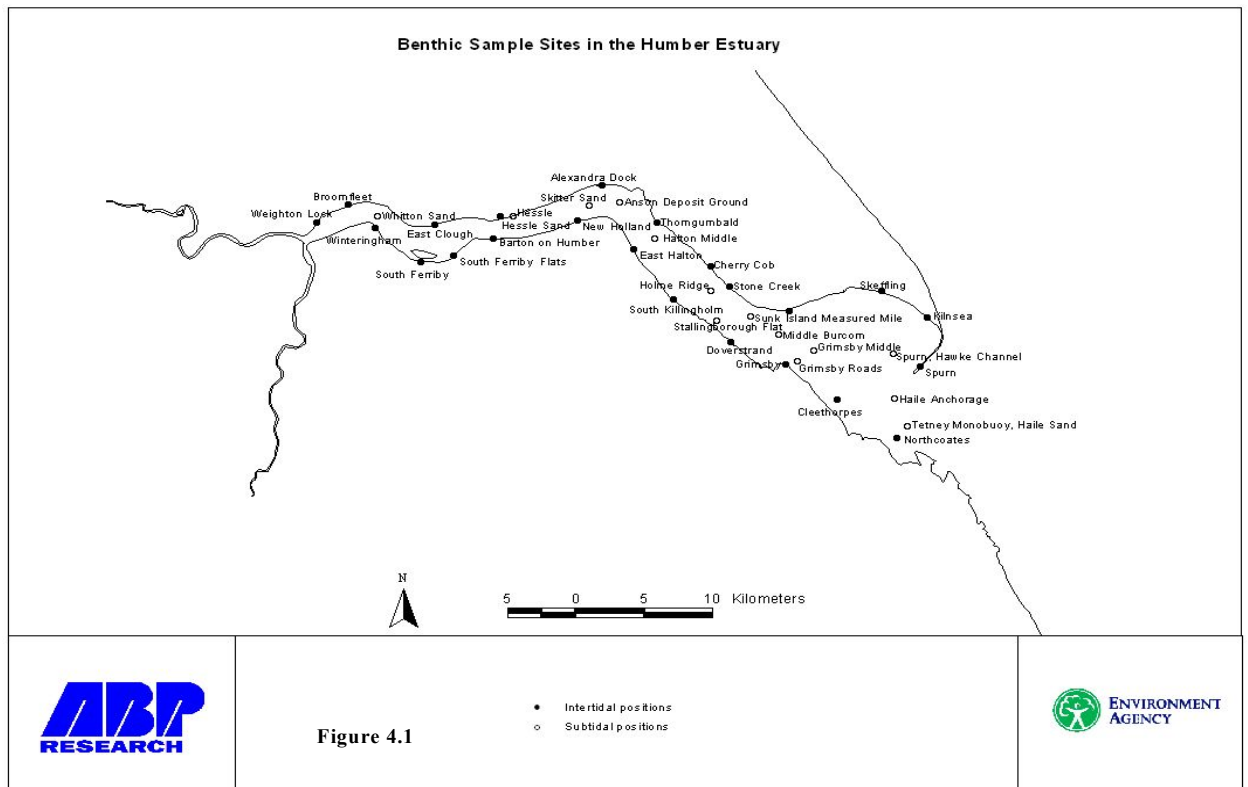


Figure 4.2 North Bank – Intertidal Midshore Macrobenthic Samples

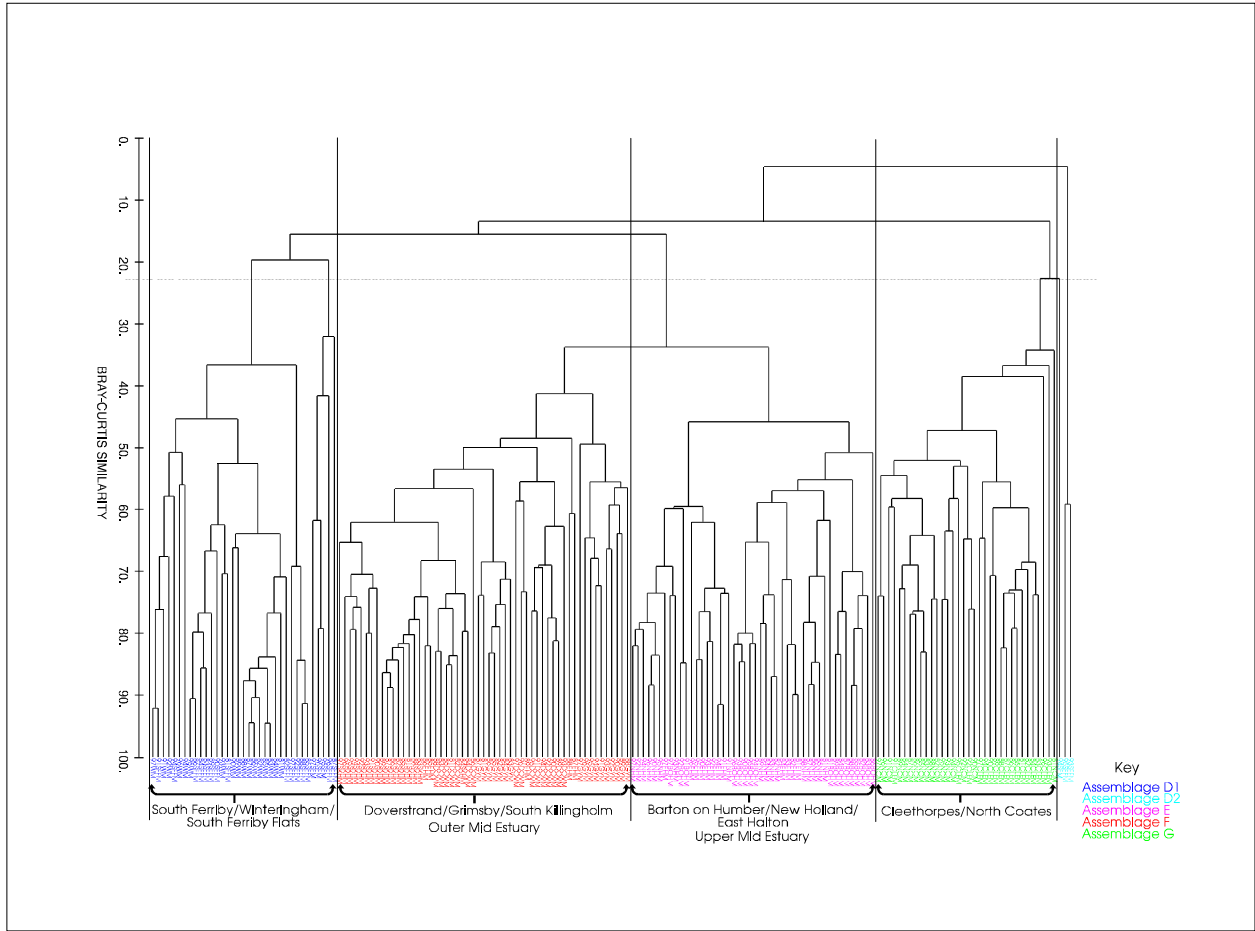


Figure 4.3 South Bank Intertidal Midshore Macrobenthic Samples

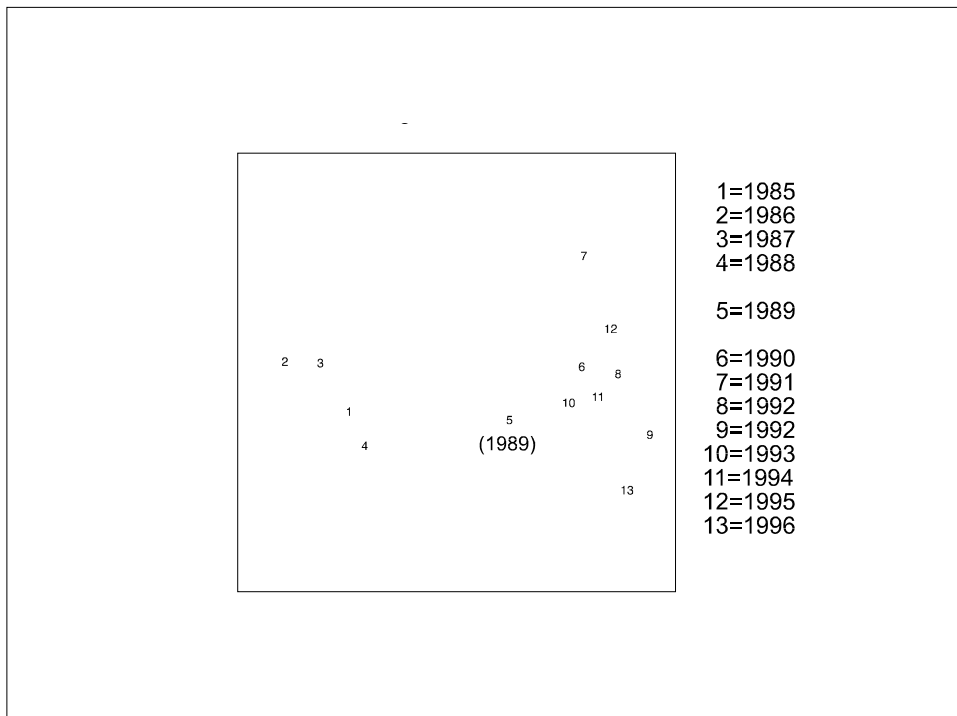


Figure 4.4 Humber South Bank Midshore Intertidal Macrobenthic Samples Assemblage E – MDS Stress 0.08

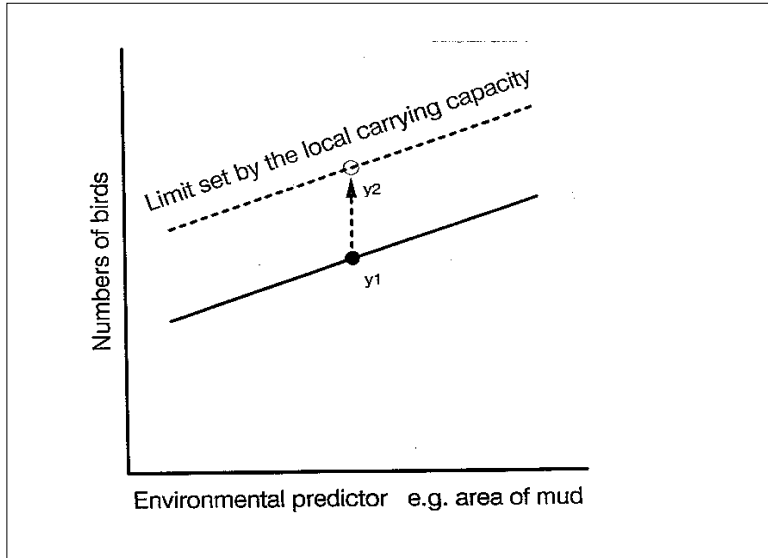


Figure 5.1 A hypothetical relationship between an environmental predictor variable and bird abundance, illustrating how bird abundance at a particular value of the predictor variable could increase if bird density is not already at capacity

THE IMPORTANCE OF PHYSICAL, BIOLOGICAL AND GEOLOGICAL INFLUENCES ON ESTUARINE MORPHOLOGY WITHIN THE UK

Rose Wood

email: r.wood@pml.ac.uk

Plymouth Marine Laboratory, Prospect Place, West Hoe, Plymouth PL1 3DH

1. INTRODUCTION

At a fundamental level, the evolution of estuarine morphology on a historical timescale is determined by the underlying hard geology (and hard engineering works), sediment supply from sources external to the estuary, and sediment erosion, transport and deposition within the estuary. In the southern half of the UK, estuaries have been in the process of 'rollover' while relative sea levels have risen for the last few thousand years. In this state, estuaries move landwards, as the rising sea progressively drowns ancient river valleys. The hard bedrock, which is not erodable on this timescale, provides a basin within which the estuarine bed must lie. This basin may be well-covered with soft sediment and hence not limiting to estuarine evolution, or may be bare, in which case it forms a strong constraint on estuarine morphological change. The amount of sediment entering the estuary from the river or sea determines sediment availability for overall deposition (rather than sediment redistribution) within the system. (For supratidal and intertidal areas of high productivity, and to a lesser extent subtidal areas, locally-produced biomass forms an additional source of organic sediment, in the form of detritus, once broken down and subject to diagenesis e.g in saltmarshes.) The transport of sediment within the estuary and its accretion or erosion is governed by a wide range of physical processes such as tides, storm surges, wind-waves, fluvial flow. In turn, some of these processes are influenced by biotic parameters, such as vegetation effects on boundary layer dynamics (saltmarsh, macroalgae), biotically-enhanced erosion rates (bioturbation), or biologically enhanced deposition rates (biodeposition), shielding of fine sediment by animal shells (mussel beds), or the formation of algal or bacterial mats which cover bed sediment. It should also be noted that chemical processes occurring within estuaries can affect flocculation and cohesiveness, and can be significant for fine particle sedimentation.

To identify the conditions under which the physical, geological and biological processes are at their most important, estuarine areas will be considered as split into 3 zones: upper to supra-tidal, mid to upper tidal and sub to mid-tidal, and 2 extremes of energy level: high energy (large tides or large wind-wave energy) and low energy (small tides or low wind-wave energy). A qualitative table of areas of importance is given below and discussed in the subsequent paragraphs.

	Low energy		High energy
Upper to Supratidal	Physics, Biology	→	Physics, Biology, Geology
Mid to Upper tidal	Physics, Biology	→	Physics, Geology
Sub to mid tidal	Physics	→	Physics, Geology

2. PHYSICAL EFFECTS ON MORPHOLOGY

Clearly, physical forcing is important for all areas of UK estuaries. The location around the coast, and the shape and length of the estuary will determine the tidal forcing. This in turn will influence the net flux of sediment into or out of the estuary. Estuaries must always have a net transport of water seawards, and this will carry with it the finest particles of riverine suspended sediment. However, grains of larger size will only be transported when wave and current induced velocities are strong. The largest grains will remain close to the bed, and only experience bottom currents, whereas lighter particles may be lifted higher in the water column during peak flow, and experience currents at various vertical levels. So, the resulting direction of transport may be landwards or seawards, and will vary with location in the estuary and with weather conditions.

Although tide-induced current flow is invariably the main forcing in estuary evolution, the relative

importance of riverine and tidal flow will change through the length of the estuary. It will also vary seasonally and over spring-neap (and other longer) tidal cycles. The size, soil characteristics and rainfall exposure of the catchment will determine the fluvial flow through the estuary. The interaction of riverine and estuarine flow causes a gradient in salinity (and hence water density) along estuaries which can result in significant enhancement of landward sediment transport.

Lengths of fetch along the direction of prevailing winds, and bathymetry profiles along these and nearby directions will influence exposure to waves. Wind-wave erosion effects will be greatest in exposed zones of shallow water, where the energy penetrates to the bed; and in areas near high water, where the waves are incident on the shoreline for the greatest length of time. The bed slope in this region will also partly determine the exposure to attack by the waves. High energy systems will experience larger velocities, resulting in greater capacity for transport of external sediment into or out of the estuary, and greater mobilisation of sediments within the estuary.

The physical forcing will dominate morphological evolution for all subtidal systems, and sufficiently energetic inter- and supra-tidal systems, provided there is geological scope for morphological change.

3. BIOLOGICAL EFFECTS ON MORPHOLOGY

Benthic biota will have the greatest effect on sediment transport in supra-tidal and upper-tidal, sheltered regions where there is a muddy substrate. Bioturbators will influence sediment supply to higher shore zones, particularly during periods of low to moderate water velocity, by increasing the amount of erodable sediment. Large populations of bioturbators can occur in intertidal areas with greater than 50% fine sediment. These animals are active all year round, and their populations show greater variability between years than within years. Sediment stabilisers, including diatoms and macroalgae, occur within the photic zone, and are seasonal, with spring and sometimes autumn peaks in numbers. Trophic interactions between grazers and algae, as well as spatio-temporal changes in the balance between bioturbators and

bio-stabilisers will alter sediment erodability and thus complicate the seasonality of the effects. Vegetation cover (saltmarsh and macroalgae) in the upper and supra-tidal zone influences water velocities, tending to diminish erosion during storms. Mussel and oyster beds can form large bed features (recorded on geological maps), causing flow separation, and having a large effect on local friction and hence sediment transport. In addition, they actively filter the water, converting small suspended particles into larger, mucus-laden faeces and pseudofaeces (biodeposits). Small, shallow, low to moderate energy estuaries with low sediment loads would be most open to this influence. The bottom-up prediction of flow effects on morphological change is critically dependent on accurate bathymetry and frictional parameterisations, as well as the erosional properties of the bed sediment and depositional properties of the suspended sediment. Macro-biota may influence bathymetry (e.g. mussel beds may be 1-2m high) and friction for shallow estuaries and bays. Biological and chemical effects will influence erosion, flocculation and deposition behaviour in low energy systems. Pollutants may also have adverse effects on key species responsible for bio-stabilisation and bio-destabilisation processes within estuaries.

4. GEOLOGICAL EFFECTS ON MORPHOLOGY

As the general trend of sea level rise continues, and man-made flood defence and reclamation works constrain the morphological evolution of estuaries which are naturally moving landwards, the geological limits on scope for erosion are more likely to be reached. A particular estuary may then, for example, reach a maximum possible width or depth for some of its length. High energy, erosional environments are more likely to be constrained in their morphological evolution by hard underlying geology. Supratidal, intertidal and subtidal zones of the estuary will all be affected. Indeed, on these long timescales (hundreds to thousands of years), supra- and intertidal zones become subtidal as relative sea level rises. Peat deposits formed from ancient land vegetation form part of the hard bedform for some estuaries. Geology of the watershed, estuary and surrounding coastal areas will influence the nature and availability of the suspended sediment supplied to the estuary, and hence its erosional and depositional properties.

5. TEMPORAL AND SPATIAL SCALES

Processes occurring on different time-scales.

Short :	<p>minutes</p> <p>hours</p> <p>days</p>	<p>Erosion by individual waves. Erosion by passage of turbulent flood-edge. Deposition as turbulence falls after flood-edge passes.</p> <p>Erosion by tidal currents and wind waves. Deposition at slack water. Bioturbation by sediment-dwelling animals (while sediment flooded) and birds (while sediment exposed). Drying-out and contraction of sediment during exposure; wetting and swelling of sediment during flooding. Daily migration of microphytobenthos through surface sediment.</p> <p>Spring-neap variation of tide giving changes in current-induced erosion, and changes in sediment advected in from deeper water (fluid mud can be moved in on spring tides). Spring-neap variation also changes relative timing of high water and daylight exposure, giving changes to biotic activity. Weather systems move through over few day time-scales, with associated winds, rainfall, and possibly storm surges.</p>
Medium	seasonal	<p>Variation in storm strength and frequency. Variation in saltmarsh biomass: root volume affects sediment volume, leaf litter is a supply of organic sediment). Variation in algal biomass: effect on sediment protection, sediment cohesiveness. Variation in invertebrate numbers: effect on bioturbation and biodeposition and sediment type Variation in feeding birds: effect on bioturbation and nature of sediment particles. Variation in rainfall. Variation in fluvial flow of water and suspended matter. Variation in direction of prevailing wind -giving difference in wave exposure of sites. Variation in suspended sediment supply from coastal and offshore sources (coastal erosion, sea-bed erosion). Variation in water temperature giving changes in turbulence structure of bottom boundary layer. Individual storms giving morphological changes large enough to change flow e.g. shifting sand banks, building or destroying shingle ridges on shores, breaching of shorelines. Dredging effects, and other engineering works.</p>

continued

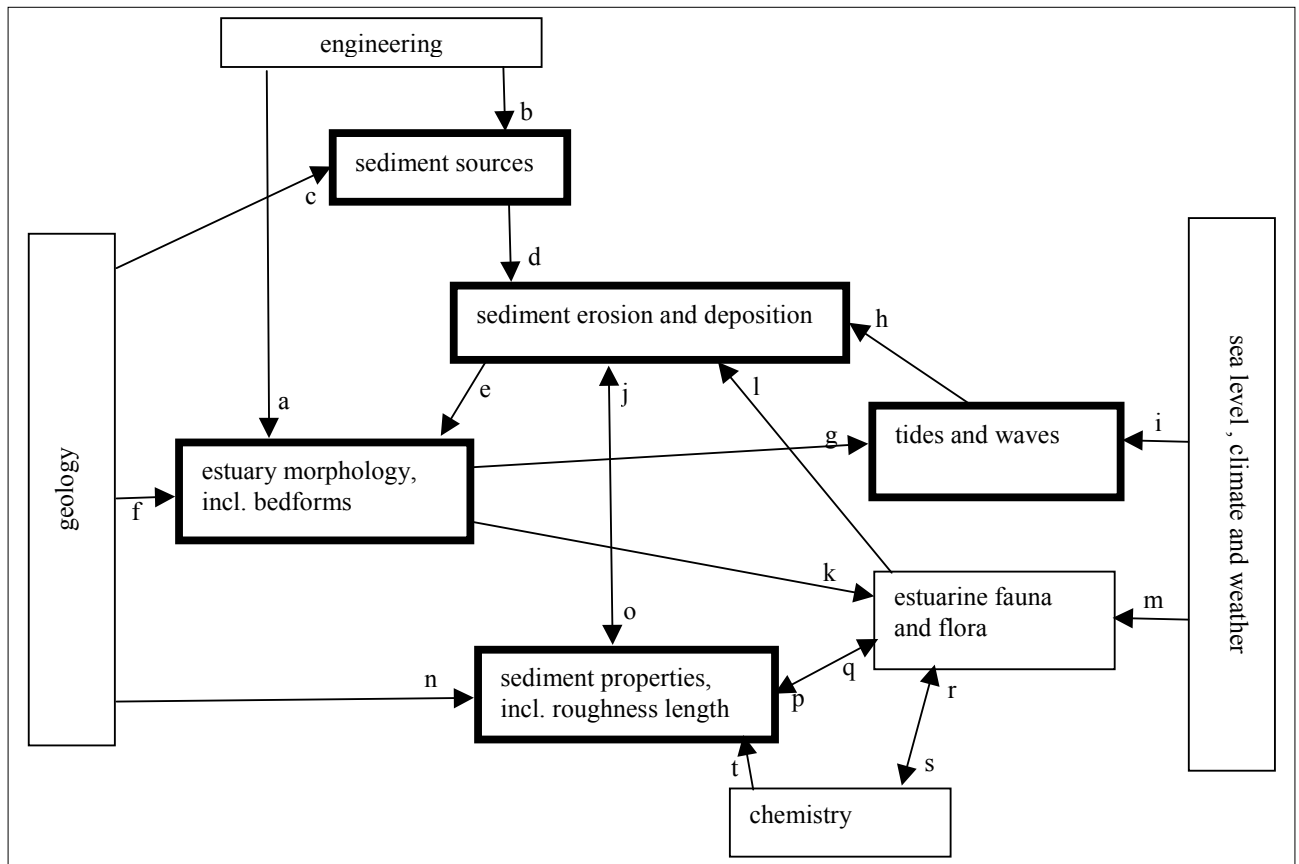
Long	1 to 10 years	Cyclical changes in tides due to astronomical parameters. Changes in biota due to natural population dynamics, or man-made changes to habitat or environmental quality. Morphological change having direct effect on flow, habitats and bed sediment composition.
Very long	decades to hundreds of years	Changes in biota due to species succession. Sea-level rise or fall due to climate change and glacial rebound. Morphological evolution steered by limits of reaching hard substrate, exhausting localised supplies of soft sediment. Changes in fluvial flow and sediment supply due to changes in land use and climate.

Parameters varying at different spatial scales.

Short: (i.e. amongst sites at the same distance from the estuary mouth)	Variation in size spectrum of bed particles on scale of a few m, associated with ripples etc. Variation in biota populations, due to natural patchiness. Depth variations due to small bedforms, and to biota e.g. mussel beds, and drainage channels (carrying either ebb flow or fresh water). Man-made structures and disturbance.
Medium: within an estuary (i.e. along the length of an estuary)	Variation in tidal signal and river flow signal. Different exposure to waves. Different bed sediment and bank sediment. Different pathways from sediment sources. Localised dredging and dumping. Different biota - dependent on exposure time, substrate, salinity, disturbance. Variation in depth and bed slope, giving different currents and runoff flow, and attack by waves.
Large: between estuaries	Geological variation gives different sediment composition, different coastal and offshore sediment supplies, different fluvial supplies of water and sediment (due to different catchment area, rainfall exposure and soil type). Different length and volume of estuary, and different tidal forcing at mouth (due to geographical location) give different tidal response. Aspect of estuary compared to predominant weather patterns gives wave exposure and wind exposure and likelihood of storm surges. Socio-economic variation gives extent of impact of dredging, shipping, coastal protection engineering works. Ecology gives importance of habitat protection.

6. INTERACTIONS

Flow diagram for physical, biological and geological effects on estuarine morphology.



6.1 A selection of references for processes in the flow diagram

(a) Effect of engineering works on morphology:

The erosion caused by the tidal eddies forming behind causeways in the Fraser River Delta is discussed by Barrie and Currie (2000). Spearman, Dearnaley and Dennis (1998) discuss observed siltation resulting from the construction of training walls in the river Lune (UK).

(b) Effect of engineering works on sediment sources.

Barrie and Currie (2000) estimate that all most of the riverine sand supplied to the Fraser River Delta is dredged, and increased flood flows due to confinement of the river have scoured the bed, forming migrating subaqueous dunes.

(c,f) Effects of geology and the availability of accommodation space on morphological change.

This is discussed by Pontee, Tastet and Masse (1998) in relation to the morphological evolution of the Gironde, with decreasing accommodation space leading to salt marsh formation, and export of sediment to the shelf. Fitzgerald et al (2000) show the importance of exposed hard rock in determining deposition of riverine sand.

(d,e) Effect of external sediment sources on morphology, and effect of erosion and deposition on morphology and bedforms.

Dyer and Huntley (1999) consider the links between hydrodynamics, sediment transport and morphology which determine the shape and movement of sandbanks. Pye (1995) discusses the supply of coastal and offshore fine sediment as a control on salt-marsh accretion in the Wash.

(g,h,j,n) The fundamental physical processes of estuarine sedimentation are presented by Dyer, 1986 and Soulsby, 1997.

(i) Effects of sea level change, climate and weather on tides and waves.

Gonnert (1999) discusses an observed increase in the frequency of storm surges, while Carretero et al (1998) debate decadal variations in storm and wave climate.

(k,q) Effects of sediment properties and morphology on fauna and flora.

Yates et al (1993) relate sediment characteristics to densities of wading birds and their prey animals; in later work, sediment characteristics have been related to morphology.

(l) Direct erosion and deposition caused by biota.

Direct bioresuspension by natural populations of a bivalve (*Yoldia limatula*) in Narragansett Bay is inferred to be greater than 15.8 kg dry sed $m^{-2} y^{-1}$ by Bender and Davis (1984). Biodeposition is estimated by Vedel et al (1994) for several species. e.g. *Nereis diversicolor* at 1.08 to 2.1 gC $m^{-2} d^{-1}$.

(m) Effects of climate and weather on biota.

Beukema et al (1998) relate the recruitment of a bivalve mollusc (*Macoma balthica*) to processes (spawning and predation) which are affected by winter temperature.

(o) Effects of erosion and deposition on sediment properties.

The importance of time-varying erosion thresholds caused by consolidation of bed sediment while tidal amplitudes decrease towards neap tide, and subsequent disturbance during spring tide erosion is demonstrated by Clarke and Elliott (1998).

(p) Effects of fauna and flora on sediment properties:

Bottom shear stress is dependent on roughness height, which is determined by grain size or microtopography of the bed. Graf and Rosenberg (1997) and Wright, Schaffner and Maa (1997) show benthic biotic structures such as mounds, tubes or vegetation dominating microtopography in some areas. Burrowing biota are shown to reduce sediment compaction and decrease wet shear strength of surface sediment (Rhoads and Boyer, 1982). The

stability of a mudflat in the Westerschelde was observed to double due to seasonal biofilm presence by de Brouwer et al (2000). Widdows et al (1998) discuss observed effects of a small clam (*Macoma balthica*) on sediment erodability.

(r,s) Effects of biota on chemistry, and chemistry on biota.

The effects of biota on nutrients in an intertidal zone are discussed in Magni and Montani (2000). Macroalgal influences on nutrient cycles are explored by Valiela et al (1997).

(t) Effect of chemistry on sediment properties.

Flocculation, affected by chemical and biological factors, is shown to change the settling velocity of suspended fine-grained sediment by van Leussen (1999).

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THE LINKAGE OF MORPHOLOGICAL MODELS TO END-USER NEEDS FOR WQ AND ECOLOGY

Ruth Parker, John Aldridge and Steve Malcolm

email: e.r.parker@cefas.co.uk

CEFAS, Lowestoft Laboratory, Pakefield Road, Lowestoft, Suffolk, NR33 0HT

EMPHASYS Phase 1 focussed on developing understanding of morphological change and making morphological predictions for the six Emphasys estuaries. For this reason there was less focus on direct modelling of water quality (WQ) and ecology. This discussion paper is designed to present the linkages from the physical process/morphological modeling undertaken in Phase 1, to the requirements for end users of these aspects. This will involve making clear the application of the existing morphological models and models developed/tested by the EMPHASYS Consortium in Phase 1, to water quality and ecological questions. Water quality and ecological concerns cover a wide range of topic areas. A spectrum of applications and models from chemistry to biology and ecology will be considered.

1. KEY FACTORS FOR MODELLING WATER QUALITY AND ECOLOGY

Hydrodynamics, morphology, water quality and ecology together with their interactions are the core aspects of the physicochemical and biological estuarine environment and therefore are essential elements for estuarine management. As discussed in the initial Emphasys scoping study (HR Wallingford, 1997a and b) and appendices in the EIAS Mk 1A (HR Wallingford, 2000) a great number of parameters are expected to link morphology with the processes controlling ecology and water quality. For nutrients the key parameters might be:

1. Total intertidal area and ratio of intertidal to sub-tidal area. The rate of nitrate cycling in the bed is likely to be different in the two cases as will the biological consumption of these substances.
2. Position of intertidal areas relative to nutrient sources.

3. Composition of the bed (mud/sand ratio) - particularly in intertidal areas. Different process rates and biological activity might be expected in predominantly muddy as opposed to sandy regions.
4. Flushing rates of the estuary, linked to changes in tidal and freshwater flows.
5. Sediment recycling and the position of the turbidity maximum, especially for particle reactive phosphate and nitrogen processes (nitrification/denitrification).
6. Turbidity levels, (controlling water column utilisation) and other factors affecting biological activity.

There are similar controlling features for ecological questions. For example; for birds: intertidal/habitat/vegetation area and quality/type, sediment type, food source type, biomass and density. For contaminants the key parameters are likely to be changes in areas of erosion and deposition that could lead to historical accumulations of contaminated bed sediments being resuspended, released, processed/transformed and redistributed.

The utility of morphological models in dealing with water quality and ecological issues thus comes down to their ability to make predictions concerning changes in these controlling factors.

2. GENERIC APPROACHES TO APPLYING MODELS TO WATER QUALITY/ECOLOGY

Two main approaches to linking morphological model predictions to changes in water quality/ecology have been identified and are summarised here.

If it is assumed that no feed back of water quality and biology on the morphological change occurs, then direct bottom up scenarios based on past, present, or predicted future estuary morphology can be made. This

reasonably straight-forward approach would make use of a process based water quality model to simulate the nutrient, sediment and biological cycling for a given estuary configuration. A typical application would carry out short term simulations for an estuary at a given point in time. Estuary modifications would typically be derived from changes suggested by expert analysis, in combination with top-down, hybrid, or bottom-up morphological models. Alternatively, if historical data on an estuary is available, the change in estuary configuration over time might be based on observations. The estuary morphology would be modified in light of predictions and the bottom up WQ or ecology calculation repeated. This approach is termed the 'indirect' approach in the user guide appendices (EMPHASYS Consortium 2000).

1. If the feedback between the biology, chemistry and physics is important, it may be necessary to develop long term and linked morphological and water quality/ecological models. Further research would be required to evaluate the feasibility of coupling a parameterised water quality model with (say) a hybrid morphological model. As well as allowing feedback between the components, this challenging approach would give additional insight as to how water quality/ecology co-evolved with morphological change. This approach is termed the 'direct' approach in the user guide (EMPHASYS Consortium 2000).

In addition, some studies may lead into improving the morphological predictions themselves rather than being directly applicable to water quality or ecological issues.

Thus, many of the current approaches to estuary change are potentially applicable to ecology and water quality issues; from expert assessment based on observations, to top-down, hybrid and bottom up modelling. All these approaches involve consideration and integration of the rates of biochemical and physical processes in comparison to rates of morphological change.

3. APPLICATION OF SPECIFIC MODELS

An assessment of the utility of available models (as categorised in the user guide by modelling approach; Top-down, bottom-up and hybrid) for estuarine management from the end-user point of view is given here, along with future recommendations and utilisation of the model. Summaries of the available models are given by Posford Duvivier (2000).

3.1 Top down

Regime models and others based on empirical relationships provide information on gross bathymetry and hydrodynamic change over long time periods. Combined with expert analyses they may provide some information on how intertidal areas, for example, change over time. However, for water quality issues it is not clear that these models by themselves can provide sufficient information to enable changes in water quality to be estimated. One approach to increasing the applicability is, of course, to combine the top-down relationships into a hybrid model which in principle yields greater detail in changes.

Another way forward would be to use top down models to suggest morphological changes that can guide scenarios for bottom up modelling. Thus for a given bathymetry in a bottom up model, if long term predictions suggest changes in morphology, the bathymetry might be modified to reflect this and bottom up runs with the two bathymetries undertaken. The outputs could then be used in process driven water quality models to compare the effect of the two estuary morphologies.

Models classified under this heading include, Accommodation space (BGS), Sediment budget analysis (HR), Regime theory (UoN, HR Wallingford), mudflat analysis (HR), Rollover (UoN), sediment balance (UoN), Estplan (ABP), Estform (ABP), Niche (ITE), Polant/anst/anse (POL), SHAPE-SED (ITE), Historical trends/Expert analysis (RHC), Estplan, Estform (ABP).

3.2 Bottom-up or process based methods

All these methods are designed to represent detailed processes over short timescales and are capable of linking gross morphology to important aspects of estuary management, such as ecology and water quality. The bottom up

approach employs process models based on currently understood physical/chemical/biological principles and are generally used to give local, short-term (few weeks) predictions of morphological change. The information on hydrodynamics, waves and sediment transport provided by these process models can be used directly for process-based predictions of changes in water quality and perhaps ecology.

There are a number of uses for such bottom up models for addressing water quality and ecological concerns.

1. Short term predictions of flow fields, waves/tides and sediment movement from bottom-up models under different conditions (i.e. with changing scenarios of intertidal location/estuary shape/volume/training walls etc) could be used as inputs to process based models of water quality and ecology. An example of this might be EstBed (ABP) which has been used to look at changes in bathymetry in the Humber due to the impact of training walls and the effect of high freshwater flows on channel switching. The flow fields and bathymetry output of this model could be used as the basis for a bottom-up WQ/ecology model (or direct coupling would enable conjunctive modelling of morphology and water quality/ecology). However this use would be possible for short-term change only.
2. For longer term morphological applications, bottom up models might provide the intermediate step between gross predictions from top-down models and the more detailed results needed by process based water quality models. Gross morphology changes suggested by long-term models could guide the scenarios for bottom up models that would provide the short timescale sediment transport, hydrodynamics and waves which in turn will feed into ecology/WQ models. Most of the 2D bottom-up models, e.g. TELEMAC, POLEST, EstBed, would be suitable for this application.
3. Improved understanding at the process level. Not all the bottom-up models are applicable for direct linkage with

WQ/ecological models or give information directly on wide scale morphological change. For example: BIOTIDE investigates the effects of changing biota, external sediment supply, and tidal height on sediment stability and the resulting intertidal profile. Although this type of model might not be implemented directly with water quality/ ecological models it provides valuable information towards improving the morphological predictions themselves and may feed in to improved modelling of sediment transport processes in bottom-up or hybrid models. Many of the models included so far fulfil this role. For the Tamar, observations together with the model of transverse processes have led to improved understanding of sediment dynamics. Similarly, comparison of 1D/2D and 3D models of the Mersey (POL) was designed to indicate the capabilities and limitations of predicting tidal propagation, salinity intrusion and sediment concentrations, and to link this assessment of performance to the availability of observational data and the accuracy and robustness of process algorithms.

4. Use of bottom up models to suggest and validate simple, parameterised water quality and ecological relationships that might be included directly in longer-term hybrid calculations. If successful, these relations could be regarded as water quality analogues of the regime concepts that guide a number of hybrid morphological models. Incorporated into hybrid models they would lead to simulations of changes in water quality and ecology through time and also allow possible biological feedback on morphology to be explored.

The process based models include EstBed (ABP), BIOTIDE (PML), ISIS (HR), TELEMAC (HR), Transverse (PML, Uncles), POLEST (POL), MIKE21 (DHI).

3.3 Hybrid

Hybrid methods are a flexible combination of a process based model with top-down methods and provides a means of attempting to predict morphological change over a range of timescales. These model types have great potential for linking morphological change to

water quality and ecological processes over various spatial and temporal scales.

In principle they offer greater scope than top down models for predicting changes in the key morphological factors controlling water quality and ecology. In particular, changes in intertidal regions, flow rates and possibly sediment types. A number of roles might be envisaged for them with respect to WQ and ecology.

1. To suggest and guide scenarios for change in more detailed bottom up models which would include or supply information to a process based water quality/ecology model.
2. Coupling of a hybrid morphological model with a parameterised water quality model to yield variation in water quality/ecological parameters through time. This also allows the possibility of building in feedback, e.g. through biological mediation of sediment stability.
3. As with the other model types, some models may feed into end-user needs indirectly by improving the modelling of morphological change. An example of this is EstEnt (ABP). This model does not predict morphological change *per-se* but aims to predict the most probable long-term form of an estuary (i.e. the target state) based on entropy arguments.

The hybrid models developed through Phase 1 like this give various insights to morphological prediction and change. Several are capable of modelling changes in morphology over differing timescales. For example: ESTMORF (WL 1 Delft) utilises empirical relationships with a 1D flow and sediment transport model to produce 1D predictions of morphological development. This includes predictions of changes in channel and mud flat area, aspects particularly important from water quality and ecology perspectives. The model has been applied to predicting long-term (decades) morphological development of an estuary in response to sea level rise/ bottom subsidence and human activities such as dredging and dumping. EstReg (ABP) also utilises empirical relationships and an iterative procedure to investigate the changes in estuary volume changes/bathymetry. Effects from environmental factors such as sea level rise or increased discharge on the shape of the estuary and hydrodynamics were tested. Another hybrid

model, HYMORPH is capable of simulating the morphological evolution of a tidal creek in response to managed retreat. In principle it seems these models are capable of giving long and short-term changes in morphology that could feed into bottom up models of WQ and ecology. As will be discussed later, ESTMORF has already been linked with ecological assessments in the Humber to provide long-term morphological development and habitat evaluation.

Examples of hybrid models include ESTMORF (Delft), HYMORPH (HR), EstReg (ABP), EstEnt (ABP), and mudpack (UoN).

3.4 Existing Linked models

Few models directly linking WQ and ecology were established in Phase 1 as this part of the programme was concerned primarily with predicting changes in estuarine morphology.

BIRD-POP (CEH) has not been used directly in Phase I, but is clearly capable of using model outputs of morphological change (namely intertidal area). BIRD-POP is designed to predict the effects on birds of predicted changes in invertebrate abundance and exposure time of intertidal flats. It could be used in Phase 2 as a means of predicting the consequences for birds of anticipated changes (derived from morphological models, Delft, ABP) in estuary morphology/intertidal area and resulting changes in food supply. Possibilities of linking BIRDPop and ESTMORF are feasible and would allow investigation and prediction of ecological impacts of morphological change.

Only one directly integrated model has been developed through Phase 1, but it gives an idea of the possibilities for linking morphological model output to WQ / ecological questions. The hybrid model ESTMORF has been combined with biological data and assessments to give an overall biogeomorphological state of an estuary (Humber) with time horizons ranging from decades to a few centuries. Due to the hybrid character of the model it supplies the information of long-term morphological development as well as changes in the hydrodynamic conditions, and takes into account the changes between the two. The model not only gives morphological changes in

the channel part of the estuary but also the intertidal areas. This information is then linked (via existing observational data) to habitat characterisation / fysiotores which dictates benthos and bird foraging. In this way, changes in the area of fysiotores due to land reclamation or sea level rise, can directly impact on habitat availability and bird feeding opportunities. The functionality of this tool allows for further improvement by inclusion of more detailed modules relevant to water quality and ecology (e.g. BIRD-POP), but also to hydrodynamics, waves, sediment transport.

4. SUMMARY/CONCLUSIONS

The models developed and utilised during Phase 1 of the Estuaries Research Programme contribute to the understanding and prediction of morphological change in various ways.

Several models, (ESTMORF, EstBed, EstReg, HYMORPH, Regime), are capable of predicting estuarine morphology and change over a range of times scales (days to decades) and model types (hybrid, bottom-up and top-down).

Some models lead into improving the morphological predictions themselves rather than being directly applicable to water quality or ecological issues. This may involve, for example, improved understanding of the role of biota on sediment stability (BIOTIDE) and inclusion of associated physicochemical feedback mechanisms, changes in estuarine form (EstEnt) or comparative capabilities of 1/2 or 3D model application.

For models that deliver morphological outputs, there are several generic ways of linking the models to end-user needs, depending on the models timescales and resolution.

Regime models are capable of predicting long term changes in gross estuarine morphology (i.e. forced by sea level rise) but would be difficult to link directly to water quality and ecological controlling parameters. In this case they could be used in conjunction with bottom-up models which would incorporate the gross morphology changes provided by regime/rollover models, whilst resolving the detail and rates required for WQ and ecological modelling.

Hybrid models are also capable of predicting longer term change and their output can potentially be very useful, as a template for bottom up WQ or ecological models models. Alternatively it may be possible to incorporate parameterised WQ and ecological models directly within the hybrid framework. Although difficult, this approach addresses the contrasting rates of processes involved in determining morphological and water quality/ecological changes.

Bottom-up/process and hybrid models are capable of addressing short term WQ impacts/disturbances or construction/dredging effects. Linkage of these models to WQ and ecological issues will depend on the resolution of the hydrodynamic model output. Fine scale models have the potential to be integrated directly with WQ and ecology modules run at the same interval and in real time.

Although some models (BIRDPOP and ESTMORF) already provide links between morphological modelling and water quality/ecology, it is essential in the next phase of research that the understanding developed in Phase 1 is implemented and progressed. This may involve further improvement of the predictive morphological models (i.e. incorporation of biostabilisation and feedback effects) but also a clear targeting towards their linkage with water quality and ecological modules. This will ultimately lead to fully integrated models capable of delivering improved answers to management issues relevant to end-users concerned with water quality and ecological issues.

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RESULTS, CONCLUSIONS AND RECOMMENDATIONS FROM POL'S MODELLING CONTRIBUTIONS TO EMPHASYS

David Prandle

email: dp@pol.ac.uk

Proudman Oceanographic Laboratory, Bidston Observatory, CH43 7RA, UK

1. BACKGROUND

This paper summarises results, conclusions and recommendations from POL's Phase 1 contributions to both 'bottom-up' and 'top-down' modelling. The aim is to relate these directly to the additional 'tasks' concerned with: (i) guidelines related to estuarine morphology and (ii) recommendations for Phase 2 involving basic research and monitoring. All results shown can be found in related POL Papers 6 and 18.

The wider recommendations arising from all the research in Phase 1 are contained in a separate report (EMPHASYS Consortium, 2000).

2. FORECASTING BATHYMETRIC EVOLUTION – PRE-REQUISITES

Reliability of model forecasts is generally assessed against success in reproducing historical events or sequences. Further assessments can be made on the basis of robustness and portability, i.e. effectively measures of the generality of prescribed parameters and process algorithms and of the extent to which predictions may extend the parameter range (or window) in which the model remains valid.

For estuarine bathymetry, there are few accurate time sequences of estuarine bathymetry. Generic bottom-up models of tidal propagation have been applied widely – requiring only adjustment of the bottom friction coefficient. Conversely, sediment transport models require extensive adjustment to reproduce observed concentrations. Their further extension to calculation of bathymetric evolution generally involves extrapolating beyond accuracy limits.

3. DYNAMICAL AND SEDIMENTARY RELATIONS IN ESTUARIES – THEIR SENSITIVITY TO INTERNAL AND EXTERNAL CHANGE

While subsequent phases of the EMPHASYS programme will consider the problems noted

above, the urgent need for broad 'Guidelines' were addressed by re-examining existing theory and related estuarine classification systems.

3.1. Dynamical balances

Figure 1(a) shows the relationship between tidal elevation (for the predominant M_2 constituent) amplitudes, tidal current amplitudes and water depths. Figure 1(b) shows the related influence of bed friction (as a ratio to the inertial term). The grey circles in these diagrams represent values at the mouth for 25 UK estuaries (prior survey by CEH). These figures indicate that most UK estuaries are shallow and, hence, their tidal dynamics are 'frictionally dominated'. The magnitude of the tidal velocities shown refers to a mean value of the bottom friction factor. This factor may increase by up to about threefold for beds of coarse sands with pronounced bed forms. Conversely the factor may decrease to as little as one-third in smooth muddy conditions. For estuaries within the frictionally dominated region, the tidal velocities shown will vary by the square root of the inverse ratio of the change in friction factor i.e. tidal velocities double for a fourfold decrease in friction factor.

3.2. Sedimentary balances

Typical maximum (depth- and time-averaged) suspended sediment concentrations are shown in Figure 2. Observed values are generally significantly less-by a factor that indicates the degree to which the sediment regime is 'supply limited'. Two approximate expressions can be used to estimate these maximum tidally-averaged concentrations, C (in mg l^{-1}):

$$\begin{aligned} &\text{for } w_s/D > 0.4 \text{ (coarser sediments } C = \hat{u}^3/750 w_s^2 \\ &\quad \text{or shallow water)} \\ &\text{for } w_s/D < 0.4 \text{ (finer sediments or } C = 1500 \hat{u} \\ &\quad \text{deeper water)} \end{aligned}$$

w_s fall velocity (m s^{-1}), D water depth (m), \hat{u} tidal velocity amplitude (m s^{-1}).

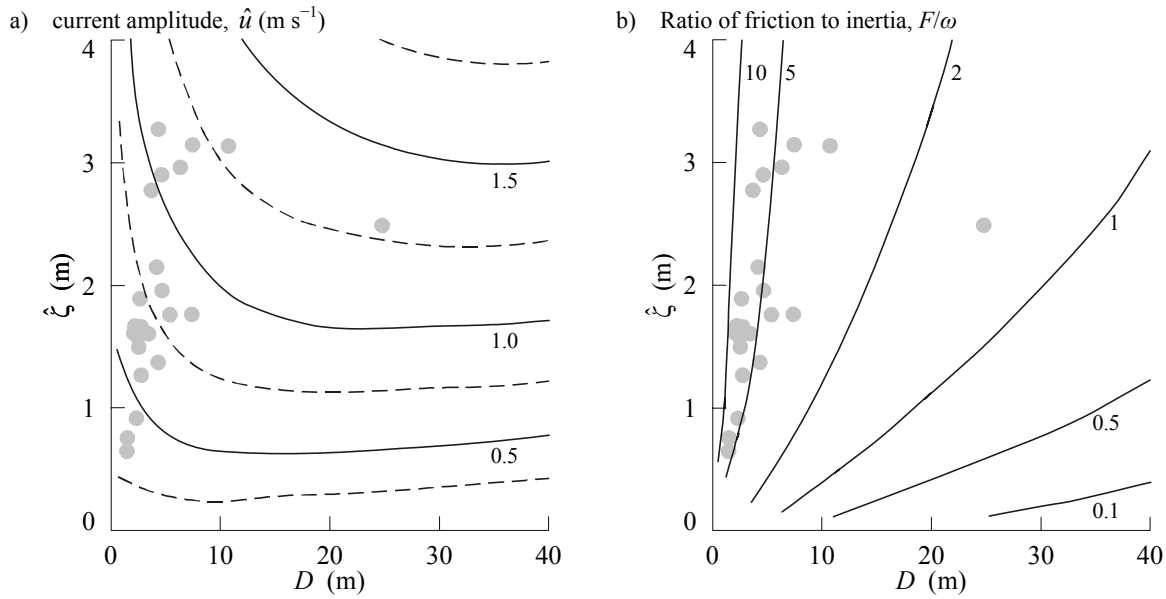


Figure 1 a) Current amplitude and b) ratio of friction to inertial terms for M_2 tidal propagation as functions of water depth, D and tidal elevation amplitude, $\hat{\zeta}$. ● observations of 25 UK estuaries

Thus concentrations of fine sediments are generally much larger (depth-averaged) than for coarser sediments. Moreover the concentration of coarser sediments is proportional to the square of the bed friction factor, k , and the third power of tidal velocity whereas finer sediment concentrations are effectively independent of bottom friction factor and are directly proportional to tidal velocity. (Further consideration of respective half-lives are described in Paper 18). The net effect is that concentrations of coarse sediments are far more variable in both space and time, moreover their movement may be confined to scales of less than 1 km. By contrast the higher concentrations of fine sediments are ubiquitous, staying in suspension over long periods and large distances (often exceeding the estuarine length), thus they are likely to control whole-estuary bathymetry. Moreover, in combination with their much greater surface area:weight ratio, they act as important vehicles for transporting adsorbed contaminants and can influence productivity with their occlusion of light.

3.3. Bathymetry

Figure 3(a) indicates the axial bed slopes consistent with the values of tidal current and

elevation amplitudes, $\hat{\zeta}$, and water depths, D , shown in Figure 1(a). Estimation of these

slopes assumes smoothly varying morphology approximating triangular form with constant lateral slopes. For any given value of tidal elevation amplitude and water depth at the mouth, successive upstream calculations of slope (assuming either current amplitudes or elevation amplitudes remain constant) provide an estimate of net estuarine length, L , approximating:

$$L = 2200 \frac{D^{\frac{5}{4}}}{\hat{\zeta}^{\frac{1}{2}}} \text{ (m)}$$

These values, shown in Figure 3(b), are sensitive to the specific bed friction coefficient, k' . The lengths varying by $\sqrt{k/k'}$ in frictionally dominated regions and by k/k' in areas of little friction influence.

This approximate formula represents a mid-point fit to the data from the 25 UK estuaries but observations indicate substantial variability consistent in kind and degree with this sensitivity to the bed friction coefficient.

Noting that changes in mean sea level anticipated over the next century are unlikely to

modify the tidal elevations at the coast, ζ , then the incremental change in estuarine length $\delta L/L \approx 5/4 \delta D/D$, will be largest in shallow estuaries.

4. MODELLING BATHYMETRIC EVOLUTION IN ESTUARIES WITH ‘BOTTOM-UP’ DYNAMICAL MODELS

4.1. Tidal dynamics

Subject to the provision of accurate bathymetry and coastal tidal constituents, 1-, 2- and 3-D models provide accurate descriptions of tidal elevations. Accurate simulation of related depth-averaged currents is dependent on adequate (2-D) spatial resolution. In shallow areas ($\zeta \gg 10D$), the influence of bed friction predominates and current profiles will be especially sensitive to the prescription/calculation of the effective bed friction coefficient. The ready availability of accurate observations of both elevations and currents with good resolution in major estuaries, indicated by Table S1, enables detailed assessment of model performance.

4.2. Suspended sediments

The sensitivity of mixing models, shown in Table S1, to prescription of horizontal diffusivity coefficients can be circumvented by the use of fine-scale horizontal resolution. Likewise the prescription of the sink (or settlement) term can be circumvented by fine-scale vertical resolution (often involving increasingly finer resolution closer to the bed). However the prescription of the source term, especially where a range of sediment types/ages is involved, remains problematic. Thus with a fine resolution 3D model incorporating erosion terms appropriate to the local conditions, moderately accurate simulations of ebb and flood concentrations can be achieved. However, determination of net residual upstream/downstream fluxes may be unreliable.

The difficulty, cost and limited resolution of associated instrumentation with which to measure sediment concentrations, a parameter that is often patchy and intermittent, exacerbates both model assessment and development.

4.3. Morphology

Since morphological changes generally involve integration over years and decades, two

fundamental problems arise. First, conditions can vary significantly over seasons (biology, consolidation, bioturbation, coastal and fluvial sediment supply) and as a result ‘up-scaled’ parameterisation of the bed friction coefficient may become inaccurate. Likewise, over such time periods, the impact of occasional extreme events (often inaccurately simulated) may outweigh progressive steady trends. In consequence of both problems, successive calculations of bathymetric evolution, and their consequent adjustments to the dynamics and sediment regimes, accumulate ‘errors’ in a ‘chaotic’ fashion. Thus such models have limited deterministic predictive capability. However, using ensemble simulations to encompass a range of event scenarios and variability in empirical coefficients, useful probability estimates of future bathymetric configurations can be made.

Recent advances in the accuracy and spatial resolution of bathymetric surveys in the intertidal regions using LIDAR (Table S2) may be used to accumulate regular (quarterly) observational data for a number of estuaries. Thence, intercomparison of trends and variability in bathymetries as indicated by models and surveys may be used to assess and develop models and to identify relative impacts of extreme events.

4.4. Processes understanding – up scaling

Continuing research is clearly necessary into the basic (small scale) processes involved in erosion, settlement and related interactions/impacts on bed forms and turbulence generation, facilitated by developments in sensors and the availability of near-full scale laboratory flumes. However, incorporating advances from such research into estuarine models also requires studies of the related problem of up-scaling both spatially and temporally, including flexibility to accommodate diverse events.

5. REQUIREMENTS FOR BASIC RESEARCH AND MONITORING IN PHASE 2

Figure 4 summarises schematically the fundamental processes involved in maintaining both short term, local water depths and longer term, larger scale bathymetry. The general failure of existing bottom-up models to

reproduce existing quasi-stability of bathymetry within a frequently highly dynamic sedimentary regime must be the primary focus for process studies. Substantial progress in determining erosion and deposition rates together with related impacts on turbulence structure and bed forms has been made in programmes such as COAST3D, TRIDISMA, INDIA, PROMISE etc. A subsequent phase must address the more complex non-linear, interactive processes that, most likely, produce stable feedback links. These involve immediate interactions between bottom boundary layer turbulence processes generated by tides and waves, modulated by both surficial and suspended sediments alongside longer term influences of consolidation, biological binding/bioturbation and complex biogeochemical cycling.

Whilst such studies inevitably focus on specific sites (inter-tidal, submerged and flumes or mesocosms) the related problems of up-scaling (Section 4.4) must be addressed concurrently. Serious consideration should be given to a limited number of test-bed sites (e.g. Liverpool Bay including 3 diverse estuaries, Thames Approaches including 5 estuaries) with regular (quarterly) bathymetric surveys (inter-tidal LIDAR and ground truth) over several years interspersed with shorter intensive whole estuary and localised detailed surveys. These should aim to provide data required for concurrent development of both bottom-up and top-down models.

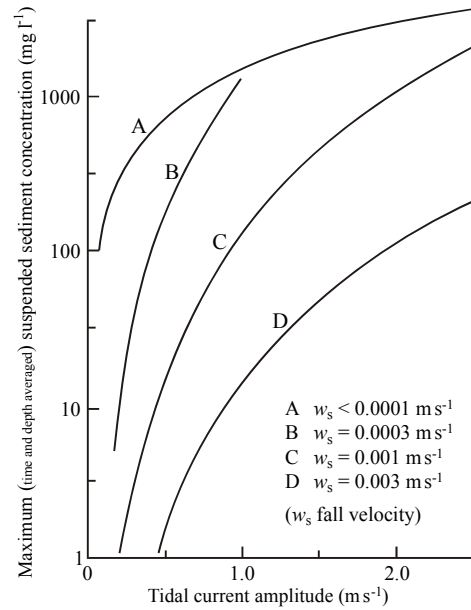


Figure 2 Maximum (assuming full availability) time and depth-averaged sediment concentrations for a range of tidal velocity amplitudes \hat{u} and settling velocity w_s .

Table S1 Equations for Modelling Bathymetric Evolution

Tidal dynamics

Depth-averaged x -component, momentum

$$\frac{\partial u}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} + g \frac{\partial \zeta}{\partial x} - fV = \frac{(\tau_z - \tau_o)}{\rho(D + \zeta)} \quad (\text{S1})$$

Horizontal component (3-D) of stress

$$\tau_z = \rho \mathbf{E} \frac{\partial u}{\partial z}; \quad (2\text{-D}) \quad \tau_o = \rho \mathbf{k} U(U^2 + V^2)^{\frac{1}{2}} \quad (\text{S2})$$

Continuity

$$\frac{\partial \zeta}{\partial t} + \frac{\partial U}{\partial x} \mathbf{D} + \frac{\partial V}{\partial y} \mathbf{D} = 0 \quad (\text{S3})$$

Suspended sediments

Depth-averaged mass conservation suspended tracer

$$\begin{aligned} \frac{\partial c}{\partial t} + U \frac{\partial c}{\partial x} + V \frac{\partial c}{\partial y} = \\ \frac{\partial}{\partial x} \mathbf{K}_x \frac{\partial c}{\partial x} + \frac{\partial}{\partial y} \mathbf{K}_y \frac{\partial c}{\partial y} + \frac{\text{sources} - \text{sinks}}{\mathbf{D}} \end{aligned} \quad (\text{S4})$$

Morphology

Bathymetric evolution

$$\frac{\partial \mathbf{D}}{\partial t} = \frac{\text{sources} - \text{sinks}}{\rho_B} = -\delta (U^2 + V^2)^n + \alpha C \quad (\text{S5})$$

Parameters in **bold** indicate common difficulties in modelling

- i.e. prescription of initial depths \mathbf{D} ,
- prescription/calculation of: eddy viscosity \mathbf{E} ,
- effective bed stress coefficient \mathbf{k} ,
- prescription of: horizontal diffusivities \mathbf{K}_x and \mathbf{K}_y ,
- formulation of: erosion term coefficients δ and \mathbf{n} (threshold velocity U_c),
- formulation of: deposition half-life $1/\alpha$ or equivalent bed settlement algorithm.

6. REFERENCES

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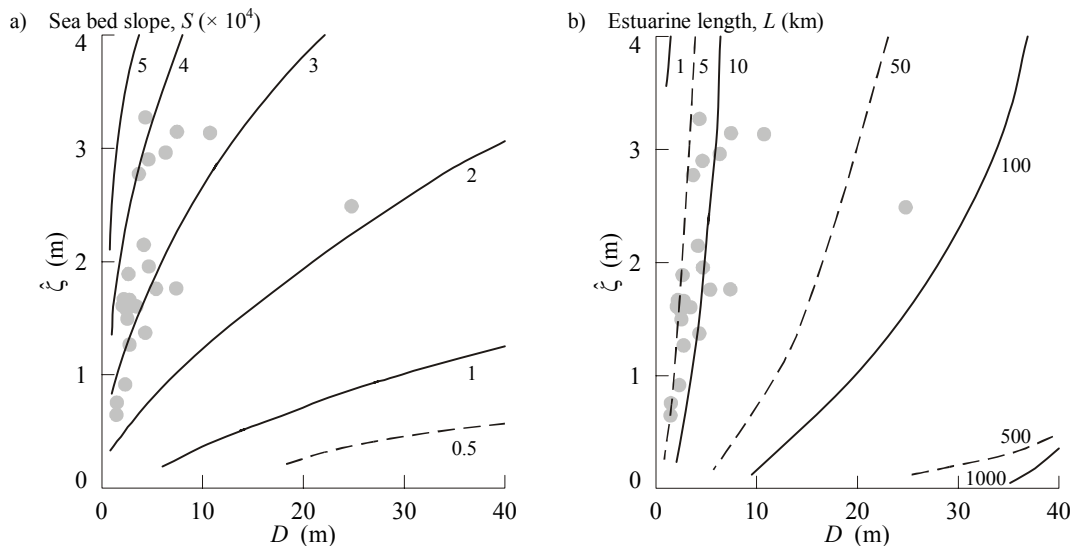


Figure 3 a) Sea bed slope and b) estuarine length for M_2 tidal propagation as functions of water depth, D and tidal elevation amplitude, $\hat{\zeta}$. ● observations of 25 UK estuaries

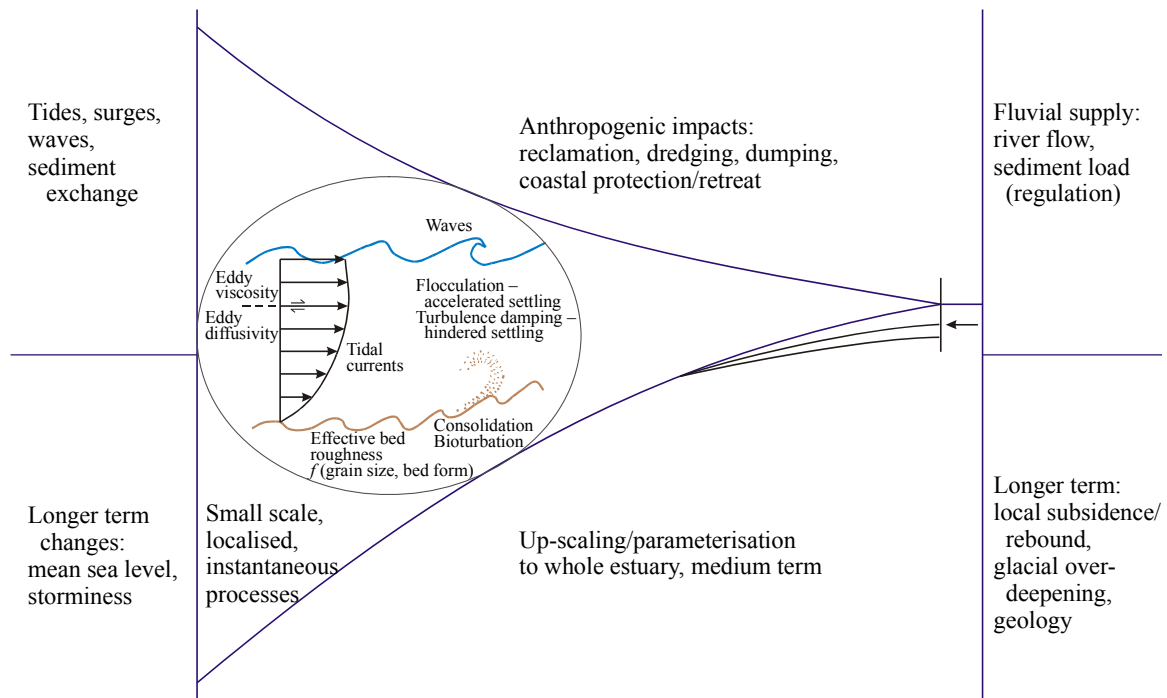


Figure 4 Schematic of internal and external factors determining estuarine bathymetry

Table S2 Accuracy and sensitivity of estuarine modelling; availability, accuracy and cost of observations

	OBSERVATIONS											MODELLING		
	Parameter	SINGLE POINT			SPATIAL ARRAY			VERTICAL PROFILE			ACCURACY	SENSITIVITY TO		
		ACC	CO ST	FEAS	ACC	COST	FEAS	ACC	COST	FEAS				
TIDAL DYNAMICS	elevations	G	L	A										
SUSPENDED SEDIMENTS	currents	G	L	A	G	H	A ¹	G	M	A ²	G			Prescribed depth bed friction eddy viscosity
	concentration	M	L	A	P	H	S ³	M	M	A ²	M			Sources and sinks
MORPHOLOGY	particle size	M	M	S ⁴										
	features				M	H	S ⁵							Chaos: long-term error accumulation
	heights				M	H	S ⁵				P			

ACCURACY: **GOOD** ±5%; **MEDIUM** ±25%; **POOR**

COST: **LOW** < 5000; **MEDIUM**; **HIGH** > 25,000 (UK Pounds Sterling)

FEASIBILITY: **AUTONOMOUS** 'PERMANENT'; **SPECIFIC SURVEY**

- 1) H.F. Radar,
- 2) ADCP,
- 3) Surface values: aircraft/satellite r/s,
- 4) Laser and acoustic in-situ particle sizers,
- 5) Sonar surveys, lidar & aerial photography (inter-tidal).

