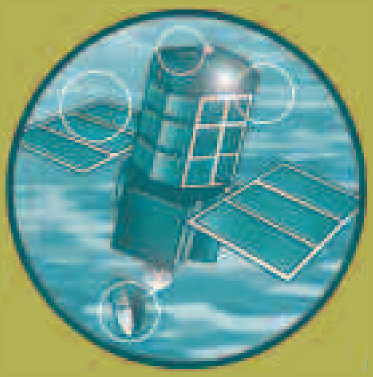
Defra/Environment Agency
Flood and Coastal Defence R&D Programme

Integrated Research Results on Hydrobiosedimentary Processes in Estuaries

Final Report of the Estuary Process Research Project (EstProc)

R&D Technical Report FD1905/TR2



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R&D Technical Report FD1905/TR2

Authors: Estuary Process Consortium for the Fluvial, Estuarine and Coastal Processes Theme

Produced: January 2006

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This report provides information for Defra, the Environment Agency and their consultants about estuarine processes and constitutes an R&D output from the Joint Defra / Environment Agency Flood and Coastal Erosion R&D Programme. It is intended for use by experienced modellers who are able to exercise judgement on the applicability of the work to specific situations. Reliance on the information in this report is not a substitute for the necessary expertise or site specific studies and investigations. This report is a contribution to research generally and it would be imprudent for third parties to rely on it in specific applications without first checking its suitability. Various sections of this report rely on data supplied or drawn from third party sources. The members of the EstProc Consortium accept no liability for loss or damage suffered by Defra or the Environment Agency or third parties as a result of errors or inaccuracies in such third party data.

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Collaboration Statement

The report was prepared by the EstProc Consortium comprising: HR Wallingford (lead), Proudman Oceanographic Laboratory, Professor Keith Dyer / University of Plymouth, St Andrews University, Gatty Marine Laboratory (Sediment Ecology Research Group), ABP marine environmental research, WL | Delft Hydraulics, Plymouth Marine Laboratory, University of Cambridge, Cambridge Coastal Research Unit, University of Southampton, School of Ocean and Earth Sciences, Digital Hydraulics Holland B.V., and Centre for Environment, Fisheries and Aquaculture Science.

SUMMARY

This report describes the results of integrated multidisciplinary research on estuarine hydro-bio-sedimentary processes and their interactions. It addresses issues related to:

- Estuary wide modelling;
- Tidal flat sedimentation;
- Mudflat-saltmarsh interactions; and,
- Morphological / physiotype modelling.

The report has been produced by the EstProc Consortium from a 3-year research project which had the following two main aims:

- Improved understanding and modelling of hydrobiosedimentary processes; and,
- Improved understanding and modelling of sediment erosion and deposition and, hence, the capability to predict the resulting changes in estuary morphology.

The research focussed on topics, which were defined by previous research, and revealed by modelling, to be ones where shortfalls existed in definition of the processes and interactions, which constrained the application for prediction. The advances in understanding were made by further analysis and collation of data (data interrogation).

The project team covered the disciplinary headings of modelling and process research in hydrodynamics (waves and currents), sedimentary (sands and muds) and biological processes (vegetation and marine organisms). Although the research team worked from within these backgrounds, real advances were made from the integrated team effort. The focus was on specific problems where the disciplines interacted, and where significant feedback occurred between the various processes. It was in these areas that the greatest advances on the existing predictive capabilities have been made. All estuarine processes include important elements of the three discipline areas. For instance, waves running into shallow intertidal areas are capable of considerable erosion, but their characteristics in only a few centimetres of water are poorly understood. Additionally, the plants and algae present exert a control on the hydraulic roughness of the bed, and hence on the wave progression, and on the shear stress available to move sediment. The plants and other organisms also engineer their environment through direct controls over sediment erodibility and deposition. The interaction of biologists and sedimentologists was maintained at all stages of investigation to ensure that these factors and their limits were properly defined.

The advances in understanding these types of process interconnections were achieved through exchanges of knowledge, and use of data for particular estuaries, for example on the Humber, where there was already a large multidisciplinary dataset available.

The research has led to the development of new ideas and algorithms as described in EstProc Consortium (2004b) and this report. Where appropriate, existing wave-current-sediment ‘bottom-up’ process models were adapted and used to demonstrate that the algorithms could be implemented directly into models. The models were then used to test the algorithms and to explore the sensitivity and relative importance of particular processes or interactions. The shortcomings of the models themselves as simulation tools and the difficulties sometimes faced with using measurement-based

determinations of sediment parameters within these models have been explored. These aspects are covered in the present report.

The outcomes of the research are improved knowledge and understanding of estuary processes relating to prediction of hydrobiosedimentary parameters (EstProc Consortium, 2004a). Also it has been possible to produce improvements on existing predictive algorithms for application by estuary modellers and to generate new algorithms covering a wider range of parameters (EstProc Consortium, 2004b). Finally, key datasets accessed during the project have been documented in a separate report (EstProc Consortium, 2004c).

It was noted that the approaches to integrating the short-term processes and responses forward through time needed researching to achieve adequate representation of the long-term processes and responses. This required an examination of the changing balance of importance of the various processes with time, particularly the seasons, and with events, such as storms and river floods, and global climate change. This has been undertaken with data interrogation and modelling. Results of the research have been taken forward in other related programmes such as the ERP2 Broad Scale Modelling projects on predicting estuary morphology.

The new research has led to the identification of areas where additional benefits can be realised by further research in the future. Recommendations for this further research have been presented in this report.

More information on the project and a copy of this report can be obtained from the website: www.estproc.net or from the Defra website: www.defra.gov.uk

Key reports produced by the project

EstProc Consortium (2002). Estuary Process Research Project (EstProc): Inception Report. Report prepared by the Estuary Process Consortium for the Defra and Environment Agency Joint Flood and Coastal Processes Theme. Report No FD1905/TR1.

EstProc Consortium (2004a). Integrated Research Results on Hydrobiosedimentary Processes in Estuaries. Final Report of the Estuary Process Research Project (EstProc). R&D Technical Report prepared by the Estuary Process Consortium for the Fluvial, Estuarine and Coastal Processes Theme. Report No FD1905/TR2 – Synthesis Report.

EstProc Consortium (2004b). Integrated Research Results on Hydrobiosedimentary Processes in Estuaries. Final Report of the Estuary Process Research Project (EstProc). R&D Technical Report prepared by the Estuary Process Consortium for the Fluvial, Estuarine and Coastal Processes Theme. Report No FD1905/TR3 – Algorithms and Scientific Information.

EstProc Consortium (2004c). Integrated Research Results on Hydrobiosedimentary Processes in Estuaries. Final Report of the Estuary Process Research Project (EstProc). R&D Technical Report prepared by the Estuary Process Consortium for the Fluvial, Estuarine and Coastal Processes Theme. Report No FD1905/TR4 – Metadata Report.

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1. BACKGROUND TO ESTPROC

Estuaries are complex, as well as important areas, where often the changes made by man have significantly modified the natural systems. It is apparent that a change in one area may have impacts elsewhere within the system through a chain of 'change and response'. It is convenient to consider three main environments at any estuarine cross section – the subtidal section of the estuary, intertidal sand and mudflats, and, where they exist, fringing saltmarshes (Figure 1.1). We can also expect variations in different regions of the estuary – inner, middle and outer, at the mouth. Throughout the estuary there is a continuum of form, process and change, with the governing processes altering in emphasis and importance both in time and in space. Some of these aspects are indicated on the conceptual diagrams presented in Figures 1.2 and 1.3 indicating the interactions of flow, turbulence and sediment, and the role of biology and subaerial processes.

An integrated-multidisciplinary approach is the most appropriate way forward to deliver advances in the descriptions of key processes and associated modelling tools. This will lead to extended and improved predictive capabilities for estuaries, and provides improved information for the management of estuaries.

To achieve this aim the Estuary Process Research project (EstProc) was initiated as part of the Defra/Environment Agency Joint Flood and Coastal Defence R&D Programme within Phase 2 of the Estuaries Research Programme. The project objectives were two-fold; to perform:

- Innovative and fundamental research in estuarine hydrodynamics, sediments and biological interactions; and,
- Improved underpinning knowledge and sound scientific results for the estuary research community and end users.

EstProc project started on 1 December 2001 and ran to the end of November 2004; it was completed by a team with a strong and diverse background in estuary processes research and project work, the Estuary Process Consortium.[1] The conceived project (EstProc Consortium, 2001) responded to a specific Terms of Reference (ToR) issued by Defra and the Environment Agency in July 2001 (Mouchel, 2001), which recognised the prioritisation of research arising from the EMPHASYS project (EMPHASYS Consortium, 2000a) and the further prioritisation project (French et al, 2002).

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[1] Project Team (contact details are provided in Appendix 2):

- HR Wallingford
- Proudman Oceanographic Laboratory
- Professor Keith Dyer / University of Plymouth
- St Andrews University, Gatty Marine Laboratory (Sediment Ecology Research Group)
- ABP Marine Environmental Research
- WL | Delft Hydraulics
- Plymouth Marine Laboratory
- University of Cambridge, Cambridge Coastal Research Unit
- University of Southampton, School of Ocean and Earth Sciences
- Digital Hydraulics Holland B.V.
- Centre for Environment, Fisheries and Aquaculture Science

The project objectives were addressed directly through the commissioned research programme and through opportunities to collect and access new data from parallel programmes, as well as extended research through PhD and MSc studies. The EstProc work built on other projects and data sources including:

- Use of data from EMPHASYS (EMPHASYS Consortium, 2000a, b, c; Whitehouse, 2002) and the ERP1 uptake project FD2110 (Williams et al, 2004);
- Humber estuary SMP2;
- EC projects (e.g. COSINUS http://www.kuleuven.ac.be/bwk/cosinus/cosinus.html);
- UK projects (e.g. NERC core-science programmes);
- NL projects (e.g. RIKZ funded research programmes).

A large effort was placed into utilising existing datasets from recent and ongoing projects. The team recognised that forming links with other projects and interaction with other groups strengthened EstProc, both from the point of view of giving and learning (EstProc Consortium, 2002).

The project improved understanding and knowledge was developed in 10 areas identified as priority (Table 1.1). This work has been synthesised and applied during the project and these aspects are also presented in this report.

The research plan led to tractable process descriptions for application in numerical models of estuary processes and morphology. However, as is the case with any scientific discipline, not all the results produced are immediately leading to testable algorithms but demonstrate improved understanding. Wherever possible and in cases where the subject is mature and the research has yielded a practical result, the project provided testable algorithms. A suite of these is presented in another report (EstProc Consortium, 2004a). The present report provides information on the bigger picture regarding the way in which the multidisciplinary team has worked together, the results that have been produced that allow a clearer perspective on hydrobiosedimentary processes and the ability to represent (e.g. biological) processes into existing numerical methods. The research applies to all of the 9 JNCC estuary morphological classifications to a greater or lesser degree. In some cases, empirical correlations will be relevant to specific estuaries on which the original data was collected, but will still relate to other estuaries of that type elsewhere.

The integrated, interdisciplinary research undertaken in EstProc feeds primarily into both project objectives by exploring the suite of processes affecting sediment transport in the estuary (Figure 1.2) and the interactions during tidal inundation and exposure on the intertidal areas (Figure 1.3).

The outcomes of the project have been improved knowledge, understanding and improved predictive algorithms for application by estuary modellers (EstProc Consortium, 2004a). These algorithms have been checked by the originating organisations and in many cases by other members of the project team. In addition the implementation of algorithms in existing bottom-up models was a valuable exercise in checking the usability and applicability of the results, with lessons learnt being fed back to the originator of the algorithm for improvements to be made. However, they have not been tested outside of the project and hence further implementation, testing and validation is recommended as part of further research and practical applications of such models. Therefore, reliance on the information in this report is not a suitable substitute for necessary expertise and site-specific studies and investigations. Third parties should not rely on the algorithms without fully testing and validating them.

Interrogation of data formed a key strand of the research. The datasets accessed during the project have been documented in a separate report (EstProc Consortium, 2004b). This provides the metadata from which the originator of the data can be contacted by anyone who wishes to use that dataset, subject to prevailing conditions of supply.

For more information contact the project leader, Dr Richard Whitehouse at HR Wallingford (r.whitehouse@hrwallingford.co.uk or tel: +44 (0)1491 835381).

1.1 Report structure

This structure of this report is as follows:

- Section 2 – provides a summary of the scientific achievements in hydrobiosedimentary processes and interactions;
- Section 3 – provides a summary of issues relating to the interaction between process scientists and numerical modellers, and a more detailed description of the improved understanding of biology interactions;
- Section 4 – provides a review of example modelling applications which build on the results of the process research;
- Section 5 – provides a summary of the recommendations for further research arising out of the present work;
- Section 6 – contains the report references; and,
- Appendices 1 and 2 provide a project bibliography and contact details for the EstProc team.

Table 1.1 Scientific objectives of EstProc and report sections in which work is described

Hydrodynamics (Section 2.2)
1. To improve the ***modelling of waves in estuaries;***
2. To improve the prediction of the ***impact of extreme events and major anthropogenic influences;***
3. To investigate the ***interrogation of existing data*** to extract further information, interrelationships and correlations between parameters;
4. To improve the ***representation of near bed stresses.***
Sedimentary Processes (Section 2.3)
1. To undertake further investigation into the ***transport of mixed sediments***, where mixed sediments includes sand, mud, gravel or shell mixtures and dredged material with sizes upward of 5 microns;
2. To expand the ***understanding of the sediment transport profile;***
3. To improve the ***understanding of general sedimentary processes.***
Interactions Between Biological and Sedimentary Processes (Sections 2.4 and 3.2)
1. To review and prioritise, at an early stage, the relevant ***biological process parameters*** that effect the stability, erodibility and deposition of sediments;

2. To undertake investigations into the ***effect of biological processes*** on the stability; erodibility and deposition of sediments. Format results for incorporation into existing models for morphological prediction and assess validity through use in different models;
3. To develop understanding of the ***impact of benthic life*** (primarily macrofauna) on performance of intertidal areas and the effect of the change in flow regime related to tidal stage.

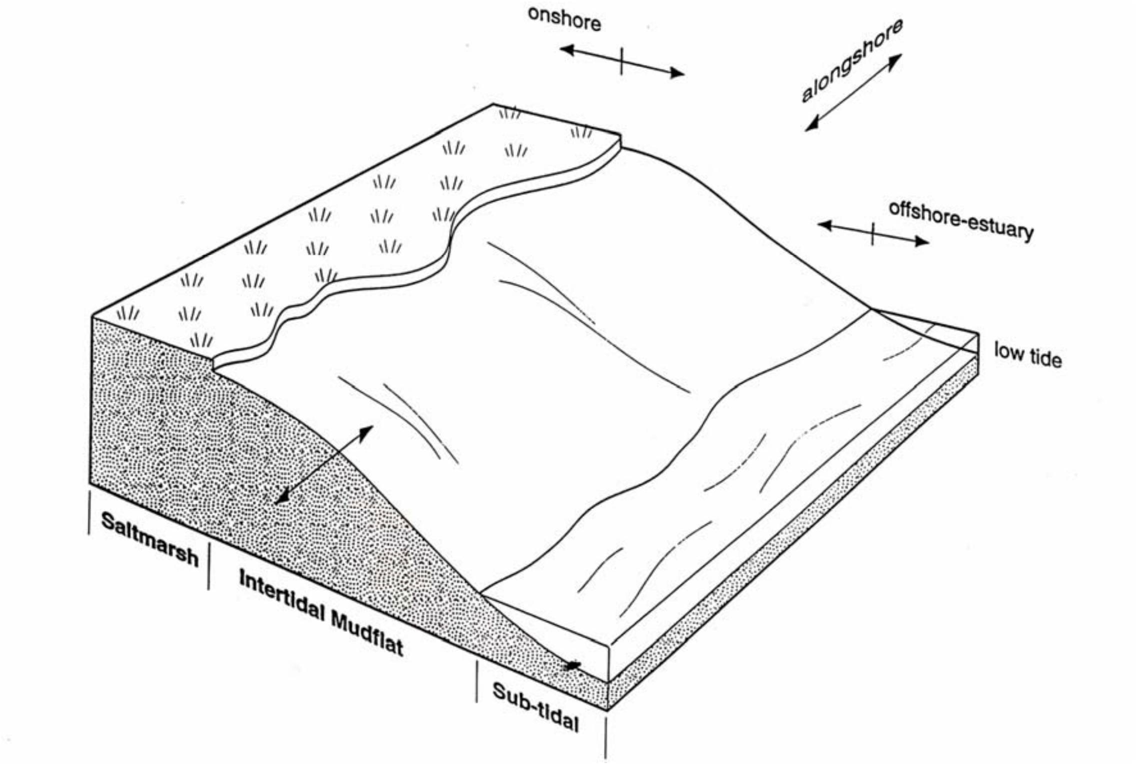

Figure 1.1 The cross-section components of the physical estuary system

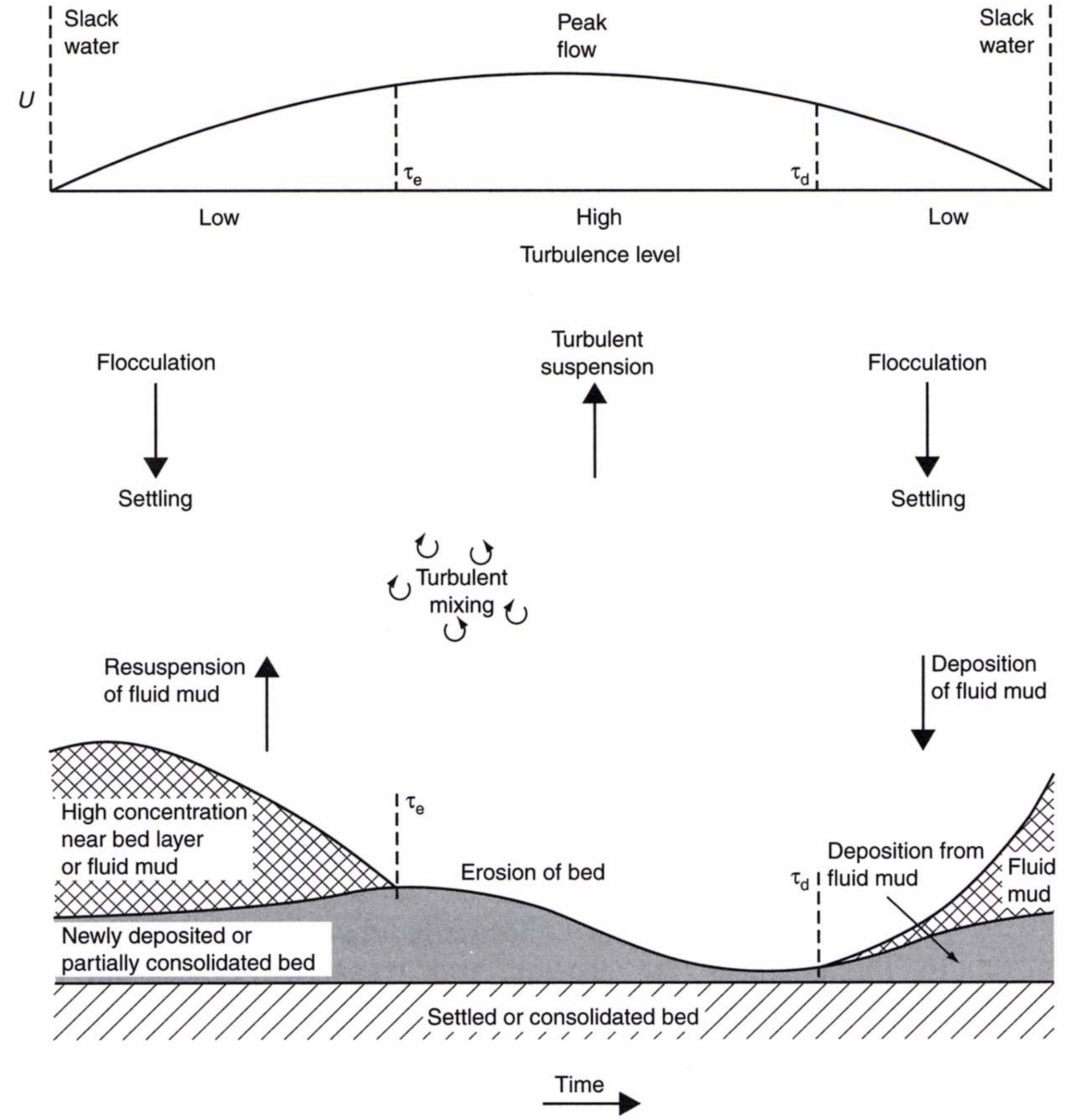

Figure 1.2 A conceptual model of cohesive sediment transport through the tide (Whitehouse et al, 2000)

1.2 Associated reports

There are two other reports associated with this final report, which have been included in the reference list in Section 6 as EstProc Consortium (2004a and b):

1. EstProc Consortium (2004). Integrated Research Results on Hydrobiosedimentary Processes in Estuaries. Final Report of the Estuary Process Research Project (EstProc). R&D Technical Report prepared by the Estuary Process Consortium for the Fluvial, Estuarine and Coastal Processes Theme. Report No FD1905/TR3 – Algorithms and Scientific Information.

2. EstProc Consortium (2004). Integrated Research Results on Hydrobiosedimentary Processes in Estuaries. Final Report of the Estuary Process Research Project (EstProc). R&D Technical Report prepared by the Estuary Process Consortium for

the Fluvial, Estuarine and Coastal Processes Theme. Report No FD1905/TR4 – Metadata Report.

They are referenced for short as TR3 and TR4 in the rest of the present report.

In the algorithms report TR3 the new EstProc algorithms are labelled as EP1, EP2 etc. and this cross-referencing is used in the present report, e.g. Reference TR3 – EP4.

More information on the project and a copy of this report can be obtained from the website: www.estproc.net or from the Defra website: www.defra.gov.uk

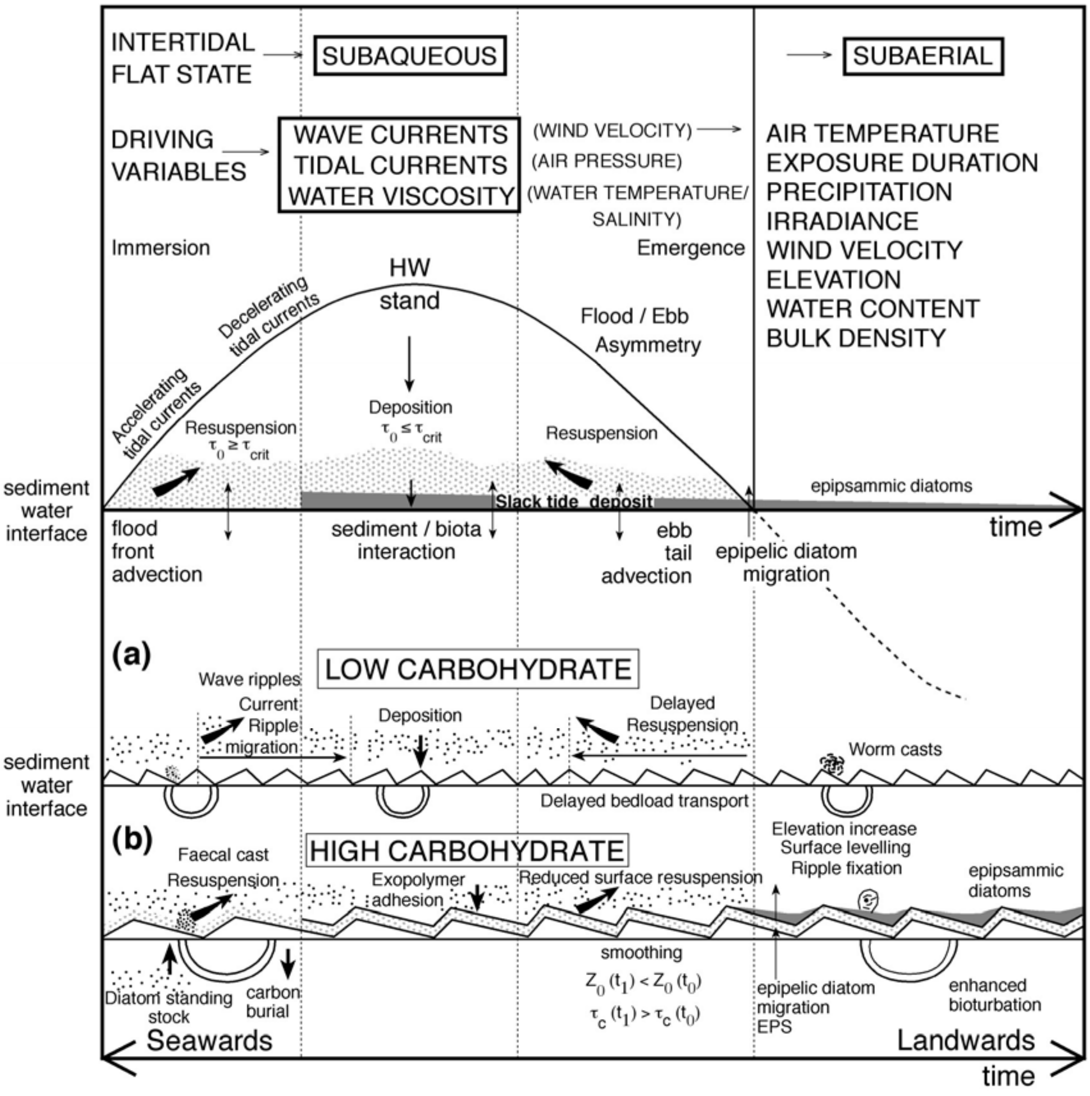

Figure 1.3 A conceptual model of non-cohesive intertidal flat processes illustrating two states: low and high sediment carbohydrate content (Friend, 2001)

2. SYNTHESIS OF ESTUARY PROCESS RESEARCH LINKING HYDRODYNAMICS, SEDIMENTS AND BIOLOGY

This chapter provides an overview and synthesis of the work done and results delivered by the project. It builds on the paper published at the Defra 2003 conference (Whitehouse, 2003) and draws on the results of EstProc presented in associated reports and papers (Appendix 1) and the new algorithms (EstProc Consortium, 2004a also referred to as TR3).

2.1 Introduction

The synthesis of results from the EstProc research are discussed in this chapter. By way of introduction some text is provided on the commissioning of estuarine modelling studies covering the exploitation of new tools and methodologies from EstProc.

The earlier project EMPHASYS included a critique of bottom-up models such as TELEMAC, DELFT3D and POLCOMS, providing a summary of their capabilities, limitations and sensitivities (EMPHASYS Consortium, 2000b and c). In particular, the need was emphasised for improved descriptions of:

- Bathymetry (including surficial sediment distribution);
- Sediment erosion, deposition and suspension- with their dependency on turbulent intensity;
- Marine sources and sinks (exchanges)-over particle size range.

As a prelude to whole-estuarine modelling studies, more limited and localised initial observational surveys are often undertaken to provide insight into the nature, variability and scaling of the sediment types, nature of transport, spring-neap and seasonal cycles. Related developments in EstProc are of direct benefit to the interpretation of such surveys and have led to more advanced predictive capabilities for process-based estuarine models.

Since it is neither technically or economically feasible to extend such observations to provide adequate whole-estuary axial and tranverse descriptions, process based ‘bottom-up’ (EMPHASYS Consortium, 2000c) models provide this spatial and temporal interpolation. Potentially, they can be used to extrapolate and to indicate how conditions may vary over a wide range of changing conditions, including extreme episodic events and with more gradual cumulative change over extended periods. However, validation of the simulations made with such models is extremely limited, generally to scalar concentrations rather than to the vector fluxes responsible for net sedimentation/erosion. To overcome these acknowledged limitations in the application of bottom-up models, multiple simulations encompassing uncertainties in model set-up, forcing and parameterisation are used, which provide results in an ensemble form.

Developments in EstProc are of direct benefit in determining the approach by providing a wider appreciation of all of these aspects. The benefits to the end-users of the research is achieved through the improved representation of processes within the decision tools (models and methodologies) that are used, so that end-users of the research and managers can reduce the level of uncertainty in their predictions and make more informed decisions.

EstProc can make no claim to have resolved all the problems and the complexities associated with the processes for which new methods and algorithms have been proposed, owing to the necessarily restricted conditions under which these have been derived. However, the results provided within expand the available tools for dealing with estuarine processes. The results also act as a vehicle for further constructive interaction between modellers, process scientists and end-users to further advance the present knowledge.

The following sections describe the highlights of the research in each of the areas of hydrodynamics (Section 2.2), sedimentary processes (Section 2.3), and the assessment of impact of biological process parameters (Section 2.4). Each section is illustrated with examples of the research completed within EstProc.

2.2 Hydrodynamics

2.2.1 Wave propagation, dissipation, role of vegetation including morphology of high water zones

An improved understanding of the morphological evolution of estuaries, together with the better assessment of the impact of human modifications on estuarine morphology, requires an understanding of the deeper channels and the intertidal mudflats and saltmarshes which characterise estuarine margins. It has become clear, for example, that wind-waves within estuaries are important drivers of local change; local wave generation depends upon fetch lengths, which can vary considerably with tidal level. Furthermore, the nature of the estuarine margins exerts an important influence on sediment transport in estuaries as a whole. Thus, improved methods for the determination of the driving nearshore waves and the surface roughness and energy dissipation on intertidal surfaces are required, as are appreciations of the morphodynamic feedbacks between surfaces (often vegetated) and input conditions over a range of space and time scales.

One task that has been tackled in this particular area of the project has been in the development and application of the community model SWAN. The application of SWAN to open-coast and estuarine environment in Liverpool Bay and the Dee estuary has been evaluated (Wolf, 2003) and, likewise, an intercomparison of results obtained against (simpler) Tucker (1994) and USACE (1984) methods has been provided. The results from the SWAN model have been parameterised for application in estuaries. It was found that the parametric formulations for fetch-limited wave growth, e.g. Shore Protection Manual formulae, work well for the estuary. The discrepancies between the parametric and numerical model results were largest in the nearshore zone and the entrances of the main channels of the estuary. Here there is likely to be some transmission of waves along the estuary mouth channels. In very shallow water near the coast (depths less than 10m) the attenuation due to dissipation processes, bottom friction and depth-limited breaking, becomes important and in this zone the full complexity of processes requires a more detailed model such as SWAN. A similar comparison of methods within the Blackwater Estuary has been made by Wolf (2004).

The performance of SWAN for the Outer Thames Estuary has been evaluated from comparison of model results with measurements of waves at two sites within the Estuary (Tozer et al, 2004). Specific examination of the model performance to represent the change in wave activity over the tide concluded that stationary[2] model runs performed as well as non-stationary runs; and that the effects on the waves, and particularly wave period, from the currents was important. There remained, however, a number of unexplained inconsistencies between the model results and the measurements. The performance of two alternative models, TOMOWAC, which is equivalent to SWAN (Benoit et al, 1996) and the simpler HINDWAVE model (Hawkes, 1987) was undertaken and this led to the production of an algorithm for tide dependent fetch limitations on simpler wave generation and transformation models for application in estuaries. The Outer Thames Estuary, HINDWAVE-TELURAY resulted in predictions of significant wave height and mean periods with root-mean-square errors against data within 0.6m and 0.7s respectively. This can be compared with the results from the spectral wave models SWAN and TOMAWAC run for the same area, in which the root-mean-square errors in predicted significant wave height and mean periods were between 0.2 to 0.5m and 1 to 2s, respectively.

The project team also examined the considerable challenges arising as a result of four aspects:

a) The stochastic nature of estuarine hydrodynamics;
b) The interlinked hierarchy of controls at different spatial scales (including the relative importance of elevation, distance from saltmarsh feeder creeks and distance from marsh edge);
c) The temporal variability (seasonal, inter-annual, decadal) of hydrodynamic inputs, sedimentation rates and vegetation growth patterns (and the place of 'extreme' events alongside more 'normal' events), and;
d) The complexity of both mudflat (e.g. mudmound topography) and saltmarsh (creeks, pans, vegetation community structures) surfaces and variations in the nature of the mudflat / saltmarsh transition (i.e. cliffed versus ramped topography).

Measurement and analysis of wave energy dissipation along shore-normal transects at Dengie Peninsula, Essex, has shown that patterns of wave attenuation over cliffed marsh edges correspond to patterns observed in previous laboratory scale physical model experiments; although dissipation landwards of the cliff face was less pronounced in the field (Reference TR3 – EP3). Over ‘ramped’ mudflat-to-saltmarsh transitions wave dissipation is initially less pronounced. However, once waves reach the permanently vegetated surfaces further landwards, dissipation was found to exceed the levels predicted by the earlier laboratory experiments. Observed intra-annual variability in energy dissipation patterns suggests that variations in vegetation canopy structure and biomass may influence the dissipation rates. Progress has been made in modelling this dissipation process over vegetated saltmarsh surfaces in the upper intertidal zone, using new algorithms implemented in the SWAN model. The vegetation friction factor, based on the existing Collins Coefficient, was modified in a physically meaningful fashion so that it mimics the change in vegetation height across marsh surfaces as community composition changes. As a result it has been possible to develop a dedicated coefficient for flexible vegetation, within SWAN. The parameterisation of the 3-D vegetation structures remains, however, a formidable modelling challenge although image analysis of 'side-on' photographs showing the canopy density has been trialled and shows promise. Empirical relations between the upper limit to observed root-mean-square

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[2] Stationary runs use one set of input conditions and non-stationary runs take a timestepping approach with continuously varying input conditions

wave height (H), in relation to water depth (h) over different intertidal surfaces, have been presented showing how the wave height to water depth ratio varies between the mudflat, the edge and interior of the saltmarsh.

Intertidal surfaces evolve over time under the spatial and temporal (individual tide to inter-annual change) patterns of sedimentation that result from tidal flooding. At the shortest time-scale, repeat airborne imaging spectrometry, ground-truthed with field spectra, has been used to establish patterns of suspended sediment dynamics on rising tidal stages at the managed re-alignment site at Tollesbury, Essex (Elsner et al, 2003). Whereas short-term sedimentation measurements suggest the key control of distance to feeder creek as the prime control on sedimentation rate, extended monitoring assigns prime importance to surface elevation through its control on the number of submergences in the long-term. Even at this time-scale, however, ‘at-a-point’ measurements of surface elevation change (using the Sedimentation-Erosion Table (SET)) have shown inter-annual variations in elevation change, which relate to both sediment supply and surface consolidation processes. From the results obtained some indicative relationships for saltmarsh elevation - distance to creek - sedimentation have been presented (Reference TR3 – EP31).

Considerable variability is apparent also in the position, as well as configuration, of the marsh edge boundary. Databases on historical changes in intertidal mudflat and saltmarsh extent for UK estuaries show oscillations between periods of rapid mudflat accretion and saltmarsh progradation, with periods of mudflat lowering and saltmarsh retreat. However, the linkages between changes in wind-wave climate and changes in the position of intertidal mudflats and saltmarshes are less clear. Various process links have been proposed (for example Figure 2.1) at the level of broad correlation including changes in sea level and water levels within estuaries, changes in storminess, changes in weather types, but none have been as yet tested comprehensively through estuarine-scale modelling. Based upon the analysis of data (Reference TR3 – EP3, 6, 30, 31), a concept for the relationship between maximum observed wave energy experienced compared with the form of the mudflat - saltmarsh margin topography has been presented. This provides indicative threshold values of the maximum observed incident wave energy for the topography. A change in topography from smooth transition, through mud-mounds to cliffs is proposed for increasing values of wave energy.

The physical controls for salt marshes developing on mud flats have been examined, concluding that whether or not these are stable depends, to a large extent on the local energy conditions, of wave climate and sediment availability. Vegetation can engineer their own habitat by reducing the energy conditions and by trapping sediment. Laboratory and *in-situ* experiments have been carried out to establish wave-attenuation by vegetation (Mol, 2004). It appears that stem stiffness and drag, plant height and density are the major parameters affecting wave attenuation. Figure 2.2 shows the site where wave attenuation by a *Spartina anglica* vegetation was measured. The effect of vegetation on wave height has been implemented also in the SWAN wave prediction model through a friction coefficient; this also utilises a formula based on the Collins friction coefficient, to quantify the impact of vegetation on wave height (Reference TR3 – EP5).

The vegetation wave modelling work has been undertaken in close collaboration with Nico Booij one of the originators of the SWAN code. The algorithm produced incorporating the modified friction factor in the SWAN model, to represent vegetation canopy effects applies to: a) a floristically-diverse UK East Coast open coast saltmarsh, and b) a single species *Spartina* stand in The Netherlands estuarine saltmarsh.

At the level of input to integrated morphological modelling, the impact of waves in estuaries was assessed through application to an existing Mersey 3D model (see Section 4.1).

2.2.2 Dendritic channel models

The term 'dendritic channel' is used to describe a network of single channels often found on intertidal mudflats; another channel type present on some marshes is called an 'anastamosing channel' which consists of a braid-like pattern of channels and 'islands'. Both types of channels convey a significant proportion of the tidal discharge, but are relatively small-scale features (1-10m) that cannot presently be resolved by regional-scale estuary models due to computational constraints. This limitation has driven the implementation of more relevant and efficient computer codes and led to the development of two approaches within EstProc.

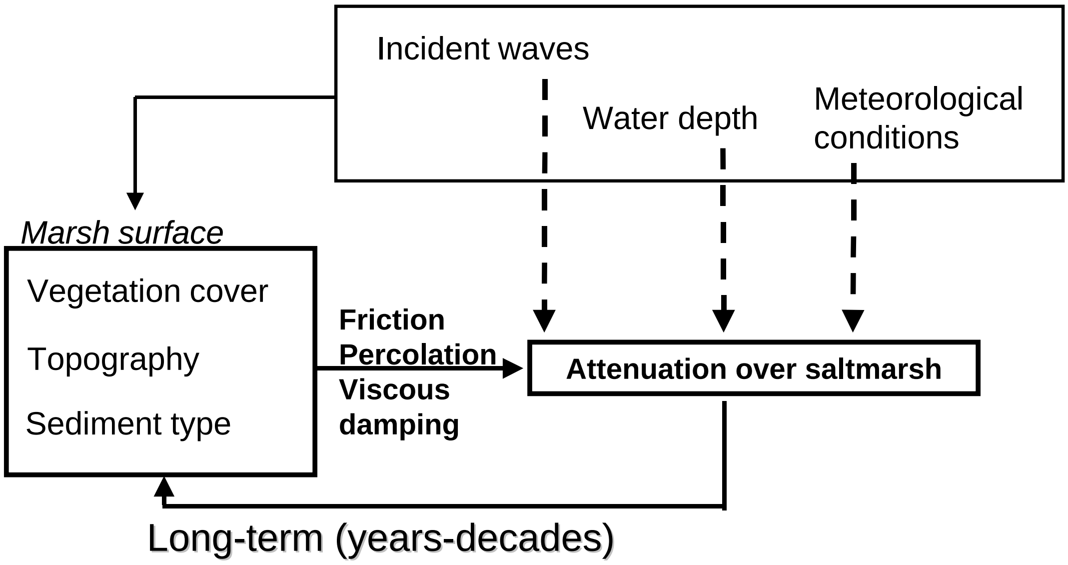


Figure 2.1 Schematic of processes and interactions on saltmarsh

Figure 2.2 Measuring wave attenuation by *Spartina* vegetation in the Western Scheldt (Mol, 2004)

The first approach is based on the development of a raster-based method similar to that used by Horritt and Bates (2001) coupled with a commercial finite element modelling system to simulate flood-plain inundation (ABPmer, 2004a). However, this approach has not been used previously to simulate flooding and drying conditions associated with tidal flows. The approach was implemented (Reference TR3 – EP8) and Figure 2.3 shows water depths at high and low water for an area within Southampton Water, where the model has been tested.

This cellular-type model is ideally suited to solving a simplified set of hydrodynamic equations and has been designed to make direct use of high-resolution bathymetric data. This type of data has become increasingly available through LiDAR altimetry, which resolves small-scale channels in intertidal areas. This raster-based approach can provide improved predictions of hydraulic conditions, in particular water levels; these are of primary concern to estuary managers when reviewing existing flood defence levels. The approach was also implemented in the algorithm test programme for an alternative site in the Blackwater Estuary.

An alternative approach has been developed for application to a saltmarsh system where dendritic systems including saltmarsh and mudflats channels have irregular bathymetry, which can vary rapidly over length-scales of 1m or less. These small length scales are considerably less than the practically viable scales of 2D flow model grids for applied modelling. For non-research estuary modelling, grid scales are typically of the order of 50-100m in estuaries and greater for large systems.

The normal course of action open to the estuary modeller is to enhance the grid resolution over the dendritic portion of the mudflat/saltmarsh, up to the point where the flow within the system becomes acceptably similar to the observations because the details of the topography are closely reproduced in the model grid. However, higher grid resolutions lead to larger numbers of grid cells, which can lead to impracticably long run times.

Hence a “sub-grid” modelling approach to represent the effect of the small-scale bathymetric variation on flows, without increasing the grid resolution has been applied (Reference TR3 – EP7). The motivation behind the research was to develop a means of including the effect of the sub-grid bathymetric variation on the current flows, whilst keeping run times to satisfactory levels. To achieve this purpose an algorithm for representing sub-grid bathymetry was developed and applied in Salcott Creek (Spearman et al, 2004); some comparative results are shown in Figure 2.4.

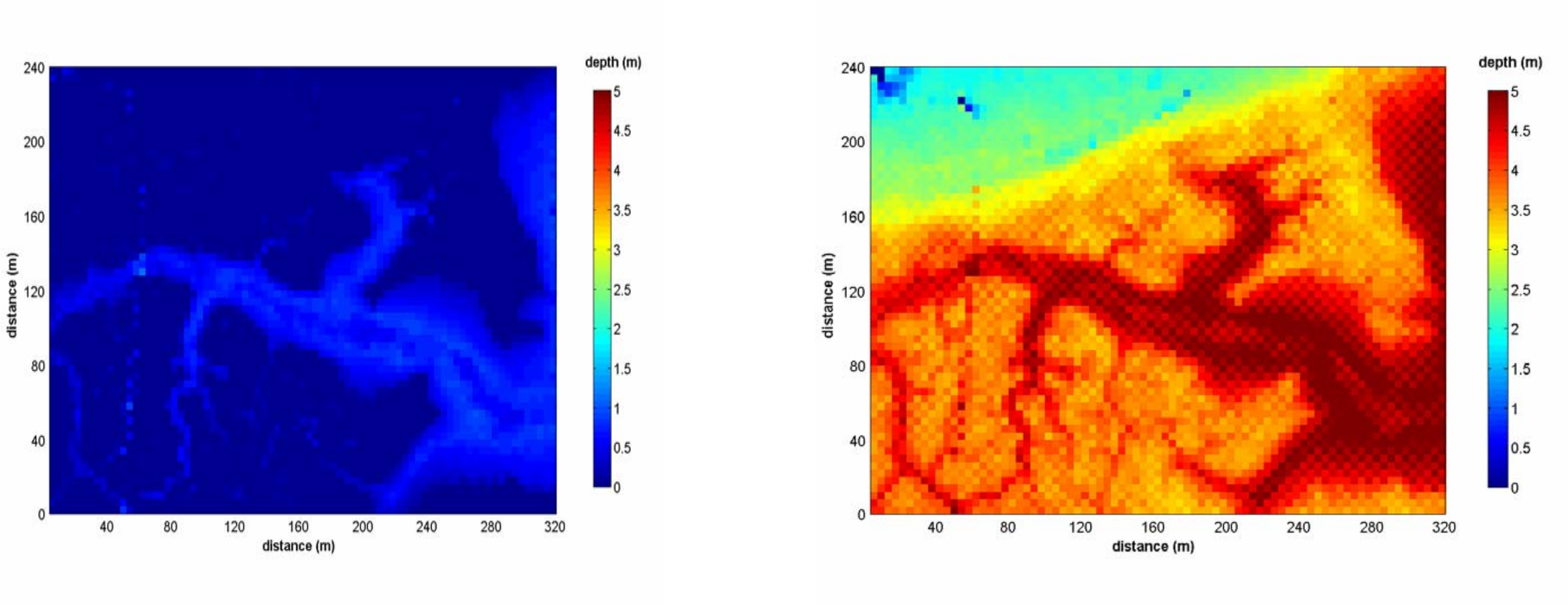
The conclusion was that the sub-grid methodology can, under certain circumstances, produce significant improvements in accuracy, both within the salt marsh and in the wider estuarine system, with minimal associated increases in run time. Therefore it was considered that the algorithm represented a useful tool for modelling, in estuarine systems with significant areas of saltmarsh or mudflat with channels of various scales smaller than the main channel of the estuary. A ‘step by step’ algorithm has been devised, showing how the sub-grid methodology can be implemented in computational flow models.

2.2.3 Role of extreme events and rapid change scenarios

The 'external' forcing driving the response of estuaries includes tides, surges, surface waves, fluvial flows, fluvial and marine sediment supplies/exchange and river and groundwater flows. The 'internal' forcing includes atmospheric exchanges (heat, evapo-transpiration, wind-generated waves) and geological/sedimentary activity (including bed-form migration and change) and seasonal and episodic biological and chemical mediation. These 'external' and 'internal' components may be subject to both gradual and relatively sudden changes via Global Climate Change, geological settlement and rebound, and 'intervention' from human processes of dredging, reclamation, and shoreline re-alignment. The following is an overview of likely changes in each of these forcing factors together with indications of the likely nature of the impacts on estuaries of differing kinds.

Some factors have been evaluated through interrogation of existing estuarine datasets and new datasets collected within EstProc:

Runoff in estuaries – an example of results produced from interrogation of data
An examination of the effects of rapidly increasing and very high runoff is important because it allows an insight into what is likely to occur under ‘extreme’ runoff conditions. Pronounced and rapid changes in suspended sediment concentrations (suspended particulate matter, SPM) and mudflat and mudbank morphology are likely to occur because of erosion in the fast runoff-induced currents, especially in smaller estuaries. Measurements in the main channel, middle-reaches of the Tavy Estuary, a 5-km long sub-estuary of the Tamar, captured a strong runoff event during summer months that demonstrated the dramatic increase in SPM concentrations (from $<< 1$ g l^{-1} to > 8 g l^{-1}) that resulted from mudflat erosion caused by the event (between 90 and 100 hours on Figure 2.5). The rapid recovery of the estuary, in terms of SPM levels and salinity, was also evident.



(a) water depth at LW

(b) water depth at HW

Figure 2.3 Flooding within dendritic channel network

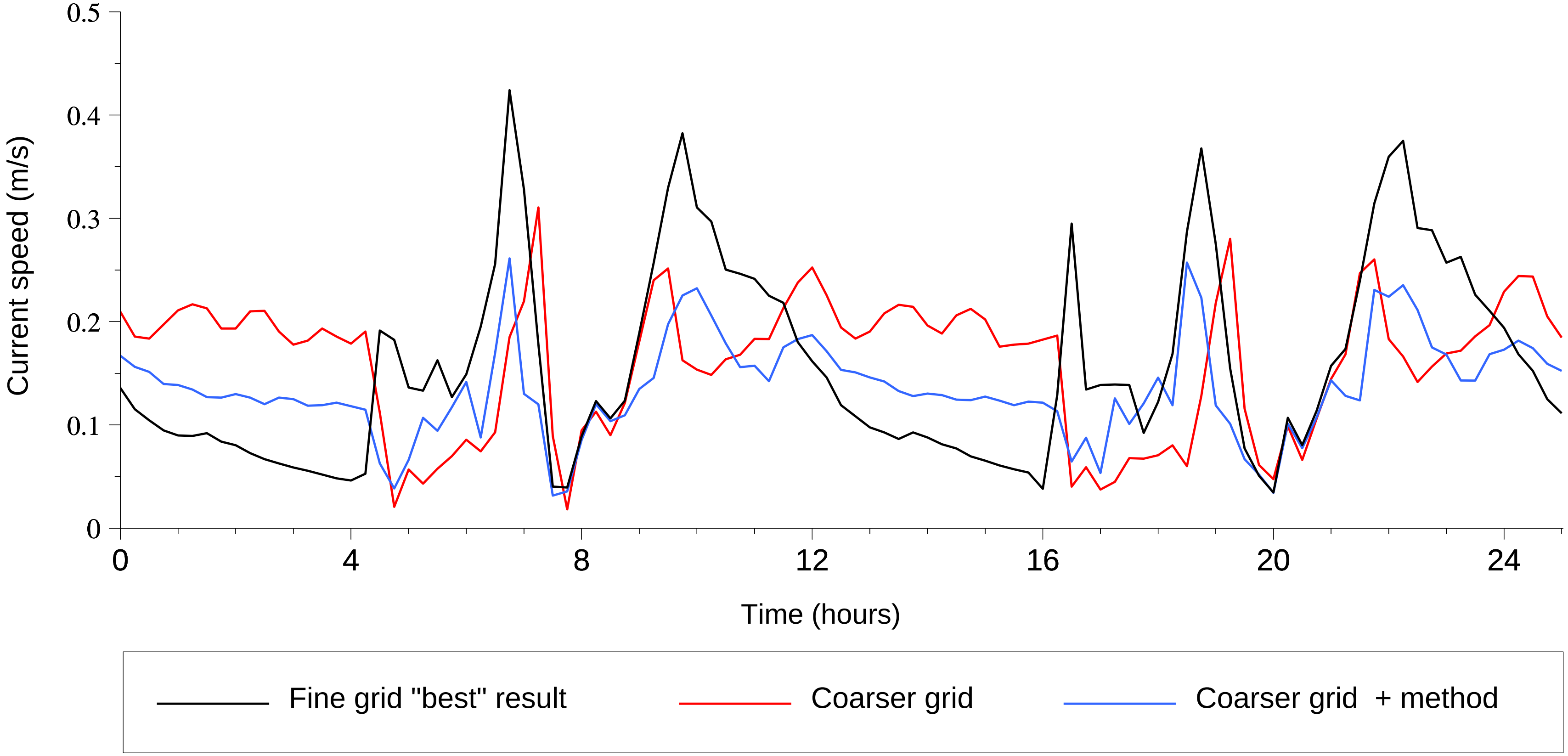


Figure 2.4 Comparison of predicted current speed within salt marsh area of Salcott Creek for fine grid, coarse grid and coarse grid with method

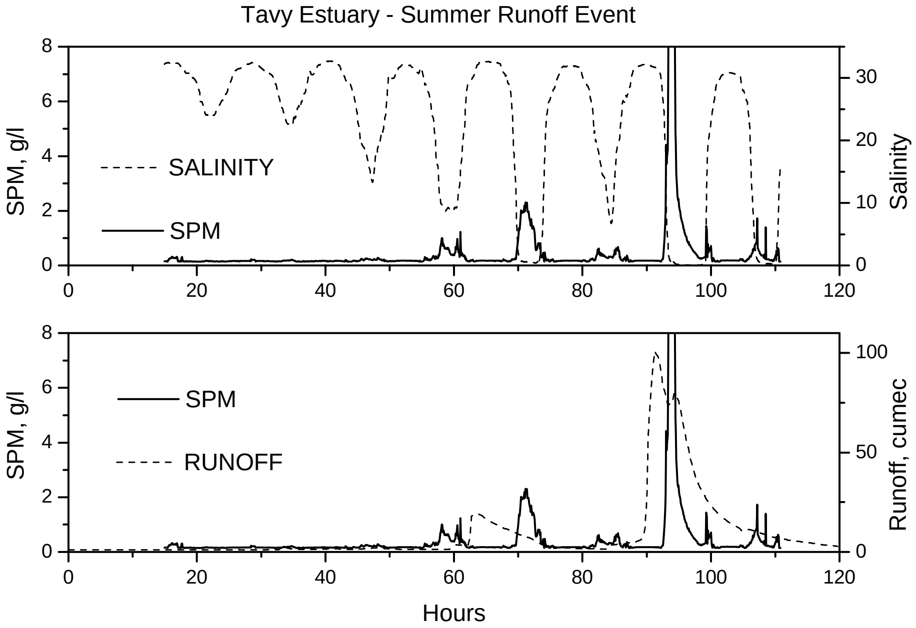


Figure 2.5 A strong runoff event in the Tavy Estuary
The upper panel shows the reduction of salinity to zero over the low water period, at approximately 95 hours, followed by a rapid recovery as the runoff returned to typical, low summer levels (upper panel); the dramatic increase in SPM due to erosion caused by the runoff 'event', which began approximately 2 hours into the ebb at 92 hours, was also followed by a rapid reduction to low levels once the runoff returned to low flows (lower panel).

In the main estuary of the Tamar the effects of strong runoff events are more persistent, especially in the upper reaches. The Tamar has a pronounced estuarine turbidity maximum (ETM) and an associated pool of mobile fine sediment that 'feeds' it. A strong runoff event transports this mobile sediment and its ETM farther down-estuary and leads to much lower SPM (Suspended Particulate Matter) levels in the upper reaches. An instrument package was moored in the upper reaches of the Tamar during winter months and recorded SPM levels at a fixed site before and after a high runoff period. The data illustrated a large reduction in SPM that occurred after the high runoff period (Figure 2.6). These low SPM levels exhibited a small maximum that occurred after the spring-tide peak in tidal range, which indicated that levels were recovering, although slowly.

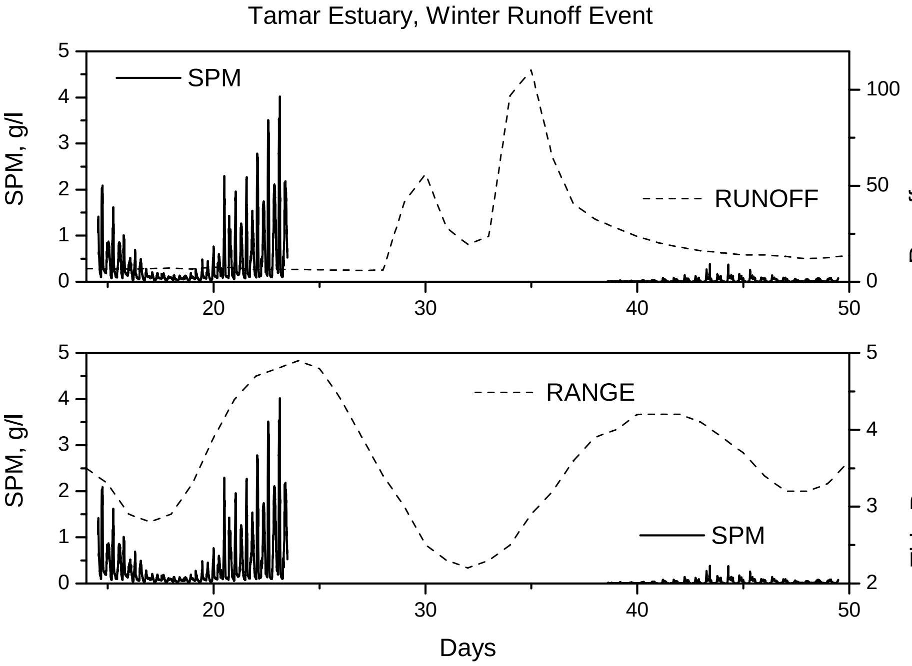


Figure 2.6 A period of strong runoff in the upper Tamar
SPM concentrations illustrated a pronounced ETM before a period of strong runoff (14 – 24 days) and greatly reduced SPM levels afterwards (40 - 50 days, upper panel). These low SPM levels showed a slight recovery following the spring-tide peak in tidal range, which indicates that levels were starting to slowly recover (lower panel).

Extreme events, by their nature, are non-stationary and not amenable to standard methods of time-series analysis. Advances in theoretical approaches have been made using wavelet transform tidal analysis methods. The continuous wavelet transform is a relatively new technique that complements traditional Fourier analyses by providing interpretation for time-series data that are not statistically stationary or exactly periodic.

An instrument package was moored in the upper Tamar Estuary and measured near-bed current velocities before and during a high runoff event (Figure 2.7). Over an 8 hour period the River Tamar's freshwater flow increased from < 30 m^3 s^{-1} to 200 m^3 s^{-1}, which led to ebb-directed flows throughout the tide (Figure 2.7). The velocity exhibited mainly semidiurnal variations and strong overtides (e.g. quarterdiurnal tides), together with high frequency variability. At approximately 1.5 days the runoff rapidly increased and the current became predominantly ebb-directed and extremely 'noisy'. Wavelet analysis has been used to interpret the time-series record. A wavelet is a small wave of finite length that has its energy concentrated in time, as opposed to a sinusoid, which oscillates with equal amplitude for all time. Wavelets can be used in the series expansion of a transformed time varying signal in much the same way that sinusoids are used in Fourier series analysis.

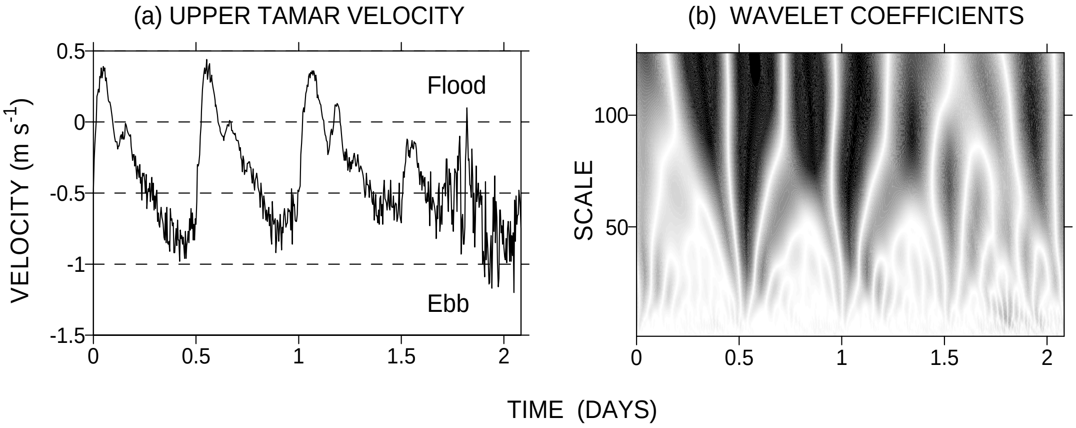


Figure 2.7 Time series of longitudinal velocity in the upper Tamar during moderate, increasing to high runoff and the wavelet scaling coefficients derived from it using a Daubechies (order 4) continuous wavelet transform

Time series (left panel) and wavelet transform (right panel). The absolute magnitude of the wavelet scale coefficients (darkest regions show largest, most significant coefficients) exhibit broad, dark bands at large scales (~ 100). These correspond to the semidiurnal tides, which are eventually disrupted by strong runoff after 1.5 days. The branching at intermediate scales (< 70) has the appearance of four 'arches' that taken together extend over the whole period and widen down to the lowest scales. Each of these 'arches' contains within its semidiurnal frame the darker banding corresponding to overtides (scales < 50). The fine banding at small scales (< 10) corresponds to high frequency variations.

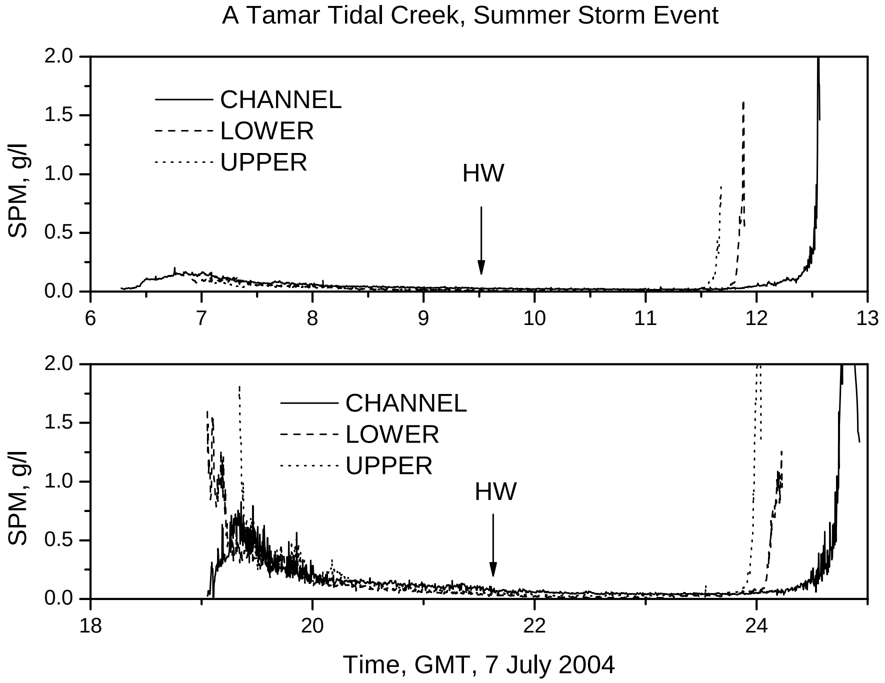


Figure 2.8 Near-bed SPM concentrations at three sites in the upper reaches of Tamerton Creek, a sub-estuary of the Tamar

Three instruments were deployed at a section of the creek: in the channel, the lower mudflat and the upper mudflat. The pre-storm SPM levels (upper panel) were 3 to 4 fold lower than those during the storm (lower panel).

Wavelet analysis has been used to interpret the time-series record. A wavelet is a small wave of finite length that has its energy concentrated in time, as opposed to a sinusoid, which oscillates with equal amplitude for all time. Wavelets can be used in the series expansion of a transformed time varying signal in much the same way that sinusoids are used in Fourier series analysis. The results in Figure 2.7 show the importance of the semi-diurnal tide identified by dark regions at large scales, and the disruption to the pattern that occurs after 1.5 days is a direct result of the transfer in periodicity to a smaller scale.

As well as very high runoff events, strong winds can also lead to high SPM levels due to sediment erosion over submerged tidal mudflats and mudbanks as a result of the action of waves and wind-induced currents in the shallow water (Figure 2.8). Three instruments were deployed at a section of Tamerton Creek, a sub-estuary of the Tamar, during July 7, 2004. They were located in the channel, on the lower mudflat and on the upper mudflat. A strong summer storm hit southern England on that day. Winds reached 25 m s^{-1} from the Northeast at 15:16 GMT, while the instruments were uncovered (Figure 2.8). The pre-storm SPM levels over the mudflat and within the channel were 3 to 4 fold lower than those that were measured on the subsequent flooding tide, during the storm.

Relative role of extreme events

The preceding examples of ‘extreme’ events have been complemented by a more complete statistical analysis of data from the upper Tamar. The influences of weather, runoff (especially strong runoff) and tides on water levels and salinity intrusion at two sites in the upper Tamar Estuary were analyzed for data measured at high water (HW) during 1988 and 1989, together with numerous along-estuary salinity surveys in the Tamar during 1981, 1982 and 1985. It was found that salinity intrusion was strongly related to runoff, with lesser dependence on tide range, but that salinity stratification was strongly related to both runoff and tide range, as might be anticipated. Peak near-bed salinity was strongly, positively related to HW level at low runoff (with a much weaker correlation at higher runoff) and it was strongly, negatively related to runoff as well as being strongly related to longer-term (2 – 8 day) winds and atmospheric pressure.

2.2.4 Estuary form analysis from existing datasets

Further work has been completed on estuary morphology examining further the relationship between tidal and fluvial forcing and estuary form (Reference TR3 – EP12). This has been achieved by interrogating the existing EMPHASYS and Futurecoast datasets. The ‘top-down’ (EMPHASYS Consortium, 2000c) O'Brien relationship states that there is an empirical power law relationship between the cross-sectional area of the estuary mouth, and the tidal prism. The dimensions of 96 estuaries from England and Wales have been examined and it was shown that there are no universal coefficients that can be generally used. Differences between estuaries relate to the sediment quantities that have been available to fill the estuary, to provide a sediment balance. This means that there can be delays between the formation of the estuary and the achievement of a sedimentary balance, and these can be of the order of thousands of years. Also the presence of rock, or another hard substrate, limits the amount of adjustment possible in the mouth cross-section to increases in current velocity required by increases in the tidal prism.

The influence of freshwater flow within the estuary is also shown to be important, with the High Water tidal prism being augmented by the ebb tide increment of river flow. Additionally, the magnitude of sedimentary processes active around the mouth determine whether spits can develop, whose presence can hinder the ready availability of finer sediment to fill the inner estuary. Man-made training walls and jetties have a similar effect. Similarly, reclamation of intertidal areas reduces the currents through the mouth and requires a reduction in cross-sectional area to produce a balance. Consequently, dimensional relationships have to be determined on an individual basis, and applying the results obtained for the whole estuary to other cross-sections within an estuary may not be valid.

2.2.5 Non-linear aspects

Due to the complexity of estuary systems, the analysis of either measured or derived data relating to estuary form can be difficult to interpret, due to highly non-linear behaviour and interactions between the various driving forces. For example, the length of the main estuary channel varies with time, due to meandering and migration. It appears that such morphological behaviour cannot be described by a single parameter, such as freshwater flow. Therefore a non-linear approach to the analysis of such data is required to identify relationships from what can initially appear to be chaotic behaviour.

Initial investigations undertaken as part of EstProc moved towards a framework for the non-linear analysis of estuarine datasets (ABPmer unpublished report). Tools have been developed to assist with the identification of morphological drivers, providing estuary managers with a better understanding of the sensitivity of the system to changes in selected parameters. **Problems arose resulting from limitations in the available data which made it difficult to interpret results from the analysis. The techniques used need high quality data covering very long periods. This leads to a research recommendation for improved long-term monitoring of driving forces within estuaries (tides, waves, river flows, sediment and salinity concentrations).** This approach is potentially valuable when assessing the possible impact of flood defence schemes, or other anthropogenic changes. Outputs from the task comprise algorithms in the form of a conceptual model and spreadsheets, including formulae applied in the analysis. The work on saline intrusion (Reference TR3 – EP26) and on settling-fluxes (Reference TR3 – EP18) have also utilised non-linear relationships.

2.3 Sedimentary processes

2.3.1 Parameteristing sedimentary processes in estuarine system models

Within EstProc, the present understanding of sediment processes has been applied to the development of a generalised theory to characterise estuarine parameters, as functions of tidal elevation amplitude, water depth, friction factor, sediment size and river flow. This has been tackled in two ways (Reference TR3 – EP26):

1. Localised relationships have been constructed for tidal current, stratification, mean suspended particulate matter SPM concentration and net export/import;
2. Based on values at the tidal limits (head and mouth) relationships for estuarine shape and size, flushing time and sediment 'in-fill' time have been constructed. These provide information indicative of the response time of estuaries experiencing a particular forcing.

Algorithms have been presented for both 1 and 2 in report TR3.

A concise literature survey and analysis concerning the physical processes in shallow tidal basins has been performed (Winterwerp, 2004). The key processes have been studied further through a sensitivity study with a 2Dh and 3D numerical model of the Humber estuary and a number of conclusions can be drawn:

1. Within the inner part of the Humber estuary, overtides are locally generated. The resulting asymmetry causes a net up-estuary transport of fine sediment;
2. The tidal asymmetry in the outer part of the estuary is sensitive to the tidal constituents prescribed at the model boundaries. When the 8 major constituents are incorporated, the asymmetry in peak velocity predicts ebb-dominant conditions in the outer estuary, whereas the asymmetry in slack water period predicts flood-dominant conditions;
3. Gravitational circulation increases the net import of fine sediment into the estuary, by about 10 %. However, further into the estuary, the effect of gravitational circulation is much larger, and increases net sediment transport rates by 60 %;
4. Intertidal trapping contributes largely to the net import of fine sediment. This contribution is very sensitive to local (re-)erosion, by for example, waves. A moderate increase in wave-induced bed shear stresses, simulated through an increase in the skin friction coefficient, yielded a considerable decrease (by~ 40 %) in net sediment import. However, sediment transport further into the estuary increased considerably (by~ 40 – 50 %). This effect is depicted in Figure 2.9, showing the influence of bed friction on the net sediment import, computed with a depth-averaged model.

A methodology for the parameterisation of gravitational circulation in depth-averaged 2Dh models has been developed (Reference TR3 – EP21). This example has also been used in Section 4 to illustrate the application of EP21.

The water-bed exchange of fine sediment, in particular on the intertidal areas appears to be a key factor in the net horizontal transports. A number of qualitative pieces of evidence lead to the conclusion that this water-bed exchange of fine sediment is much larger than predicted with formulations used commonly in cohesive sediment engineering practice:

- The erosion rates of the seabed can be very large as a result of wave activity and bio-destabilisation. This is in particular the case on the shallow intertidal areas, where small waves can generate large bed shear stresses;
- The deposition rates can be very large because of continuous deposition, with no threshold for deposition, and sediment-induced density currents acting to create an offshore flow of sediment from the turbid shallow water fringe, and bio-stabilisation.

It is reasoned further that the high turbidity levels experienced in estuaries and tidal basins can only be explained by wave activity, in conjunction with large amounts of sediment available through the sediment-importing processes. Seasonal variations in biomass and activity of biota and wave effects are responsible for a further redistribution of the sediment within the basin. It is the sequencing of waves and tides that dictate sediment erosion or re-suspension and the generation of turbidity in the estuary.

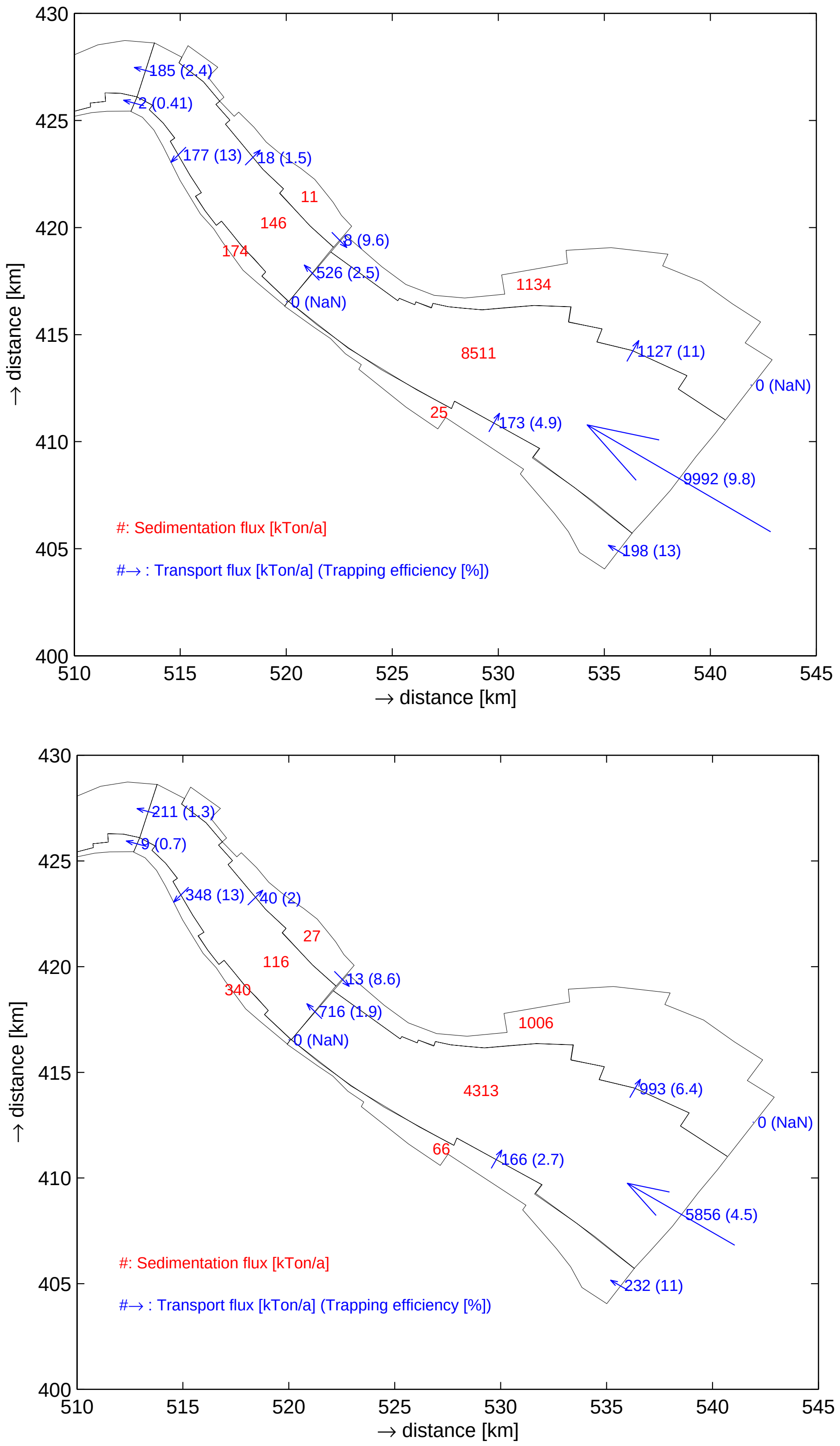


Figure 2.9 Net fine sediment transport in Humber mouth computed with 2Dh model with smooth bed (k_s = 1 mm, left panel) and rough bed (k_s = 10 mm, right panel)

For non-cohesive sediments, sediment erodibility, i.e. the threshold for sediment movement, depends upon the grain characteristics and, amongst other factors, upon the exposure to pre-threshold velocities in the overlying flow, which has the capacity to effectively rearrange the sediment grains at and below the surface, causing them to become more resistant to subsequent erosion. The effects of the applied stress 'history' leading up to the threshold condition for sediment movement under unidirectional flows has been studied in a recirculating laboratory flume. Results are shown in Figure 2.10 taken from Reference TR3 – EP23 (also Paphitis and Collins, 2005).

The sediment beds investigated consisted of cohesionless quartz sand grains, with mean grain diameters of 0.194mm (fine sand; Figure 2.10a), 0.387mm (medium sand; Figure 2.10b) and 0.774mm (coarse sand; Figure 2.10c), and narrow particle size distributions. The critical (threshold) shear velocity (Target Value) for the three beds was established, within 2.5 min of increasing the flow from zero velocity. The subsequent experiments were performed under pre-threshold velocities at 70% (for 5, 10, 20, 40 and 80 min exposure duration), 80% (for 5, 10, 20, 40 and 80 min exposure duration), 90 and 95% (for 5, 10, 20, 40, 80 and 120 min exposure duration) of the Target Value. Following exposure to these different pre-threshold conditions, the flow was then increased to reach actual critical conditions, within a period of 2.5 min. The critical condition for the initiation of sediment movement was established using visual observation of grain motion (supplemented by video recordings).

Effectively, the results show that if the exposure duration to pre-threshold velocities remains constant, then the threshold shear velocity increases with increasing pre-threshold velocity. Likewise, if the pre-threshold velocity remains constant, then the threshold shear velocity increases with increasing exposure duration. In some circumstances, the threshold shear velocity was found to increase by as much as 27%. A new algorithm was presented to account for the threshold shear velocity correction factor, in cases where sand-size sediment beds are exposed for a known duration to pre-threshold velocities.

Moving to the erosion behaviour of sandy and muddy sediments in the field three algorithms that represent new concepts have been devised. These relate to:

a) an objective method for defining a biostabilisation index on sandy intertidal flats (Reference TR3 – EP29);
b) day/night variations associated with the process of erosion, in terms of threshold, on muddy intertidal flats (Friend et al, 2005); and,
c) day/night variations associated with the process of erosion, in term of threshold, on sandy intertidal flats (Reference TR3 – EP24).

Finally, EstProc has provided local process algorithms adding value to existing knowledge for the following aspects of sediment transport in estuaries:

1. A criterion for the formation of fluid mud (Reference TR3 – EP20);
2. Entrainment of fluid mud (Reference TR3 – EP20);
3. Modelling of sediment-induced density currents (Reference TR3 – EP22).

The above algorithms have the potential to improve the representation of the processes that they describe, within existing or newly-developed models and methodologies. They have also facilitated an interaction between modellers and process scientist, towards improving and properly incorporating the algorithms within the models.

2.3.2 Morphodynamic modelling

The upscaling of transport processes to predict longer-term morphodynamic evolution can be achieved by applying morphodynamic updating strategies. A number of these strategies are used and have been discussed and compared (Reference TR3 – EP24). Various strategies of morphodynamic updating have been discussed and reviewed. The methods assessed (and defined in TR3, EP24) were ‘Brute force’, ‘Tide averaging’, ‘Tide averaging with continuity correction’, ‘RAM’ and ‘Morphological factor’.

A simple test algorithm has been developed to compare the different methods. The simple algorithm mimics the behaviour of an accreting channel, permitting a rapid intercomparison of the methods. Also, as part of the Humber Estuary Shoreline Management Plan – Phase 2 a morphological study was carried out involving model runs over periods from one to 10 years. The ‘morphological factor’ approach was applied and test runs were carried out to investigate the effect of the morphological factor on the predicted sedimentation and erosion. Results showed the predicted bed evolution in the inner estuary over one year, using a morphological factor of 60 and 12, respectively. Although some small deviations occurred, mainly in very shallow water, the overall picture was very similar. As the Humber inner estuary is extremely dynamic, it can be expected that even higher morphological factors can be used in less dynamic systems. An example of a (somewhat) less dynamic system is the Western Scheldt, where experience on a recent study found that comparison between simulations with a factor 24 and 120 showed no significant difference.

From a numerical point of view, the ‘morphological factor’ method has proven to be much more stable than the other updating methods, as the frequency of bed updating is much higher. This method is also relatively simple to implement as it allows a coupling of all processes at the flow timestep level.

For very long simulations involving a large variety of input conditions, the RAM approach where many transport simulations for different conditions can be carried out in parallel, is a good alternative.

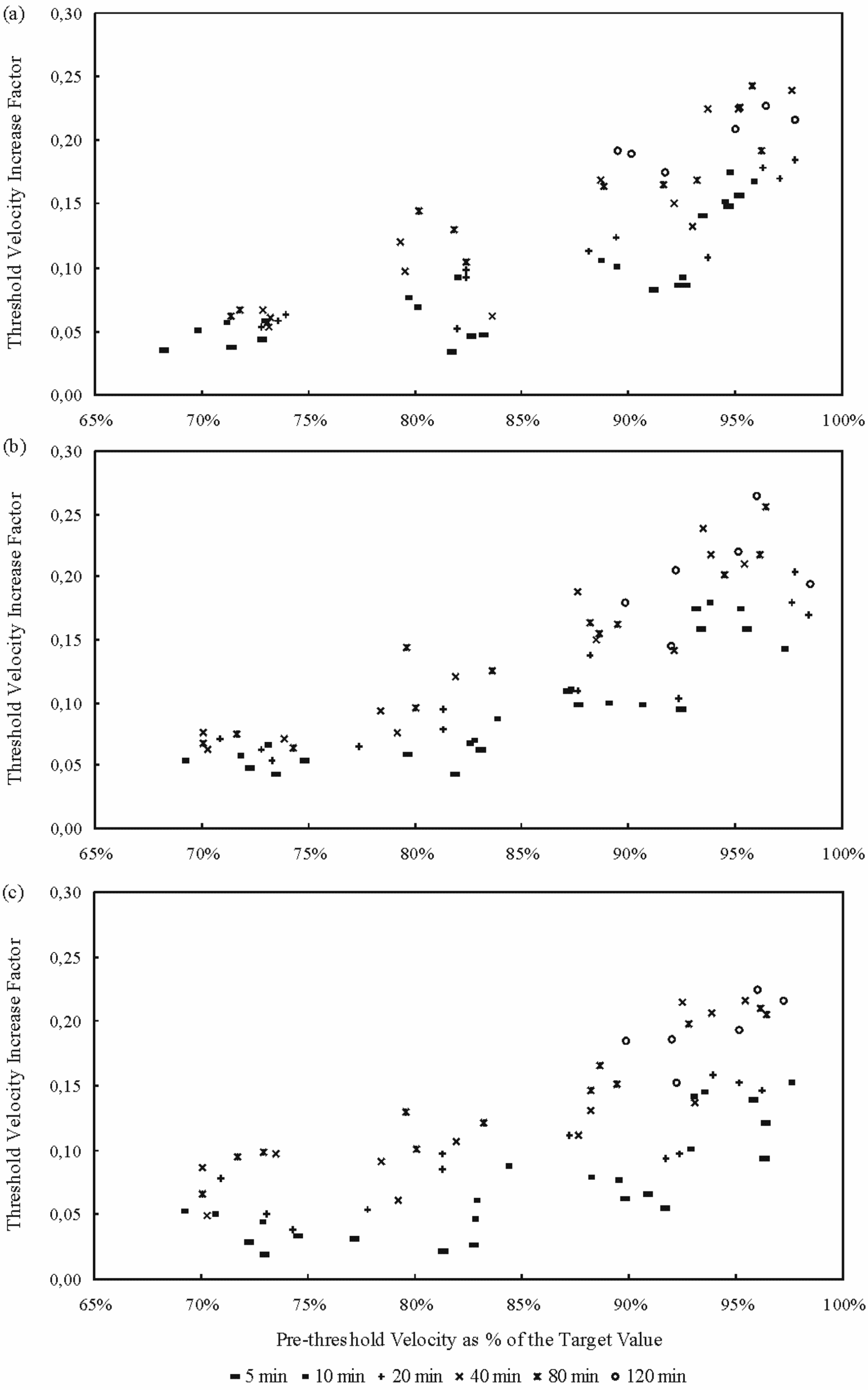


Figure 2.10 The experimental results of stress history on sandy beds (see text for more information)

2.3.3 Mud concentration profile

A number of types of problem require approximate calculations of the concentration of suspended mud at specified heights in a tidal flow, without the need for a full computational model. It is also important to understand how the concentration profile depends upon the properties of the mud, defined only by four or five key quantities (threshold shear-stresses for erosion and deposition, erosion rate constant, and settling velocity). New work has examined non-dimensional profile shapes derived previously; it has showed that the shapes are relatively insensitive to the assumptions made, and similarly that no one formulation gives unequivocally the best fit to the data. A very simple formulation for the shape, adopting a linear decrease with height was selected. The variation through a tidal cycle of the bottom concentration was deduced from the standard relationships between erosion, deposition and bed shear-stress, for a case with:
(a) a sinusoidal time variation in shear-stress; and,
(b) no net bed-level change over a tidal cycle.

Algebraic expressions have been derived for the bottom concentration at slack water, together with the maximum and minimum concentrations throughout the tidal cycle. The form of the equations provides insight into the dependence on the factors describing the mud, as well as the factors describing the flow. In future research, the method can be developed to apply to a more realistic expression for the vertical profile. The method derived provides a simple algebraic prediction method for the variation through the tidal cycle of the concentration of suspended mud at any height, for given mud-properties and flow inputs. It has been written up as an algorithm in Report TR3 – EP17.

2.3.4 Estuary processes and hydrography

This section of the report deals with the results arising from analysis of existing estuarine process data.

Estuarine processes in the Ouse and Humber – an example of results produced from interrogation of data

Following the earlier theme of data interrogation, analysis of results from longitudinal surveys along the upper Humber and Ouse has been completed (Figure 2.11). In this river-estuary there can be a bore-like tidal wave in the upper reaches. The data utilised profiling throughout the water column of salinity, suspended particulate matter and temperature. The data included spring-neap, seasonal and tidal variability.

At the time of the surveys, the Humber-Ouse had a strong estuarine turbidity maximum (ETM) in its low salinity upper reaches (Figure 2.12). During low runoff, spring-tide summer conditions the ETM is located typically 20 - 30 km from Naburn Weir, the tidal limit, at local high water (HW). Fluid mud layers can form close to the bed within the ETM. The ETM location corresponds to salinities of roughly 1 at local HW.

Although salinity is approximately vertically homogeneous, SPM stratification is high and ceases only where SPM concentrations are relatively low (< 0.1 g l^{-1} and salinity < 0.5), close to the tidal limit.

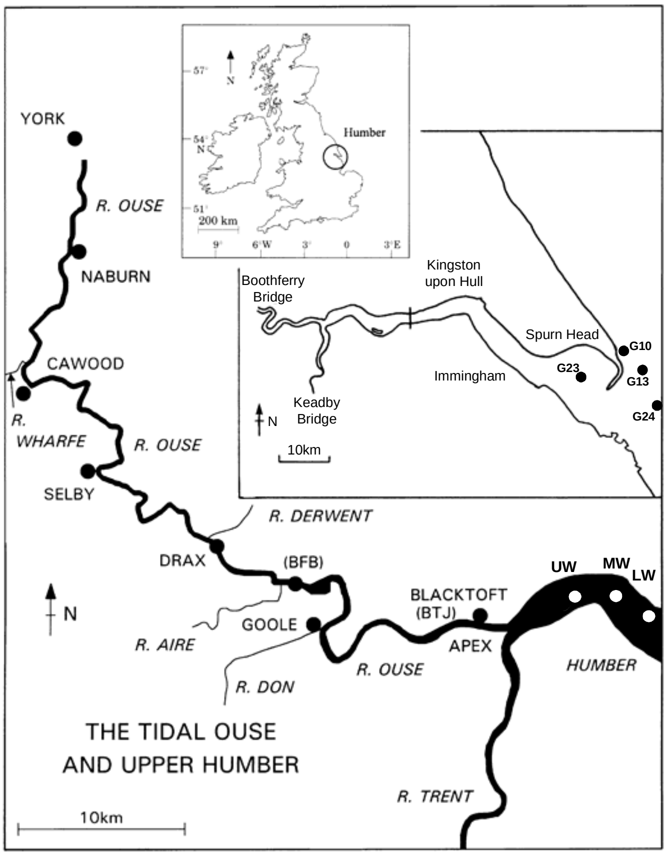


Figure 2.11 Sketch charts of the Humber Estuary, Northeast England, and the Ouse (Humber-Ouse) and Trent Estuaries, located in the Humber's upper reaches up-estuary of the Apex

Tidal cycle profiling work was undertaken at stations G10, 13, and 24 in the coastal zone, station G23 in the Humber mouth, station UW in the upper Humber and Naburn, Cawood, Selby and Drax in the Ouse.

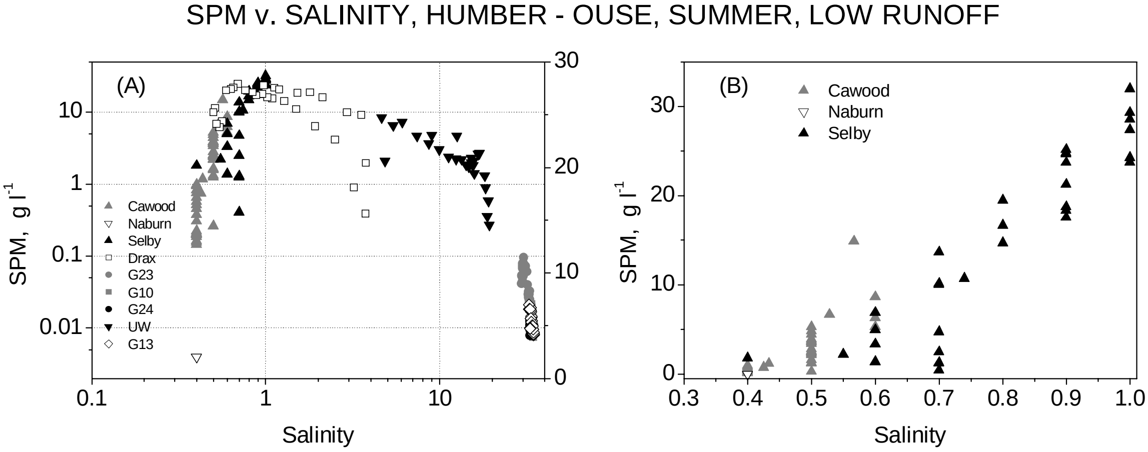


Figure 2.12 Tidal cycle station SPM data throughout the Ouse, Humber and the Humber coastal zone that demonstrate the existence of a strong ETM at salinities in the range of about 0.7 to 3

Apart from near-surface data at Drax, all these plotted data are averaged over depth. Strong, non-linear variations of SPM with salinity at all but the very low salinity stations and in the coastal zone (32-34 salinity) demonstrate the intratidal resuspension and deposition of sediment within the estuary, (a). Despite high SPM concentrations, there is approximate conservative mixing between fine sediment suspended in fluvial 'fresh' water and that suspended in much more turbid, salinity-1 water, (b).

Primary particles within the ETM are such that more than 40% (by volume) comprise very fine silt and clay-sized sediment (< 4 µm) and more than 20% is < 2 µm (clay-sized). In-situ aggregate (floc) sizes are much greater and vary with tidal state and SPM concentration (Figure 2.12). Floc sizes generally exceed 100 µm.

During low runoff summer conditions the ETM is located close to the tidal limit of the Ouse. Intratidal SPM data from the lower estuary reflect this up-estuary location of the highest turbidity zone (Figure 2.13). For example, at Blacktoft (station BTJ on Figure 2.11), the SPM concentrations at low water (LW) tend to be higher than those at HW, both during springs (Figure 2.13c) and neaps (Figure 2.13d), which illustrates down-estuary advection of the ETM during ebb currents.

At Blacktoft, the reduced turbulence and slower current speeds that occur at neap tides allow the formation of high concentration muddy layers close to the bed (Figure 2.13d). *In-situ* measurements show that the largest floc sizes (~ 800 µm, Figure 2.13b) occur within these fairly stagnant near-bed muddy layers, where concentrations can exceed 100 g l^{-1} and in the middle of the water column at approximately HW slack (~ 400 µm, Figure 2.13a).

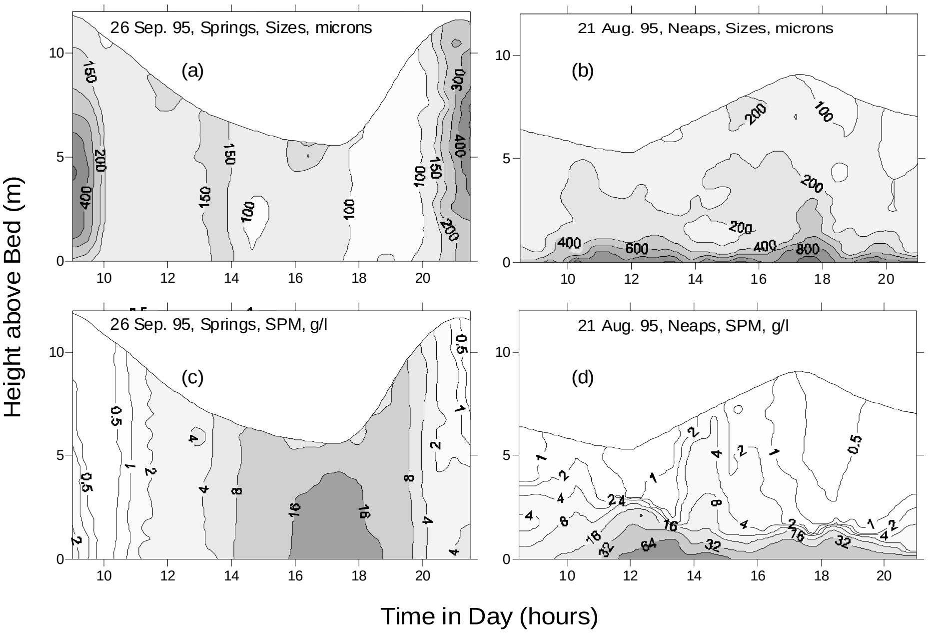


Figure 2.13 Spring and neap tidal cycles of floc sizes and SPM data measured at Blacktoft in the lower Ouse

The spring tide exhibits maximum SPM around LW, which illustrates that the ETM was located further into the estuary at that time (Figure 2.13c). The neap tide exhibits similar behaviour except for the occurrence of near-bed, high concentration layers at LW, which illustrates the reduced mixing and entrainment of fine sediment in the slower currents (Figure 2.13d). Floc sizes generally exceed 100 µm and maximize at about 400 µm at slack water of HW springs (Figure 2.13a) and 800 µm within the high concentration layers at neaps (Figure 2.13b).

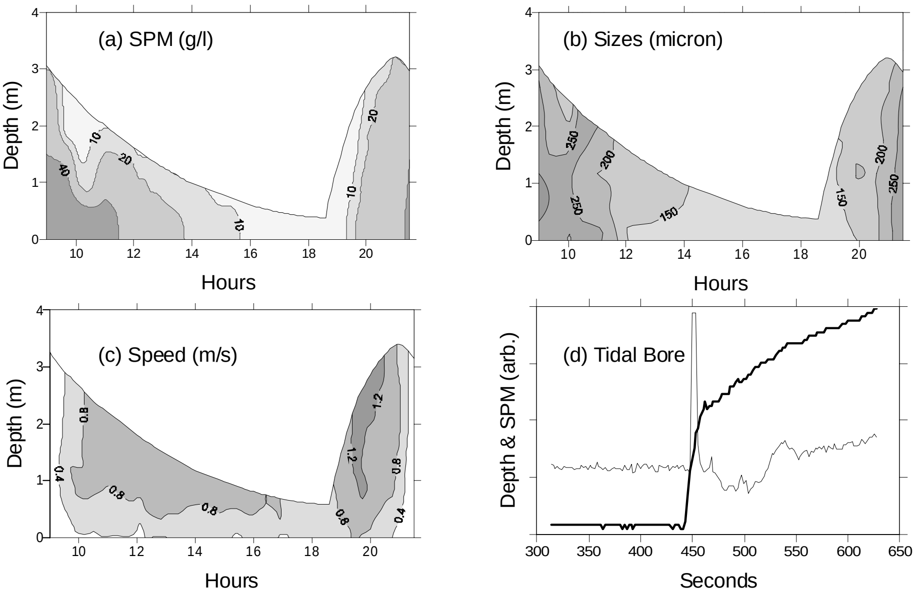


Figure 2.14 A spring tidal cycle of floc sizes, tidal current speed and SPM data measured at Selby in the upper Ouse

Maximum SPM occurs around HW, which illustrates that the ETM was located down-estuary at that time, and layering increases during the ebb (Figure 2.14a and 2.14c). Floc sizes exceed 100 µm and maximize at about 300 µm at slack-water following HW (Figure 2.14b). A tidal bore occurs in the upper estuary at spring tides (Figure 2.14d), leading to a rapid rise in water level (heavy line in Figure 2.14d) and a large but short-lived increase in turbidity (light line in Figure 2.14d).

An anchor station was worked at Selby (Figure 2.11) in the upper-estuary during low runoff summer conditions. The station was up-estuary of the main ETM region (Figure 2.14a-c). Currents are fast (> 1 m s^{-1}, Figure 2.14) and are characterized by prolonged ebb and brief, rapid flood currents and low salinity (~ 1) throughout the tide. SPM concentrations tend to reach a maximum at slack water following HW and exhibit pronounced layering of relatively lower SPM in the surface layers during the ebb (~ 10 g l^{-1}, Figure 2.14a). Near-bed SPM concentrations can exceed 40 g l^{-1}. In this region, floc sizes are typically 150 to 300 µm, with the largest flocs again occurring in the middle of the water column around slack water following HW.

A tidal bore can occur in the upper estuary during low runoff, spring tides. An example is shown for a September spring tide at Selby (Figure 2.14d). In this case the bore was 0.3 m high and had a non-vertical wave front that took approximately 20 seconds to travel through the measurement site. The turbidity was relatively constant during the late ebb flow and rapidly increased within several seconds of the passage of the leading edge of the bore's wave front. This was followed by a rapid reduction in turbidity as the bore passed, until the increasing flood currents and up-estuary transport of SPM within the ETM led to a gradual increase in SPM (illustrated for an autumn spring tide at Selby in Figure 2.14a).

Observations of SPM within the Ouse therefore demonstrate behaviour that depends both on the location of the ETM relative to the observation site and on the movement of the ETM throughout the tide. The intratidal movement of the ETM has previously not been observed in this estuary. Observations have been made of the intratidal movements of the ETM during both neap and spring tides. As an illustration, largest SPM concentrations during flooding neap tides occur on the early flood and decrease as HW is approached, during which time the ETM moves several km into the estuary, toward the tidal limit. In addition to transport by tidal currents, density effects due to SPM are likely to be an important feature of the hydrodynamics in the upper reaches of the Ouse and other highly turbid estuaries.

The main utility of these data is to provide field examples of ETM behaviour that can be used for comparison with modelling efforts. The main conclusions arising from the interrogation of this data are outlined below:

- Regarding seasonal variations in SPM
  - The ETM location and magnitude were strongly related to runoff and the spring-neap cycle (> 50 km from the tidal limit in winter and < 30 km in summer).
  - SPM stratification was related to runoff and tidal range and ceased only where concentrations were low, close to the tidal limit.
  - High concentration muddy layers (SPM levels about 0.1 m above the bed sometimes exceeded 100 g/l) had very slow current speeds.

In addition, analyses were made of vertical profiles of temperature, velocity, suspended-sediment concentration and, occasionally, in-situ aggregate sizing over tidal cycles in the upper Humber and Ouse. However, whilst floc size is an important variable, settling velocity is more relevant to sediment transport.

- Regarding vertical profiles of SPM
  - The high water phases of the tide were characterized by flocculation and settling – large aggregates were then observed at mid-depth (~400 microns);
  - Strong seasonal variations were related to seasonal movements of the ETM;
  - Entrainment of aggregates from the bed during fast currents led to their disruption.
  - Typical aggregate sizes in the ETM were ~100 – 300 microns;
  - Aggregate sizes in highly concentrated, near-bed muddy layers could exceed 800 microns in size.

Turbulence and sediment mixing in the Tamar – an example of results produced from interrogation of data

Further detailed work on turbulence and sediment suspension (Reference TR3 – EP10) utilising an existing process database has been completed during EstProc. The results of a field study on the Tamar into the effects of high concentration sediment suspensions upon the nature of near-bed turbulence, undertaken during the EU COSINUS project, have been re-analysed (Dyer et al, 2004). In this study, measurements of current velocities, associated flow turbulence and flow characteristics were measured within and above a high concentration near-bed layer in an estuarine turbidity maximum ETM. The ETM appears up-estuary from the tip of the salt intrusion in fresh water. There is a poor understanding of the formation and entrainment of these layers within which concentrations can reach several gml^{-1}.

Intermittent internal waves were important features of the measured turbulence, especially at higher Richardson numbers and above the lutocline. The Richardson number is non-dimensional quantity which compares the magnitude of the stabilising forces of density stratification to the destablising force from the flow velocity shear; at low values turbulence is effective in creating mixing, but at high values the flow turbulence is damped. The lutocline is a significant density gradient associated with transition from a low concentration surface to a high concentration near-bed layer. At lower values of Richardson number, when internal waves were less significant, the ratio of horizontal to vertical turbulent intensities were similar to previously observed clear water values, and the shear stress derived from the turbulent kinetic energy (TKE) was greater at the lower height. At higher Richardson numbers, however, the TKE was greater at the upper height. The ratio of vertical to horizontal turbulence intensities exceeded 1.0, reaching 1.6 when internal waves were present. A physical explanation for the unexpected enhancement of the vertical fluctuations in relation to the horizontal appears to lie in the observed complicated interaction of standing and progressive waves.

Shear stresses were calculated both through the turbulent kinetic energy (TKE) approach, and from the measured Reynolds stresses. Comparison between them showed the presence of turbulence when there was no exchange of momentum. This 'inactive turbulence' occurred at stresses of less than about 0.2 Nm^{-2}, both within and above the high concentration layer. Consequently, there were disorganised motions present at low stresses that may exchange mass, but not momentum. It was therefore conjectured that stresses below this magnitude were unlikely to create the break-up of flocs, but were more likely to promote aggregation of flocs, as well as allowing settling.

Calculation of the turbulent Reynolds fluxes of suspended sediment showed that, during the periods of inactive turbulence, fluxes of suspended sediment toward the bed often occurred. This indicated that at low stresses the inactive turbulence could enhance settling of the sediment, thereby adding a downward flux similar in magnitude to the normal gravitational settling. Additionally, downward fluxes were observed at times at higher stresses within the high concentration layer, because of the presence of internal waves. These appeared to increase the variability of the Reynolds fluxes of suspended sediment, allowing downwards sediment fluxes, especially beneath the lutocline.

Statistical (quadrant) analysis of the turbulent velocity and concentration fluctuations showed that above the lutocline the sweeps (downward vectors) and ejections (upward vectors) each contributed about 33% of the overall stress; this is the same as for clear water. However, near the lutocline the density layering reduced both these contributions to 24-28%, by reducing the magnitude of both the horizontal and vertical fluctuations, but increasing relatively the vertical contributions at the expense of the horizontal. Internal waves will increase the total magnitude of the fluctuations, without necessarily affecting the turbulent stresses, as the process is dependent upon the phase relationships created by the standing and progressive nature of the waves, and may therefore be significant features in the inactive turbulence.

Examination of the quadrant relationships of the velocity and concentration fluctuations showed that differences in the sign and magnitudes of the vertical suspended sediment fluxes arise because of internal waves. Because of the importance of internal waves to the specification of the fluxes further, more detailed, measurements and analysis are required. Incorporating these internal waves into computational numerical models will require careful specification of their properties.

As a further stage of research the predictive algorithms and data from the Ouse-Humber and Tamar data need to be compared with the predictive formulae for flocs and mass settling flux (Reference TR3 – EP18).

2.3.5 Bed shear stresses

Where waves and currents are present the calculations and numerical modelling of the erosion, transport and deposition of sediments in estuaries and coastal areas rely heavily on expressions that contain the bed shear-stress; this represents the friction exerted by the flowing water on the bed. In general, the bed shear-stress is generated by the combined effects of waves and currents, whose turbulent boundary layers interact non-linearly. The flow is considered usually to be:

(a) hydrodynamically rough turbulent for sand and gravel beds; and,
(b) hydrodynamically smooth turbulent for freshly-deposited mud beds.

Most existing theories and models for the wave-current-interaction have considered only the rough bed case, and they have generally been too complicated and computer-intensive to be usable in whole-estuary or coastal models.

The new work undertaken in EstProc involved the development and testing of a new method of calculating the mean, maximum and root-mean-square bed shear-stresses due to combined waves and currents (Soulsby and Clarke, 2004). The method caters for rough turbulent and smooth turbulent, as well as laminar flows, with the greatest emphasis on the less well-researched smooth turbulent case – the new method is more general than that which was presented in Soulsby (2000) and Whitehouse et al (2000). Tests of the new method against published data for smooth flows provided better agreement than existing methods. Figure 2.15 shows comparisons of predicted with experimentally-observed values of mean and maximum bed shear stresses. The new method is simple to implement, being expressed as explicit algebraic equations that are computationally fast. The detailed derivation and testing and a detailed algorithm giving the "recipe" to implement the method has been written in Reference TR3 – EP13; also contained in Soulsby and Clarke (2004).

The bed roughness is a key aspect in predicting bed shear stresses. A predictive modelling tool has been used to assess the scale of wave-generated bedforms, applicable to estuaries with a significant proportion of sandy sediments, such as the Mersey and Bristol Channel. The method, presented in ABPmer (2004b), provides a means of quantifying spatially varying bed roughness which can be readily applied in hydrodynamic models. The work has resulted in an algorithm which can be applied readily to estuaries within many existing modelling systems – Reference TR3 – EP14. Future work would seek to introduce a feedback mechanism, which would further enhance this approach by accounting for temporal variability in bed roughness.

Thus, the improved representation of physical processes can be used to provide improved predictions of hydrodynamic conditions in estuaries. An improved modelling capability will provide, ultimately, more robust and reliable model predictions, particularly for predicting estuary morphology. The representation and sensitivity of model results to the calculation of the bed-stress is a key area. This has been assessed in EstProc with a simple 1D (Z-t) single-point community model (Reference TR3 – EP19).

This approach has been extended to include 2D (y-z-t) lateral inter-tidal SPM exchange and to assess the new EstProc wave-current interaction algorithm (Reference TR3 – EP13). The wave-current algorithm has also been implemented in a 2D/3D mudflat model (see Section 4.4 and Spearman, 2004).

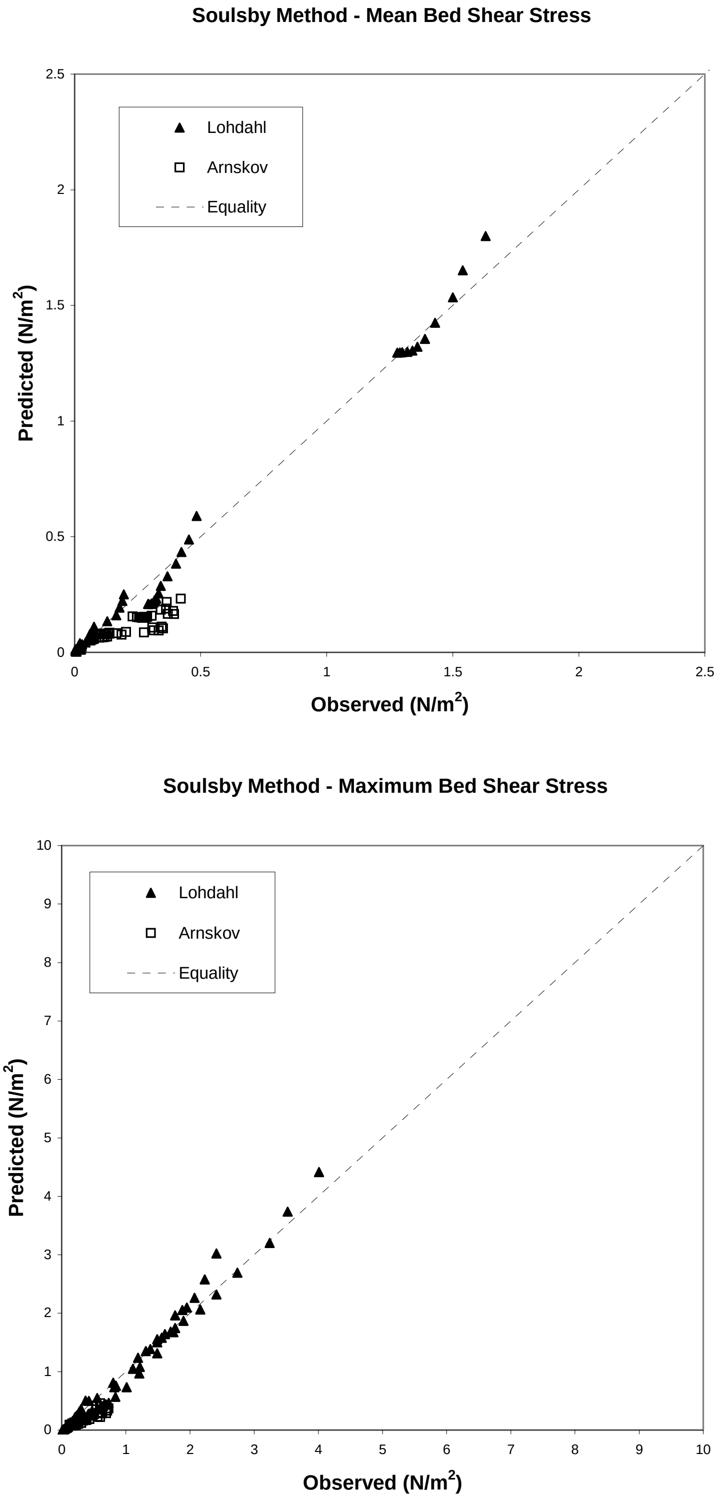


Figure 2.15 Comparison of the new wave-current shear stress method with data – top panel mean bed shear stress and bottom panel maximum bed shear stress

2.3.6 New results on the initiation and transport of mixed sediments

Natural systems, such as the Humber estuary, experience large spatial and temporal variations in sediment composition, amongst which one key characteristic is the sand-mud ratio. This is particularly the case on intertidal areas, where gradients in wave and current energy control the sediment composition; this, in turn, provides a controlling input for ecological aspects. A classification scheme has been devised to establish the bed properties and erodibility of the sediment mixture on the basis of simple geotechnical parameters (Reference TR3 – EP16.1). For a given system, the sand content and in-situ bulk density appear the key distinguishing parameters – Figure 2.16 plotted with dry density in place of bulk density. In this diagram C_u is the remoulded shear strength of the sediment in Pascals, and n^{si} and n^{sa} respectively the porosity of sand and silt fractions.

The six zones (numbered 1 to 6 in Figure 2.15) distinguish six modes of sand-mud behaviour (Winterwerp and Van Kesteren, 2004):

1. non-cohesive sediment dominated by sand skeleton;
2. cohesive sediment dominated by sand skeleton;
3. non-cohesive sediment with unstable skeleton;
4. cohesive sediment dominated by clay skeleton;
5. non-cohesive sediment dominated by silt skeleton; and,
6. cohesive sediment dominated by silt skeleton.

The available data for the Western Scheldt implies only three modes may occur in that estuary; modes 1, 3 and 6.

This type of information can be applied to aid in quantification of the erosion rate of sand-mud mixtures in computational numerical models. Also, a phase diagram for sand-mud mixtures and an erosion formula for sand-mud mixtures have been devised, building on earlier research findings (See EP16 in EstProc Consortium, 2004a).

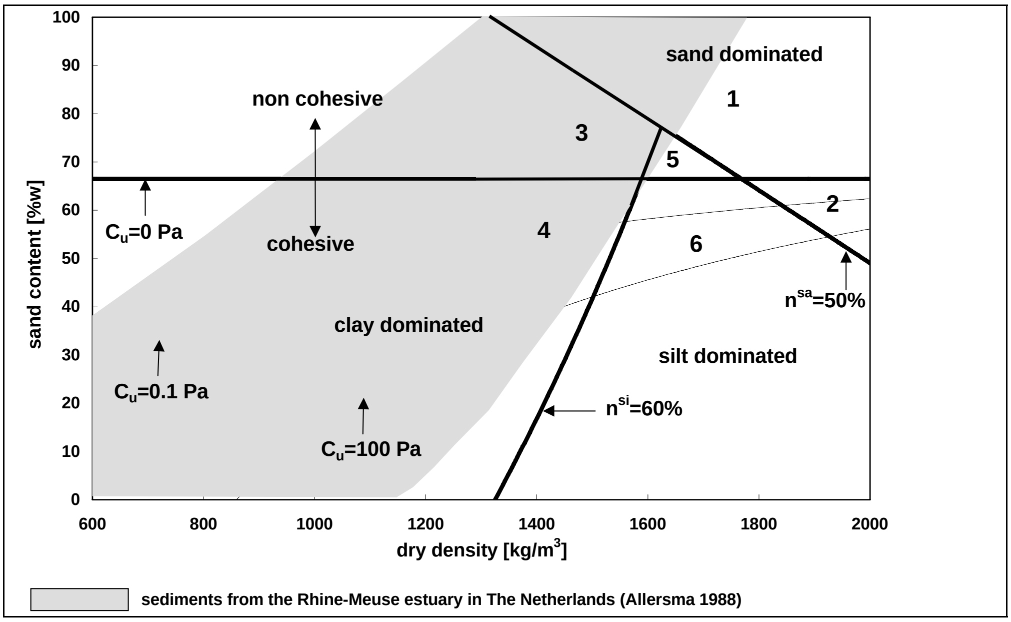


Figure 2.16 Sediment phase diagram for Western Scheldt sediments, the shaded area represents natural sediments

The distribution of sediments within the Humber-Ouse estuary have been further analysed, and particular focus has been given to the grain sizes of primary and flocculated suspended sediments and their particulate organic carbon content (POC), via loss on ignition (LOI). Similarly intertidal sediment properties along the Humber-Ouse system have been investigated.

- Relating to sediment characteristics:
  - The SPM that comprised the ETM was largely inorganic (mineral) fine sediment (LOI ~10%);
  - The primary SPM was such that > 40% by volume of the solids was very fine silt and clay sized (< 4 µm) and > 20% was < 2 µm (clay-sized);
  - Bed sediment grain sizes varied throughout the region and were much coarser than the SPM, although the great majority of bed sediment was < 500 µm;
  - The dominant bed-sediment fraction down-channel of the ETM was fine sand. Within the ETM the bed sediment was predominantly fine sand and very fine sand. Up-estuary of the ETM, the bed sediment was mainly very fine sand and compacted silt and clay-sized material.

- Relating to seasonal variations in sediment properties:
  - A strong seasonal, longitudinal transport occurred, in both subtidal and intertidal sediments;
  - Over the winter period, the up-channel margin of very fine sand moved down-estuary; a scoured, highly cohesive mud bed remained;
  - Sand was transported back into the upper reaches by flood-dominant tidal currents during low river inflow during the summer and autumn;
  - The intertidal banks of the upper reaches incorporated very fine sand during their growth in summer and autumn.

2.3.7 Sediment fluxes

A new flocculation model, which was based entirely upon experimental observations made using low intrusive data acquisition techniques under a wide range of estuarine water column conditions, has been developed (Manning, 2004 and Reference TR3 – EP18). The data utilised in this study was acquired predominantly from a series of *in-situ* EC MAST III funded experiments (COSINUS, SWAMIEE and INTRMUD) undertaken in several European estuaries. Sampling deployments were carried out on a within-tidal cycle time-scale, at periods when the flow conditions were either reasonably steady or gradually changing. Floc populations were sampled using the low intrusive INSSEV: *IN-Situ* SEttling Velocity instrument (Fennessy et al, 1994). The analysis has identified the key components which best quantitatively describe the floc population of a muddy suspended sediment:

- The changes in the macrofloc (particle size D > 160 µm) and smaller size microfloc settling velocities $Ws_{macroEM}$ and $Ws_{microEM}$ respectively; and,
- The distribution of suspended particulate matter (SPM) within each floc sub-population ($SPM_{ratioEM}$).

The importance of both turbulent shear stress (τ) and SPM concentration terms, as independent variables in controlling $Ws_{macroEM}$, was confirmed by a parametric multiple regression statistical analysis of empirical data; this produced a highly significant R^2

correlation of 0.91. The $Ws_{macroEM}$ algorithm displays a similar relationship to that proposed by Dyer (1989), with an increase in settling velocity at low shear stresses. This relationship is due to flocculation enhanced by shear, and with floc disruption at higher stresses for the same concentration. The transition occurs at a turbulent shear stress of about 0.36 N m^{-2}. This shear threshold corresponds very closely to the value observed during a series of laboratory annular flume experiments (Manning and Dyer, 1999).

The settling velocity $Ws_{microEM}$ was found to be very closely correlated with only the τ parameter. The lack of correlation with SPM concentration arises probably from them being the building blocks from which the larger macroflocs are formed. The range of sizes possible within the microfloc size fraction is much less than that in the macroflocs. As with the macroflocs, the microfloc settling velocity increased with increasing shear stress, until a limiting τ of ~0.42 N m^{-2} was reached. At this point the regression model predicted a peak $Ws_{microEM}$ of ~1 mm s^{-1}; this was significantly slower than that of the comparative macroflocs. The higher limiting shear stress for the microflocs can be attributed to their stronger inter-connective bondings. Conversely, the $SPM_{ratioEM}$ showed a strong interdependency, principally with SPM concentration.

The combination of the three empirical algorithms into a single equation to predict mass settling flux (MSF), estimated the total MSF of the 157 measured floc samples from neap and spring tide conditions, with a cumulative error of less than ±4%. In comparison, the use of single settling velocity values of 0.5 mm s^{-1} and 5 mm s^{-1} were both in error by an average of -86% and +41%, respectively. Representing mean floc settling velocity by other approaches:

(i) A simple SPM concentration power-regression relationship (e.g. Whitehouse et al, 2000);
(ii) The Lick et al (1993); and
(iii) The van Leussen (1994).

All under predicted the total cumulative MSF by ~35-43%. Further analysis indicated that the alternative methods *M3-M10* all incurred high predictive errors (at times under-estimating by over 70%) as turbidity levels rose in close proximity to the bed. The Ws_{meanEM} proved to be the second most reliable method, although the errors in MSF prediction ranged from cumulative under-estimates of 14-25%.

The research demonstrates that the new empirical flocculation model (*M1*) has extreme flexibility in adapting to a wide range of estuarine environmental conditions. Specifically, for applied modelling purposes, by producing reliable mass settling flux predictions in both quiescent waters, and the rare occurrence of very turbulent events experienced during extremely high flow velocity conditions where near-bed shear stresses can potentially reach 1 to 10 N m^{-2}. The *M1*-derived mass flux values were valid for water columns of very low turbidity and highly saturated benthic suspension layers with concentration approaching 8.6 g l^{-1} (Figure 2.17).

Although it is possible to separate the resultant floc characteristics into various interrelated sub-groups, (e.g. macrofloc settling velocity), it would be unwise to consider the independent variables of τ and SPM concentration separately, in any final analysis. The empirical model (*M1*) has shown that it is the simultaneous interaction of turbulent shear stress and sediment concentration which make *in-situ* estuarine floc characteristics intrinsically different from how they would evolve in still water conditions. It is this combined effect which ultimately governs, spatially and temporally, whether a floc population is composed of:

(i) Thousands of high density microflocs; or
(ii) A few hundred fast settling macroflocs, which are of a much lower effective density.

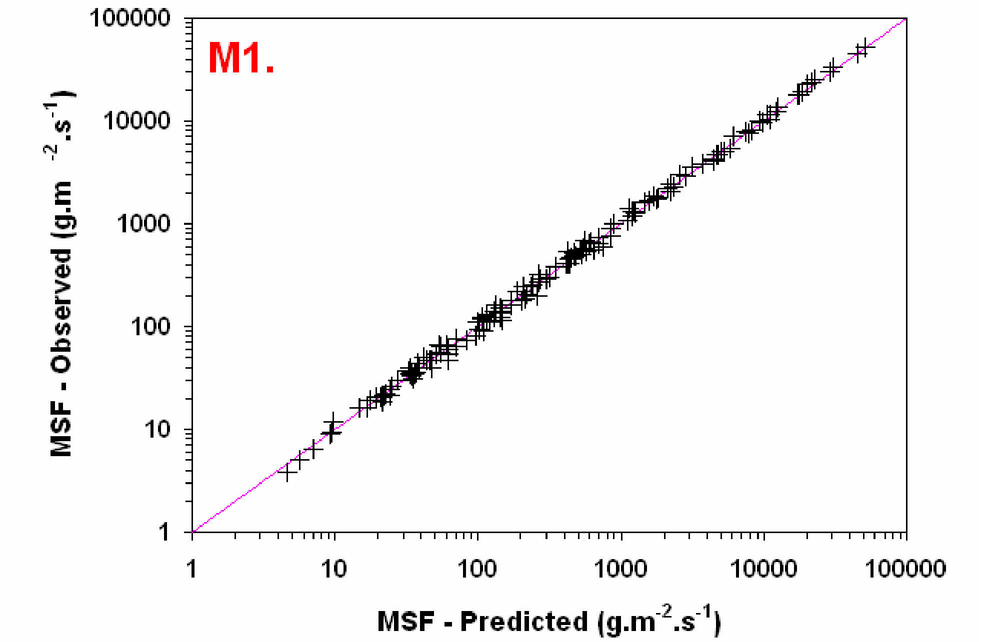


Figure 2.17 The total dataset of individual mass settling flux (MSF) observations plotted against the corresponding predicted values of MSF using the best floc model (M1) developed in the project

The reliability and robustness of the empirical model (*M1* – Reference TR3 – EP18) is a testament to the high quality of the data acquisition techniques used. The multiple regression analysis of a wide-ranging dataset has revealed an accurate insight into the particulate matter distributions within floc sub-groupings, and that such an approach observes the macroflocs and microflocs, which constitute the entire population. It is possible to conclude that studies which do not measure the entire spectral distribution of settling flocs, by low intrusive means, risk incorrect representation of the aggregational dynamics occurring within turbulent water columns. One area which has not been explored is the possible role of clay mineralogy, which may exert some control on floc formation and behaviour between different estuarine systems.

The settling flux algorithm has been tested by HR Wallingford in a 2D/3D mudflat model (Spearman, 2004) and a 3D model of flow and sediment concentration fields in the Thames Estuary (Baugh, 2004). Both applications are summarised in Section 4 of this report.

2.3.8 Estuarine sediment dynamics

An analysis of field surveys (e.g. as described in Section 2.2.3) made over intertidal areas in the central Tamar Estuary have been carried out to quantify the seasonal and tidal variability of some key physical and biological properties of intertidal mudflats and their dependence on hydrodynamics, currents.

The key findings were:

- With respect to velocity data:
  - Transverse distributions of longitudinal current velocity derived from ADCP measurements over a cross-section exhibited large differences in speeds and phases between the main channel and intertidal areas;
  - Even small amounts of channel curvature apparently produced noticeable differences in section morphology, thereby influencing the current field;
  - Model results showed strong similarities with measured data such that main channel currents were faster than those on the mudflats, except around HW - when mudflat currents had started to ebb while main-channel currents were still flooding;
  - Complementary predictions with a computational model also showed that the simulated currents on the upper mudflats, very near to the shorelines, were essentially ebbing throughout their brief periods of submergence, in agreement with the earlier field observations.

- With respect to seasonal variations:
  - The seasonal variations in 'physical' mudflat properties were relatively small in the central Tamar;
  - The biological variations were large and EPS (extra-cellular polymeric substances) in the surface 2 mm of the sediment had a dominating influence on the critical erosion threshold (CET) of mudflat sediment;
  - During biological 'bloom' conditions the stress exerted by water flows was too small to cause suspension of bed sediments, in the absence of waves, and the intertidal areas were seen to be depositional.

2.4 Assessment of impact of biological process parameters

2.4.1 Review of relevant processes and parameters that affect the stability, erodibility and deposition of sediments

Recent research has indicated that biota play an important role in estuarine ecosystem functioning; in particular, they act as as 'ecosystem engineers' with an impact on near-bed hydrodynamics and sediment dynamics. Work undertaken in EstProc has outlined the current state-of-the-art, together with the challenges to be faced in the future. A number of key points have been raised:

- Presently, there is no single measurement that can act as a proxy for sediment stabilisation. Biomass-related proxies fail to account for the variability in ecosystem function inherent in biological assemblages;

- Ecosystem processes (bioturbation, biostabilisation, biodeposition) have a central role in the erosion-deposition-transport-consolidation EDTC cycle; within this context, there has been excellent progress within EstProc in modelling individual processes. More information on the rates and variability of the process and their combined influence is required, e.g. during day/night and seasonal cycles. This work has also been progressed within EstProc, as is described above.

Given the present state-of-the-art, the most appropriate approach is to provide bibliographic information, to determine the range of effects of process in varying systems. This work has been expanded under EstProc and will assist in the production of the next generation of bio-sedimentary models. This has already borne fruit in the development of a conceptual model covering different sediment systems with varying biogenic characteristic (Figure 2.18). Parallel work is described in Section 3.2 of this report and some of this is summarised below.

The work has investigated the use of multivariate statistics to reduce information to a minimum parameter set. Publications reviewed in EstProc have been used to demonstrate the site-specific nature of even a multivariate approach. A published model was tested and found to be wanting in generic terms, under-predicting erosion threshold in untested systems. However, multivariate analysis is still believed to be the best approach, since the review data has confirmed that one proxy parameter will never be sufficient. The way forward is to apply a similar framework of multivariate analysis across a number of systems; this is to establish if a classification of intertidal and estuarine ecosystems is possible in term of their biosedimentary behaviour. If sufficient parameters are not available, a minimum set of measurements will be recommended on which to base a simple multivariate model. As part of this work a database to accept transect-based biosedimentary data has been completed and this outline database is available to be populated.

The sediment stability of fine-grained ‘beneficial use’ schemes and, in particular, the role of recolonising macrofaunal communities have been examined. Sediment erosion, which varies spatially and temporally, is dependent upon the interactions between sediment properties and physical and biological processes. In particular, this relates to the balance between the two functionally-opposing groups of biota, stabilisers and destabilisers. From a review of the macrofaunal successional changes, following sediment placement on intertidal areas for habitat creation, it was concluded that a gradual return of those species common in surrounding, non-impacted areas occurs; this is as opposed to the opportunistic responses of less common species. Consequently, biological modification of sediment stability at beneficial use schemes may be predicted, generally, from an assessment of the functional groups of reference communities. However, more studies are required to improve the predictive ability of the rate of return of the macrofaunal assemblages to ambient conditions.

Sediment stability measurements were made using a Cohesive Strength Meter (CSM – Black and Paterson, 1997) at a sandy intertidal flat station in southern England (Friend et al, 2003) six consecutive day-night emersion periods during a period of relatively high microalgal biomass (mean: 4.4 μg gDW^{-1} where DW is dry weight) in the spring. The fine sand had a mean grain size of 150 μm. Coefficients of biostabilisation for night-time emersion periods averaged at 16.7, and were significantly higher (as determined by a statistical paired t-test: $p = 0.011$) than day-time coefficients which averaged 10.5. This implies a higher stability of the sediments at night time. The detailed reason for this difference requires further research measurements and analysis.

Research in EstProc has extended coverage of both the range of biota and the nature of the biological processes affecting sediment erodibility (see Section 3.2). This has provided improved quantification and modelling of the impact of biota on hydro- and sediment dynamics, demonstrating that it varies spatially along axial and lateral / vertical gradients, as well as temporally at the seasonal and inter-annual scales.

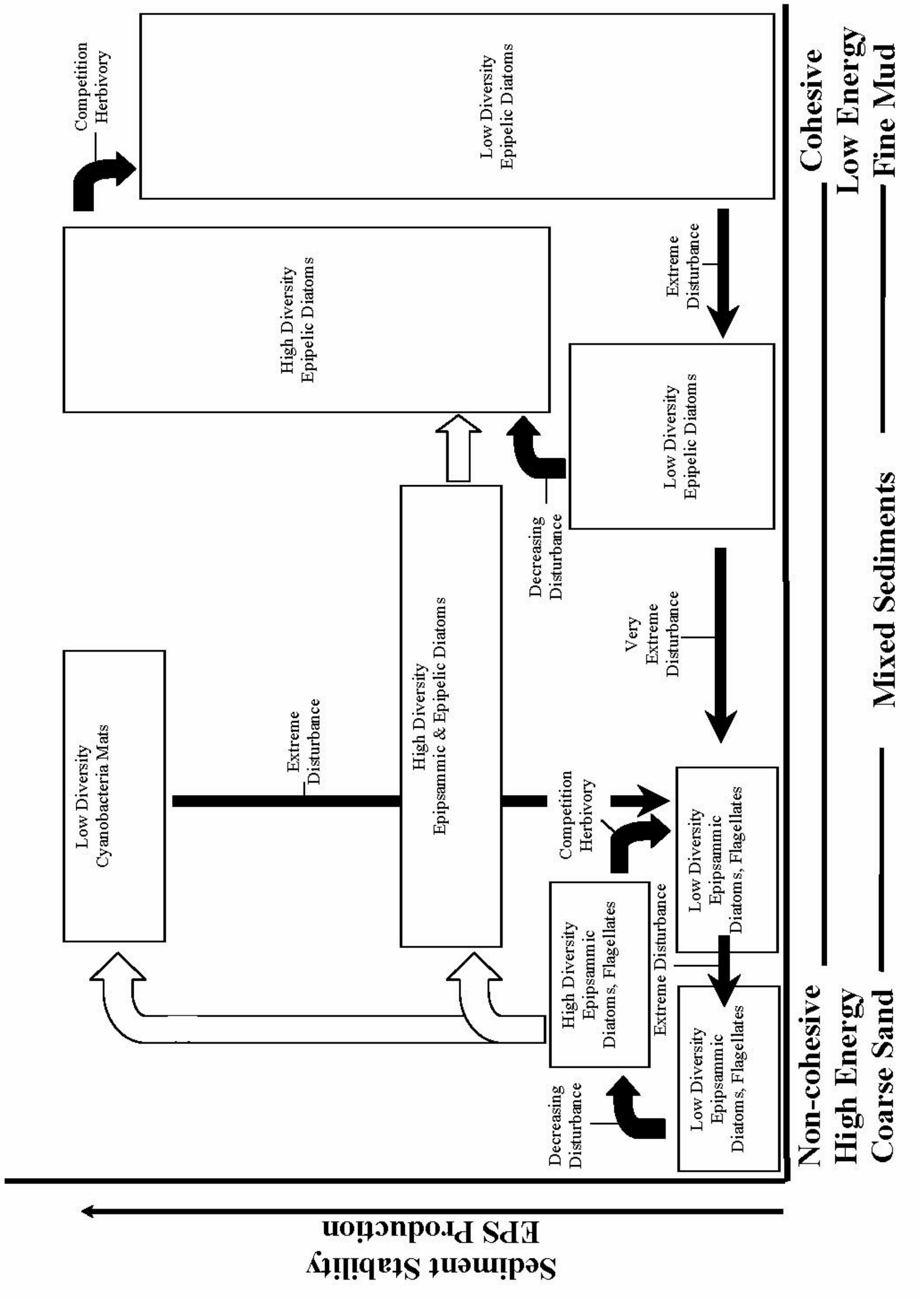


Figure 2.18 Conceptual approach to the interplay between sediment grain size and biogenic affect through sediment diatom stabilisation

The macroalga, *Enteromorpha* sp., which forms extensive algal mats on the mid-shore (Figure 2.19) of many estuaries, is often regarded as a 'nuisance' alga with deleterious ecological consequences. *Enteromorpha* density varies seasonally, growing rapidly during the spring and summer; it then dies back during the winter. The growth and persistence of macroalgae in estuaries may be due, in part, to the positive feedback that it induces. *Enteromorpha* has been shown to lower the near-bed flow, thus reducing sediment resuspension and turbidity, which in turn increases light penetration, which will enhance its growth potential. Experimental flume studies have shown that the near-bed flow is reduced by 18% to 56%, and sediment erodibility is reduced by 2 to 10-fold, with increasing *Enteromorpha* density from 10 to 60% (% cover when air exposed). The presence of *Enteromorpha* also enhanced significantly sedimentation rates of fine mud by ~50%, at 60% surface cover.

Saltmarsh plants form an important part of the natural coastal defence. Two species have been investigated, namely *Salicornia* an annual 'pioneer', and *Spartina* a perennial species. Studies have shown that both species have a significant impact on near-bed flows and sediment erodibility but that their influence is complex and non-linear. *Salicornia* grows from spring to late summer reaching a height of 20cm; it then dies back in winter, when it provides little protection to the winter storm waves. In contrast, *Spartina* persists and protects throughout the year. Flume studies examining the influence of stem and height on near-bed flows and sediment erodibility have demonstrated a 3 to 4-fold reduction in near bed flows with a marked increase in flows at densities <1200 stems m^{-2} for *Salicornia* and <400 stem m^{-2} for *Spartina*. For *Salicornia* the increase in flow at this density is accompanied by a 4-fold increase in turbulence / bed shear stress and >5-fold increase in sediment erodibility, compared to that at higher stem densities (2400 to 4000 stems m^{-2}) or bare sediment. There is no evidence of increased sedimentation rates in the presence of *Salicornia* or *Spartina* stems, this may be due also to the increased turbulence, which hinders the settling velocity. However, direct interception of sediments by the foliage is possible, increasing the retention of fine sediment in the marsh.

Small shrimps called mysid*s* are one of the few species that are able to exist in the upper estuary, at low salinities of 0 to 1ppt. They occur in high-density swarms (36,000 to 100,000 m^{-3}), which feed on the surface sediments. This active bio-resuspension of sediment has been shown to be dependent on mysid density; this may constitute an ecologically-significant process, that contributes to the maintenance of the estuarine turbidity maximum.

Algorithms describing the impact of increasing densities of key biota (e.g. benthic diatoms, *Macoma balthica, Cerastoderma edule, Spartina, Salicornia, Enteromorpha, Neomysis integer*), on near-bed flows and sediment mass eroded over a range of current velocities (0.5 to 0.45 m s^{-1}) have been derived from experimental flume studies. These are presented in Reference TR3 – EP28.

There has been further development of the BIOSED model, of biologically-mediated sediment transport across a shore-normal intertidal transect. The model is described in more detail by EMPHASYS Consortium (2000b) and Wood and Widdows (2002). Initial model runs focused on the impact of biostabilisers (benthic diatoms) and bio-destabilisers (*Macoma balthica)* on sediment erosion, transport and deposition on the Skeffling mudflat, on the north shore of the outer Humber estuary. More recently, the influence of changes in wave height, saltmarsh (*Spartina*) stem height and different offshore sediment supplies, as well as tidal currents have been incorporated into the model. The model output demonstrated the impact of these factors on intertidal sediment erosion, transport and deposition and showed the effects of *Spartina* height on wave attenuation and sediment deposition on the upper shore. Modelling the influence of *Enteromorpha* abundance on sediment erosion has been initiated. An intertidal transect model with feedback between morphological changes and flow with forcing by tides has been developed. There is good agreement with a more complex morphological model published in 2000 (Roberts et al., 2000).

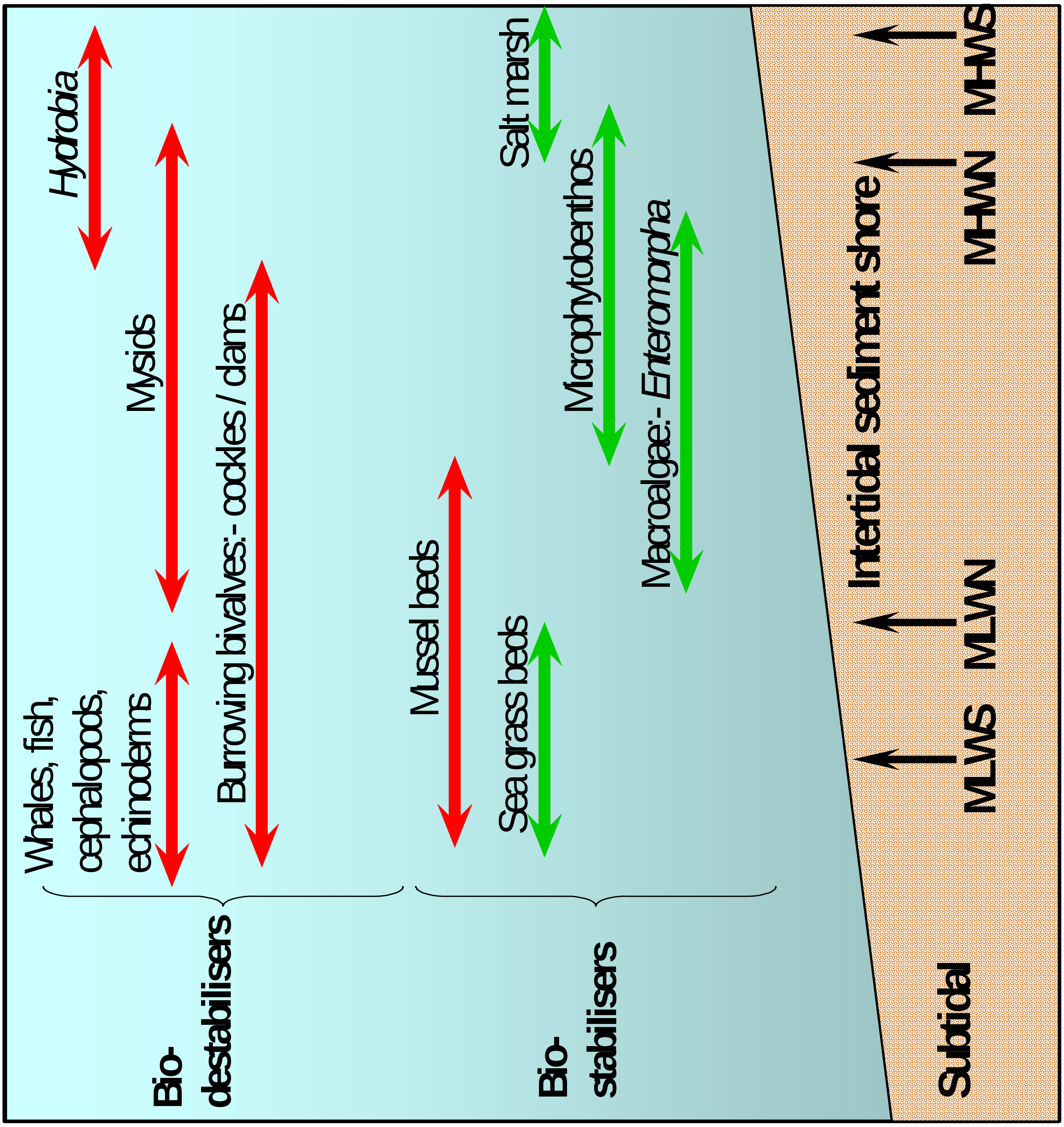


Figure 2.19 Examples of biota acting as ecosystem engineers in the intertidal. Key biota are divided into two functional groups, the bio-stabilisers and bio-

destabilisers, with varying spatial distribution along estuarine gradients (both axial and vertical)
In the project modelling of flow, waves and sediment transport on an intertidal profile using a 2D and 3D numerical model has been completed (Spearman, 2004)). This investigation studied the influence of the new process algorithms for bed shear stress, erosion behaviour, settling flux behaviour, and selected biological parameters on the predicted results.

2.4.2 Effects of physical conditions on biology

The spatial patterns of estuarine macrobenthic assemblages and their relationships with hydrodynamic regime have been reviewed by Bolam (2003). Present predictions of large-scale macrobenthic distributions rely mostly on inferences drawn from correlations between easily measured static parameters. Primarily predictions are based on correlations between particle size distributions and the patterns of faunal abundance, rather than direct tests of the factors causing those patterns. The occurrence of a species in a particular habitat results from the complex interaction between particle size, organic and microbial content, hydrodynamic and chemical conditions, and biological interactions in the food-chain and predator-prey interactions. This is because these are the factors that make a habitat suitable for a particular species. The conditions are variable, spatially and temporally, and therefore it is not surprising that correlations between fauna and static parameters have been weak. Thus to improve the understanding it is necessary to answer the primary question which is what parameters, or combinations of parameters, need to be estimated to adequately predict faunal abundance patterns on the basis of physical factors. This will require tests of the causal relationships between biota and field conditions, together with more detailed investigations of dynamic models including faunal structure. Whilst progress could be made following a detailed examination of existing survey information, confidence in the conclusions would be hampered by the lack of standardisation within and between the various surveys, for example, relating to differences in the spatial and temporal scale and sampling device and design.

Therefore a more consistent approach is required across a number of contrasting estuaries in order to capture the complexity and variability. Also it is recommended that faunal communities should simultaneously be related to both static and non-static sediment variables because inherent weaknesses have been identified in the correlations based just on static variables.

To aid the prediction of invertebrate species distribution using physical parameters, derived from model and field data, a ‘rule-based’ approach has been devised (ABPmer, 2004c). This approach has been applied in the Humber Estuary, possibly providing a generic framework for application within other UK estuaries. The approach is founded on a rule-base but relies also on computational hydrodynamic model predictions of environmental conditions. The approach outlined can be used to simulate habitat change as a consequence of managed realignment within estuaries or, more generally, as part of an environmental impact assessment of proposed developments. The application of this approach within other estuaries can be based on the algorithm provided in Reference TR3 – EP27. The discussion on this topic in Section 3.2.16 is also relevant.

3. SCIENTIFIC ACHIEVEMENTS

There are two papers presented in this section. The first (Section 3.1) is the assessment of the way in which modellers requiring algorithms or observational data for their modelling activities and the experimenters collecting and presenting analysed and interpreted data can optimise their interaction. Largely it is based on an earlier version presented by the EstProc Consortium (2002). The second (Section 3.2) is a detailed description of the improved understanding of linkages between hydrodynamics, sediments and biology gained during EstProc and linkages across to process modelling expanding the summary presented in Section 2.4.2.

3.1 Modeller-process scientist interaction

Historically the contribution to science of process scientists and computational numerical modellers has occurred in discretely different ways. The process scientist has sought to create order from the measurement of the variation of natural properties and organisms and the deduction of trends and inter-relationships from the observed data. However, in contrast to process scientists, the modeller has sought to simplify and often to ignore such variation in order to achieve his or her goal. Modellers will generally add complexity to their model only if there is a demonstrable benefit to the improved accuracy of the corresponding model results.

To allow the maximum utilisation of the output of process scientists, particularly in those research areas where progress can be slow and its relevance to the non-specialist remains obscure, it is necessary to ensure collaboration between process scientists and modellers. The resulting interaction aids the drive towards research being genuinely applicable and in modelling which represents more of the relevant natural processes and is not divorced from considerations of the uncertainty resulting from the natural world. This approach has been taken in EstProc.

In the Estuary Process Research Project (EstProc) one of the identified objectives was facilitating the interaction between field/lab researchers and modellers to better enable the overall objective of providing improved but relevant science for the end-user of the interpreted results. The scope for interaction leading to increased understanding and collaboration is large, as small-scale processes in biology and sediment behaviour can significantly influence the larger scale patterns of sediment transport, tidal currents and waves as well as each other. Whilst this interaction is important within all of the identified research topics, it is felt that interaction between biologists and estuarine modellers is particularly important as hitherto such communication and understanding has been at a relatively low level (*David Paterson, pers. comm., 2002*). It is clear that dialogue between process scientists and modelling scientists is necessary to allow the tailoring of research output for modelling purposes and to enhance the confidence of modellers in using currently available research data. One notable achievement in EstProc was recorded by the exchange at a project workshop between a sediment transport expert and a marine biology expert who, having just heard each other give a presentation of results presented in this report, noted they could understand the technical aspects of each others work. This indicated the achievement of a common language brought about by a well-focussed and common scientific goal.

The interaction between estuary modellers and process scientists was a key aspect of EstProc. This was facilitated with whole project team workshops and a workshop in May 2003 on cohesive sediment processes. The latter contained input from "experimenters" including process researchers making use of existing data, and "modellers" including those using the whole suite of single and multi-dimensional 1DV, 1DH, 2DV, 2DH and 3D process and morphology models. The headline topics covered included:

1. Recognising the importance of helping the experimenters appreciate the problems that modellers perceive in introducing new processes into their models, and identify which models the experimenters might aim their results at;
2. Encouraging modellers to add new processes into their models, and identify the most appropriate providers of such processes;
3. Determining in what format new algorithms would be most easily incorporated into models, especially to enable EstProc to deliver useable outputs.

The following broad assessment of the interactions can be made.

3.1.1 Assessing the input requirements for computational models

When considering the addition of complexity, whether through "improved" data sets or algorithms based on "improved" data sets, to an estuarine system model it is informative to consider the sorts of questions that should be asked by a numerical modeller:

- Is the data/algorithm believable?
- Is the data/algorithm representative?
- Is the data contemporary?
- Is the data/algorithm site-specific?
- Is the effect of including the data/algorithm significantly beneficial when compared to the uncertainty already in the model?

The first four of these questions are sound science based issues but the last question is fundamental when trying to move from a "process-based understanding" to inclusion of a specific mechanism in estuary models. This consideration is illustrated below using examples of specific issues relating to estuary modelling.

In estuary mud models the muddy sediment is often defined by as few as four input parameters:

- threshold shear stress for erosion,
- coefficient for erosion rate in the erosion formula,
- threshold shear stress for deposition[3], and
- settling velocity to characterise the suspended sediment.

More sophisticated models may introduce extra parameters to describe the consolidation process and thereby allow temporally variable thresholds for erosion and deposition, flocculation which allows temporally variable settling velocity, and fluid mud behaviour. The range of realistic values for these parameters produces changes in sedimentation/erosion that can vary by up to 2 orders of magnitude. In order to produce

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[3] Note: the threshold shear stress for deposition has been researched and new findings put forward (Winterwerp 2004, Appendix C4).

reliable model predictions the values of the sediment parameters thresholds are calibrated so that measured changes to bathymetry or dredging volumes are reproduced as well as observed suspended sediment distributions. The effect of biology and chemistry and other complex processes on sediment are therefore included empirically and indirectly at this stage through modification of the four parameters listed above. Introducing specific biological algorithms into the modelling may potentially increase the range of applicability and accuracy of the modelling. However, use of more algorithms introduces more parameters into the modelling and may add to, rather than reduce, the uncertainty into the results. Furthermore even if the effect of introducing more complex algorithms is considered beneficial, the corresponding increased model complexity and model run times may outweigh the benefit. These competing issues need to be evaluated for each application; and are referred to in the application to the Thames estuary in Section 4.3 (Baugh, 2004).

3.1.2 Balancing the use of process measurements: detailed representation of processes versus estuary wide behaviour

In some applications one or more of the basic parameters listed in Section 3.1.1 may be measured in the field, thereby allowing the modeller to use known values. In some cases the use of measured values of sediment parameters can lead to untenable behaviour in a model such that the estuary is eroding or accreting rapidly in its present form. This is because measurements of sediment parameters are usually locally applicable and hence compromised from lack of coverage and from wide variations in the values of the measured parameter resulting from the difficulties of *in situ* measurement. An example of these problems was encountered when HR Wallingford measured erosion threshold at a number of points in Tollesbury Creek, in this case using SedErode one of the available *in situ* devices (Mitchener et al, 1996; Black and Paterson, 1997). Of order ten measured values of threshold for erosion were obtained and the range of values varied between approximately 0 Nm^{-2} (very easily re-suspended) and 1 Nm^{-2} (harder to erode). In this specific case the modellers were unsure how to apply this knowledge because (a) they did not know how to distribute values at the few points around the entire modelled area, and (b) it was considered they would have resulted in an unrealistic pattern of erosion and accretion. What it did provide though was a range of erosion threshold values for application in sensitivity tests. However the results discussed above may not be representative of all field data collected on erosion. The characteristics and performance of different devices has been discussed by Black and Paterson (1997) and data collected using an *in situ* annular flume (e.g. Widdows et al, 1998) may provide less scatter than point measurements. It will be important to tailor the needs of the modelling to the method and scale of data collection and interpretation.

Where the use of empirical predictive sediment erosion formulae are **not** based on *in situ* measurements problems may arise because of the problem of the validity of laboratory measurements which often arises with cohesive sediment transport. Many of the basic equations used by modellers were derived in the laboratory. However, artificial beds do not necessarily behave in the same way as real seabeds due to the different conditions under which they were created. Correlations between geotechnical/physical sediment properties and erosion behaviour as proposed in EstProc may provide a workable way forward. The use of *in situ* annular flume data may provide a way forward with determining representative sediment erosion formulae for specific sites.

Often detailed features of estuary systems cannot be incorporated into models because the feature is not quantified by enough reliable measurements. This could for instance be said to apply to flocculation processes. It is known that the settling rate of flocculated mud increases with concentration, up to the point where hindered settling occurs, and also that small amounts of turbulence increase flocculation while larger amounts reduce flocculation and hence settling rate. However, the number of studies of flocculation using instruments that have reliably measured in situ settling velocity are very few and even for these the data available is limited in scope, usually being limited to one or two locations and/or heights in the water column. Until now the uncertainty in the algorithms that result from these sophisticated field studies has been relatively large and the parameters within these algorithms are usually calibrated to the available suspended sediment data or settling velocity data. Usually it is the case that the available calibration data is not good enough to merit complex flocculation models and a single value of settling velocity has been used to simplify the calibration process. The effect of biology on flocculation processes may turn out to be an extremely difficult task. Furthermore the benefit from including biology may be masked by the uncertainty already present in flocculation models and the large amount of data required for an individual model study to overcome this. It was also noted that floc settling measurements made in the River Tamar at the estuarine turbidity maximum may have been influenced by biological parameters including mysid induced suspension and the presence of faecal pellets within the mud flocs. Whilst not yet specifically considering these aspects the new algorithms for floc settling parameters developed in EstProc have taken the predictive capability and potential for application to a higher level of generality (EstProc Consortium, 2004a; Manning, 2004).

The numerical modeller’s inclination to simplification is not confined to sediments and biology. The subtle complexities involved in, for instance wave modelling, are often, through necessity or design, not included. For instance in algorithms that include the effect of waves on current shear-stresses or on sediment erosion, the waves are usually represented only by a single height and period. Hence even if spectral propagation is included to obtain the spatial/temporal distribution of wave heights and periods, they must still be boiled down to a "representative sinusoidal wave" at each grid point. Where additional model complexity is required, such as when incorporating the non-linear effect of combined wave-shear stress from oblique waves and currents, the additional accuracy derived from algorithms is not always obvious in the context of sparse and uncertain information about sediment and the numerical problems of adequate resolution of the wave profile over intertidal flats. Consequently such non-linear interaction seldom appears in estuary wide models although the new approach presented in EstProc provides an easy to implement method for including wave-current bed shear stresses on smooth and rough sediment beds (EstProc Consortium, 2004a; Soulsby and Clarke, 2004). Similarly we have known for a long time that on sandy beds the roughness is dominated by ripples, and that the ripples change their height, wavelength, and orientation to the current, and are modified by waves (ABPmer, 2004b) - but models do not usually take any of this into account. Whether they would improve or reduce the quality of results is not presently known for whole estuary models.

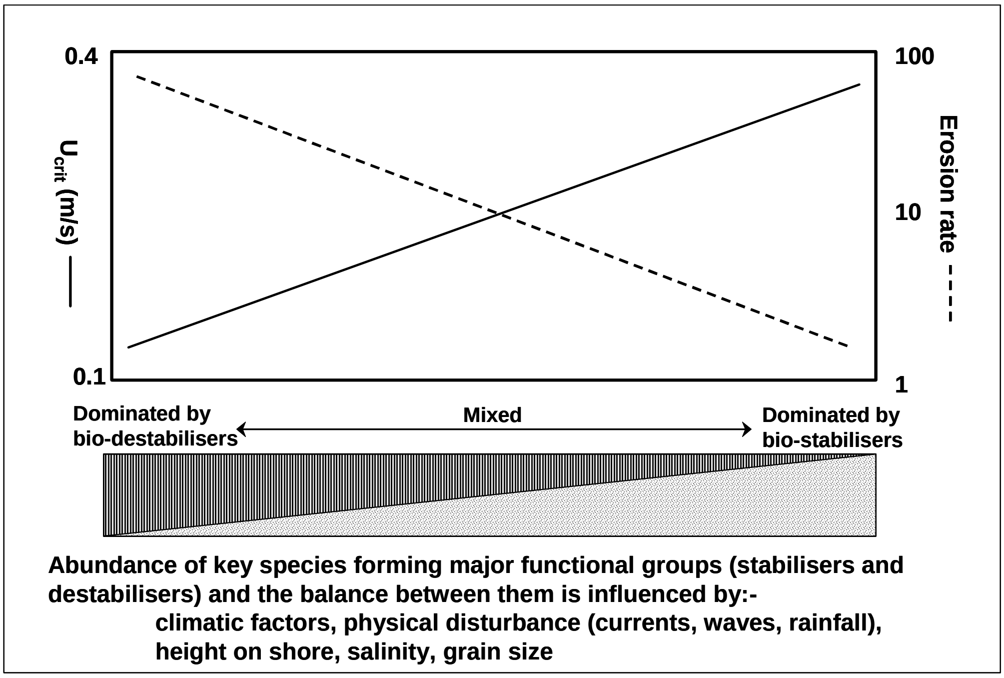
It is often assumed that the increasing speed of computer technology allows the numerical modeller to increase the number of small-scale interactions included within a model, without compromising the requirement for feasible run-times. This is also accompanied by a requirement to include more of the natural variation in forcing conditions – waves, tides, freshwater flow – in the assessment of overall change within estuaries so that the *number* of model simulations required per study is also increasing steadily for the modeller. Thus for an assessment of estuarine impact a modeller has to balance the benefit from increasing the representation of the key small-scale processes for a given number of different natural conditions, with including a more limited representation of the key small-scale processes whilst being able to represent more of the annual range of conditions with more simulations.

These issues have been tackled throughout the EstProc project. Some aspects of the small scale biological interactions are presented in the next section of the report and further information is given in EstProc Consortium (2004a).

3.2 Improved understanding of biology interactions

During the EstProc project the team has made major advances in our quantitative understanding of the impact of biota in estuarine hydrodynamics and sediment dynamics. The impact of biota on the erosion, transport and deposition of sediments (both cohesive and non-cohesive) is manifest through a range of different processes, which can either be 'stabilising' or 'destabilising'. It is now possible to identify key species within the benthic community that act as ecosystem engineers. These are organisms that create habitats and modify their environment via physical structures that they create (e.g. coral reefs, saltmarsh, seagrass beds, mussel beds) or by the transformation of living and non-living materials from one state to another (e.g. feeding pits, burrows, bioturbation, mucilage production).

Advances within EstProc enable biological processes to be placed in the wider physical context and incorporated into computational numerical models. Field studies have demonstrated that the influence of biology on sediment dynamics is complex, due to the inherent diversity of the biological assemblages, and that there is no single measure of biomass that can serve as a proxy for sediment stabilisation. However, as knowledge of the functional role of key species and biological assemblages has improved it is becoming possible to assess and forecast the overall impact of the benthic community on sediment stability. The balance between stabilisers and destabilisers changes both spatially with, for example e.g. height on the shore, distance along salinity gradient, and temporally with seasonal and inter-annual variations. This will induce a range of conditions from high sediment stability when dominated by bio-stabilisers, to low sediment stability when dominated by bioturbators, with intermediate states between depending on the relative composition of stabilisers and destabilisers (Figure 3.1). The scales are indicative.



Abundance of key species forming major functional groups (stabilisers and destabilisers) and the balance between them is influenced by:-
climatic factors, physical disturbance (currents, waves, rainfall), height on shore, salinity, grain size

Figure 3.1 Bio-complexity: Diagram illustrating changes in sediment erodibility with spatial and temporal shift in the balance between key species acting as bio-stabilisers and bio-destabilisers

The biological mechanisms of enhancing sediment stability and net accretion include:

- Sediment armouring, biofiltration / biodeposition (e.g. mussel beds);
- Enhanced cohesion via excretion of extracellular polymeric substances EPS (e.g. microphytobenthos);
- Filamentous binding (e.g. *Cladophora*);
- Reduction in near-bed flows, induction of skimming flow above vegetation, and wave attenuation (e.g. saltmarsh, seagrass beds, macroalgal mats such as produced by *Enteromorpha* spp.).

Processes responsible for the destabilisation and net erosion of sediments include:

- bioturbation by surface deposit feeders (e.g. clams);
- increased near-bed turbulence due to increased bed roughness (e.g. by burrowing bivalves such as cockles);
- grazing on bio-stabilisers (e.g. by *Hydrobia* on microphytobenthos);
- faecal pelletisation of sediment (e.g. by *Hydrobia*);
- enhanced buoyancy of biofilms (e.g. by oxygen bubbles);
- active bio-resuspension (e.g. mysid shrimps);
- corrasion by saltating shells.

Some biota act directly to influence sediment stability (mussel beds, saltmarsh, seagrass beds), while others act indirectly through their feeding impact on ‘bio-stabilisers’ (grazers such as molluscs, polychaetes, crustaceans and fish) and on ‘bio-destabilisers’ (predators such as birds and fish).

Research carried out within EstProc has been vital in extending a growing database of established relationships between species abundance and sediment erodibility. This is important information, not only for the interpretation field erosion measurements, but also for the forecasting aspects of ecosystem function (e.g. sediment stability) based on knowledge of the benthic community structure.

3.2.1 Field studies and multivariate approach

The interactions between the processes that control sediment stabilisation have been, for the most part, poorly quantified and understood making it difficult for predictive models of sediment stability to be sufficiently accurate. In past studies, chlorophyll *a* was found to be an important variable correlating with sediment stability. However, the relationships produced were often weak, suggesting that significant interactions may be missing.

Field studies were carried out in the UK and the Netherlands on a variety of mudflat systems. The dataset presented here arises from the results of a number of field campaigns carried out during the BIOPTIS (EU MAS3-CT97-0158) and CLIMEROD (EU MAS3-CT98-0166) projects. Each measurement of erosion threshold (based on the Cohesive Strength Meter, CSM) was matched with a measurement of microphytobenthic biomass (measured as concentration of chlorophyll *a* and by the technique of minimum fluorescence), macrofaunal density, sediment grain size, water content and organic content. Stepwise multiple linear regressions were applied to the sediment stability data to establish the influences of chlorophyll *a*, minimum fluorescence, water content, % gravel, % coarse sand, % medium sand, % fine sand, % silt-clay, organic content and the abundance of dominant macrofaunal species on erosion threshold. In the analysis of the entire dataset, a total of 321 measurements were considered. Significant differences in mean values between stable and unstable sediments, and between sites in the presence and absence of *Enteromorpha* spp., were tested statistically with the t-test and one-way ANOVA analysis of variance.

Multiple stepwise linear regressions were applied to the complete dataset. Seven variables were found to be significant predictors of erosion threshold at the 1% level:

- percentage fine sand^{a};
- percentage gravel^{b};
- *Nereis diversicolor*^{c};
- *Macoma balthica*^{d};
- minimum fluorescence^{e};
- water content^{f}; and,
- *Cerastoderma edule*^{g}.

Correlation: $r = 0.44$; $P < 0.001$; S.E. = 1.51 Nm^{-2}; $y = 0.013^{a} + 0.072^{b} + 0.027^{c} + 0.009^{d} + 0.001^{e} - 0.013^{f} - 0.022^{g} + 1.48$. P is the statistical significance, S.E. the Standard Error, y is the predicted value of erosion threshold, the numbers with superscripts are the regression coefficients representing the amount (and direction depending on whether it is positive or negative) the dependent variable changes when that variable changes by one unit. The last term in the equation is the constant value when the other variables are zero. This applies to recently deposited estuarine sediments.

However, these seven variables described less than half the total variation in the data, highlighting that certain site-specific features may be having an influential role and need to be investigated more closely. Data from all sites were pooled, and stable (erosion threshold determined using Cohesive Strength Meter >2 Nm^{-2}) and unstable sediments (erosion threshold determined using Cohesive Strength Meter <2 Nm^{-2}) were compared. The mean chlorophyll *a* concentrations and granulometry of the sediments were significantly different between the two groups.

Matched measurements taken on areas dominated by diatoms provided an excellent example of the complex, and in this case synergistic, interactions between physical and biological processes. Initially upon exposure, biological processes dominantly influenced the sediment stability, with stability increasing with increasing surface diatom biomass. Paterson (1989) previously described this phenomenon in the laboratory, although a greater time lag between diatoms appearing at the sediment surface and increased sediment stability was found in the laboratory. After diatoms migrated away from the sediment surface, and for the remainder of the tidal emersion period (i.e. sediment exposed to the atmosphere at low tide), sediment stability remained high. This was probably due to the additive effects of the sediment becoming more consolidated and compacted as the water content of the surface sediment decreased, and due to the residual EPS pool on the sediment surface.

The presence of a biofilm can have implications for studies that employ a unified erosion formula which predict increasing sediment density with depth related to increased sediment stability (i.e. Sanford and Maa, 2001). These studies fail to recognise the importance of the spatial scale of biological effects. For example, biofilms result in an inversion in the stability/density relationship, with highly stable low-density sediments at the surface and denser less stable sediments below the surface. Even over a tidal cycle, diatom migration can significantly alter the density-depth stability relationship of the surface few millimetres (e.g. see Hay et al, 1993). Surface diatom biomass was found to be a significant predictor of erosion threshold for some sites, although this can be a weak relationship. If a site has a highly migratory biofilm then variations found along a transect or grid could be the result of migratory behaviour linked to the time of day and/or tidal cycle.

The nature of the sediment, microphytobenthic biomass and the sediment water content have traditionally been considered the primary controls of stability on cohesive sediments, and were all found to be significant predictors in the model that incorporated all of the data. The fact that a significant predictive relationship, able to be used on all study sites, was not possible is likely to be due to the complex interaction of factors, particularly local features such as migratory biofilms and *Enteromorpha* blooms, together with temporal and spatial variation.

It has become obvious that of the factors that control sediment stability, there is large scatter in the data. In order to produce effective models, a range of parameter values of some of the variables responsible for controlling sediment stability should be available to the modelling community. Table 3.1 provides a preliminary attempt at this, comparing stable and unstable sediments. Whilst the mean values of sediment granulometry and chlorophyll *a* concentration were significantly different between the two groups, the large range of values presented in the data, will increase the difficulty of producing a definitive model.

Table 3.1 Descriptive statistics of water content, algal biomass, granulometry and organic carbon of stable and unstable sediments. Mean values compared using the t-test; n.s. defined as not significant

		Mean	Median	Std. Deviation	Std. Error	Minimum	Maximum
Water content (%)	*Unstable*	46.7	39.1	22.6	1.8	21.9	95.0
	Stable	43.6 n.s.	32.1	22.9	1.8	11.5	94.7
Minimum Fluorescence (Fo^{15})	*Unstable*	210	114	276	22	3	1768
	Stable	274 n.s.	121	388	31	7	2166
Chlorophyll *a* ($mg\ m^{-2}$)	*Unstable*	135.3	81.5	189.5	14.8	14.0	1524.9
	Stable	214.5 $P \leq 0.002$	124.6	268.7	21.4	18.5	2091.4
% Gravel (>2 mm)	*Unstable*	1.2	0.2	2.4	0.2	0.0	20.3
	Stable	3.0 $P \leq 0.001$	0.5	6.5	0.5	0.0	31.5
% Coarse sand (1-2 mm)	*Unstable*	0.4	0.2	0.8	0.06	0.0	4.7
	Stable	1.0 $P < 0.001$	0.3	1.6	0.1	0.0	8.6
% Medium sand (250-1000 μm)	*Unstable*	29.7	7.0	37.6	3.0	0.05	97.5
	Stable	17.3 $P < 0.001$	7.2	27.0	2.2	0.8	99.0
% Fine sand (63-250 μm)	*Unstable*	50.7	68.0	33.2	2.6	0.16	97.9
	Stable	67.0 $P < 0.001$	76.2	25.6	2.0	0.6	98.3
% Silt-clay (<63 μm)	*Unstable*	16.2	12.3	16.6	1.3	0.1	72.5
	Stable	11.7 $P \leq 0.003$	9.5	9.1	0.7	0.1	41.1
Organic carbon (%)	*Unstable*	7.1	3.3	9.7	0.8	0.4	53.6
	Stable	7.8 n.s.	3.2	11.1	0.9	0.9	65.7

The results presented here reinforce those of Mitchener et al (1996) who highlighted the major gaps in our understanding of the stability and thus sediment transport of mixed cohesive and non-cohesive sediments. Seasonal deposition cycles on intertidal flats may be a significant factor in the mud balance of an estuary (e.g. Frostick and McCave, 1979; O'Brien et al, 2000). Future models will need to incorporate a seasonality factor.

3.2.2 Testing a published model for bio-mediated erosion

Archived chlorophyll *a* data was subsequently used to test the published model of Riethmüller et al (1998). This model describes a relationship between chlorophyll *a* concentrations and the erosion thresholds of muddy-sand sites (fine-grain fraction 25% to 50%) measured with the EROMES device:

Erosion threshold [Nm^{-2}] = 0.0084*(chlorophyll *a* [$mg\ m^{-2}$]) + 0.34

Erosion thresholds predicted by this model were calculated and then compared to actual erosion thresholds measured with the CSM, to determine how robust this model was for large spatial scales and a greater range of chlorophyll *a* concentrations.

3.2.3 A multivariate approach

At the 1% level, only chlorophyll *a* was found to be a significant predictor of erosion threshold ($r=0.64$; $P<0.001$; S.E.=1.34 Nm^{-2}; $y=0.019x + 0.536$). Water content, fine-grain fraction, organic content and the abundance of *Nereis diversicolor*, *Corophium volutator* and *Hydrobia ulvae* were all found to be insignificant at the 1% level.

Chlorophyll *a* concentrations for muddy-sand sites were used to calculate erosion thresholds from the predictive function of Riethmüller et al (1998). Actual erosion thresholds ranged between 0.58 Nm^{-2} and >5 Nm^{-2}, whilst predicted values ranged between 0.75 Nm^{-2} and 1.61 Nm^{-2} (Figure 3.2). Whilst there is agreement with the model proposed by Riethmüller *et al* (1998) at the lower end of the chlorophyll *a* scale, the relationship deteriorates when greater chlorophyll *a* values (>100 mg m^{-2}) were used. However the Riethmüller et al relationship is fitted to data up to about 50 mg m^{-2}.

The present study found that erosion threshold was independent of chlorophyll *a* concentrations below 100 mg m^{-2}, and may explain why Riethmüller et al (1998) found no correlation in sand and sandy-mud sites, since their chlorophyll *a* concentrations did not exceed 60 mg m^{-2}. Chlorophyll *a* concentrations of sand and sandy-mud sites from the Eden estuary ranged from 18.5 mg m^{-2} to 388.7 mg m^{-2}, and had a weak positive correlation with erosion threshold (Figure 3.2).

Paterson et al (1994) found that on an intertidal sandy flat, an increase in critical erosion threshold was only observed for chlorophyll *a* concentrations greater than 500 mg m^{-2} (when a coherent mat was formed). Sandy sediments have larger inter-particle voids that require a higher biomass before an increase in the surface cohesion of particles occurs, and consequent changes in erosion threshold are observed. This indicates that the sediment type mediates the stabilising effects of diatoms, and explains why Riethmüller et al (2000) found the distinct dependencies of erosion threshold with chlorophyll *a* to be highly site specific.

The presence and abundance of macrofaunal species such as *Macoma balthica* have been shown to have a significant effect on sediment erodibility, yet in this study no effect of benthic fauna was found. The lack of influence from these species may be due to the relatively low densities found at most sites during this study.

The difference in sediment erosion thresholds between the present study and the published function of Riethmüller et al (1998) is primarily due to the use of different erosion devices, whereas the weak dependence and large scatter in the relationships presented here suggest that the natural system exhibits non-linear dynamics; that factors have not been included in the regression analysis; or a more advanced model is required. For example, Ruddy et al (1998) propose that a highly interdependent community of benthic algae, bacteria and macro-heterotrophs, acts to regulate sediment dynamics via small-scale nitrogen cycling. He suggests that the algal exudation of excess carbon, which acts as a sediment-binding agent, is critical and controlled by nutrient availability. It has also been suggested that larger diatom species may stabilise the sediment more effectively than smaller species, since they are likely to extrude more extracellular mucopolysaccharides (EPS). Initial studies have shown that different diatom species do affect sediment stability to different degrees. It is known that large species such as *Gyrosigma fasciola*, *G. balticum*, *Pleurosigma angulatum*, *Nitzschia recta* and *Surirella gemma* are found in assemblages of the Eden Estuary (Gatty Marine Laboratory, unpublished data). However, the actual proportions these species represent within an assemblage, and the amount of EPS produced by each species has not been established.

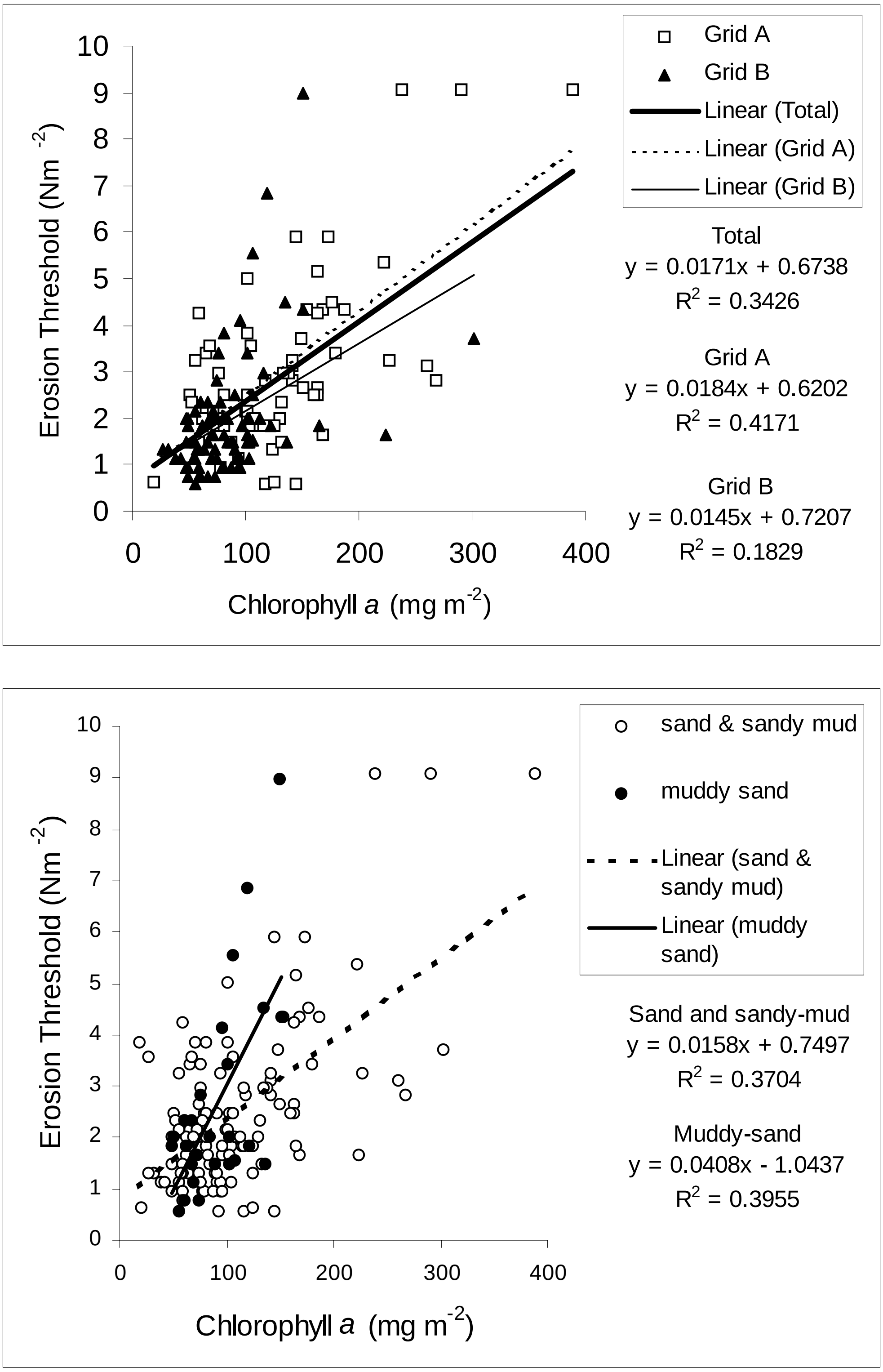


Figure 3.2 Data from the Eden Estuary for erosion threshold from CSM and chlorophyll *a* concentration in surface sediment

Notes: A) Example of field derived data. Total critical erosion thresholds plotted against their corresponding chlorophyll a concentration (r_{total}=0.59). Erosion thresholds of experimental Grid A had a stronger dependence on chlorophyll a than erosion thresholds of Grid B (r_{GridA}=0.64 and r_{GridB}=0.42). B) Data divided by fine grain fraction (<63 μm). Erosion thresholds of sediments from sand and sandy-mud (dashed line) and muddy-sand (solid line) sites increased with increasing chlorophyll a concentration (r=0.61 and r=0.63 respectively).

Biological and physical properties and processes act together and depending on the conditions, effects may be complementary, synergistic or dominant. The spatial variation in erosional behaviour can be complex. (Figure 3.3). After several decades of attempts to find a simple predictive parameter for biotically mediated sediment stability, it must now be recognised that due to the high complexity of the system this is unlikely. It is only where a single mechanism of biostabilisation is dominant that a single parameter for a biological effect is likely to be the best predictor of sediment behaviour. Whilst some efforts have been made to elucidate the effects of some components of the system, there has yet to be a study that investigates all of the possible biological and physical factors that may be influencing the system. It is clear that we are missing some very important interactions. At present, it is possible to offer a "suite" of single mechanism based (and possibly site-specific) biological and physical parameters that can be used to estimate critical erosion thresholds. Furthermore, using a data set that covers large areas of an estuary, it may be possible to categorise sites according to their biological status and physical characteristics, and that according to such functional groupings, a range of potential erosion thresholds could be presented.

3.2.4 Assessing impact of fine-dredged material following addition to the upper shore

Recent field studies in Essex estuaries have used annular flumes to quantify the spatial and temporal changes in sediment stability following placement of fine dredged material on the upper shore mudflats. This forms part of the **D**etermination of the **E**cological **Co**nsequences of **D**redged-material **E**mplacement. DECODE programme funded by Defra (Widdows et al, 2003). The findings were that there was an initial increase in sediment stability over a period of 7 days due to consolidation and a decline in water content. During the subsequent 18 months there were spatial (between site) and temporal (seasonal) differences dependent on the colonisation of the dredged sediment, particularly the relative balance between bio-stabilisers such as microphytobenthos and *Salicornia*, and bio-destabilisers and grazers of the microphytobenthos such as the burrowing worm – *Hediste diversicolor*, the crustacean – *Corophium volutator*, and the snail – *Hydrobia ulvae*. The statistical correlations between biota abundance and sediment erodibility in the field studies were consistent with the findings of experimental flume studies establishing cause-effect relationships for these key species (Table 3.2). Therefore the results of field studies with temporal and site specific changes in sediment erodibility could be interpreted and explained mechanistically in relation to changes in the benthic assemblages.

Table 3.2 Summary of statistical analysis and mechanistic interpretation of changes in sediment erodibility at sites following deposition of dredged material on the upper mudflat of sites in Essex estuaries (Reference: Widdows et al, 2003)

Biological process	Field derived relationships	Correlation	Relationship derived experimentally
Bio-stabilisation	U_{crit} vs Chlorophyll *a* and EPS	R^2= 0.7; $P<0.005$	Sutherland et al 1998
Bio-destabilisation	U_{crit} vs *Hediste diversicolor*	R^2= -0.85; $P<0.001$	Sobral & Fernandez
Bio-destabilisation	U_{crit} vs *Corophium volutator*	R^2= -0.65; $P<0.01$	De Deckere et al 2000
Bio-destabilisation	Mass eroded vs *Hydrobia ulvae*	R^2= 0.56; $P<0.01$	Anderson et al 2002
Bio-destabilisation	Mass eroded vs *Hediste*	R^2= 0.76; $P<0.005$	Sobral & Fernandez
Trophic interaction	Chloro *a* vs *Hediste diversicolor*	R^2= -0.64; $P<0.05$	
Trophic interaction	Chloro *a* vs *Corophium*	R^2= -0.60; $P<0.05$	

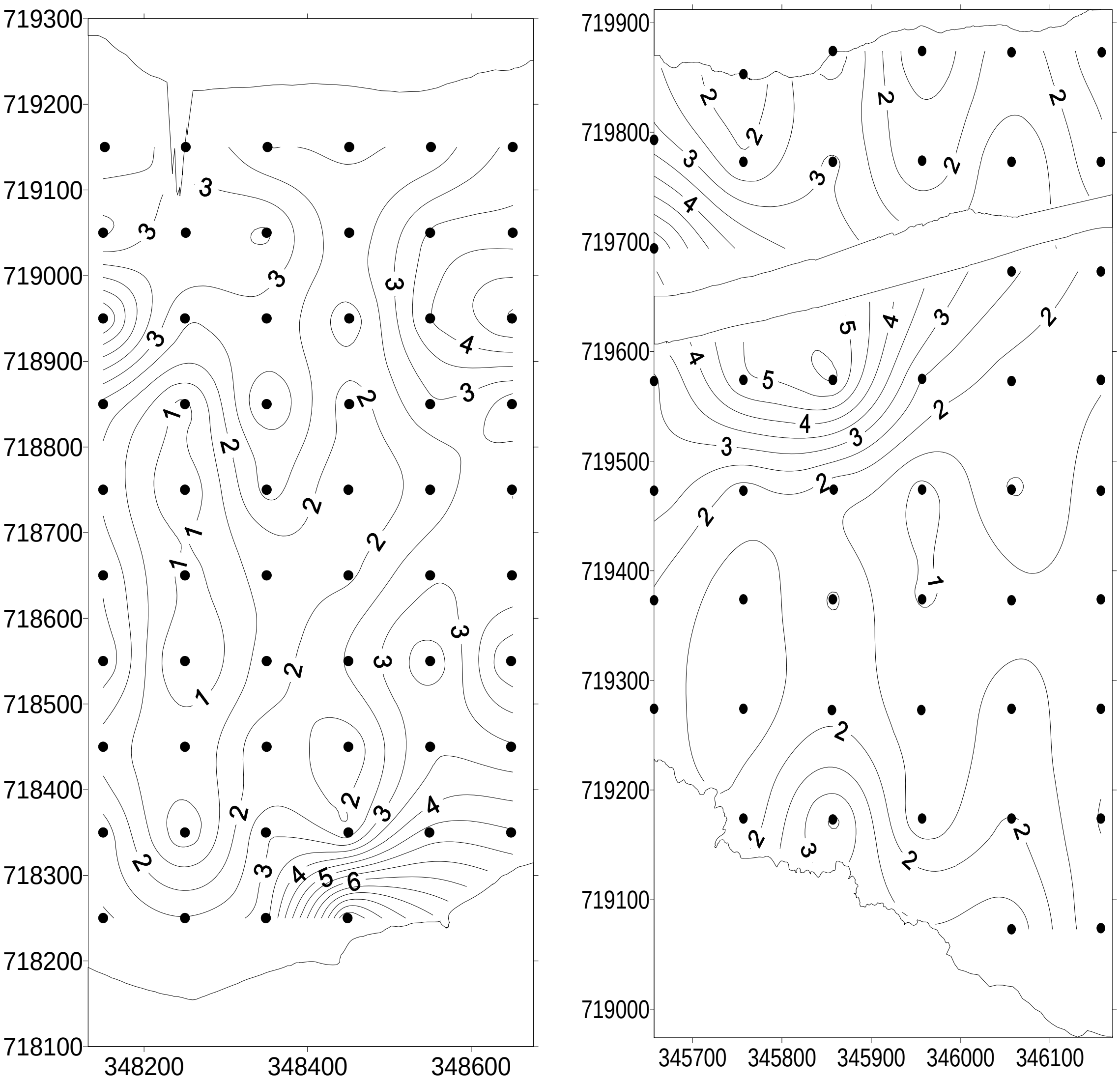


Figure 3.3 Contour maps of surface sediment stability on two sites of the Eden Estuary

Grid A on left (900m x 500m) consisted of 52 grid nodes, spaced 100m apart, running from the top shore down to the channel of the River Eden. Grid B on right (800m x 500m), was further upstream, and consisted of 46 grid nodes, spaced 100m apart, with the channel of the River Eden running through a portion of the grid. Contour lines represent erosion thresholds from CSM tests (Nm^{-2}) and x,y, axes represent Northings and Eastings (m).

At present we have only a limited quantitative understanding of the relationship between the abundance of key intertidal biota acting as ecosystem engineers and the resulting sediment stability. Further research is required to study a wider range species which contribute to a complex and dynamic benthic community. In future, however, it should be feasible to forecast the stability of intertidal sediments from knowledge of the basic physical properties and the composition of the benthic community, based on experimentally determined relationships between the abundance of key species and their impact on sediment erodibility (i.e. critical erosion threshold and erosion rate).

3.2.5 Experimental flume and field studies to quantify impact of key biota on sediment erodibility

During the EstProc project there has been a significant enhancement in our understanding of the impact of key intertidal biota on sediment stability through establishing quantitative relationships between near-bed flow, bed shear stress, sediment erodibility and species abundance. The species and different mechanisms studied, include:

- Attenuation of near-bed flow by the annual pioneer saltmarsh plant, *Salicornia europea* with the resultant reduction in sediment erosion;
- Attenuation of near-bed flow by the macroalga, *Enteromorpha intestinalis* with the resultant reduction in sediment erosion;
- Burrowing and sediment destabilisation by the cockle, *Cerastoderma edule;*and,
- Feeding and the active bio-resuspension by swarms of mysid shrimps in the upper reaches of estuaries.

3.2.6 Protection of sediments by saltmarsh plants

Saltmarsh plants form an important part of the natural coastal defence. Two species have been investigated, namely *Salicornia europea* an annual ‘pioneer’, and *Spartina anglica* a perennial species. Studies have shown that both species have a significant impact on near-bed flows and sediment erodibility but that their influence is complex and non-linear. *Salicornia* grows from spring to late summer reaching a height of 20cm and then dies back in winter when it provides little protection to the winter storm waves. In contrast, *Spartina* stems persist and protect the upper shore throughout the year. Recent flume studies examined the influence of stem density and stem height on near-bed flows, turbulence and sediment erodibility. These demonstrated that saltmarsh plants induced a 3 to 4-fold reduction in near bed flows compared to bare sediment, but flow attenuation was reduced significantly at stem densities below 1200 stems m^{-2} for *Salicornia* (Figure 3.4) and <400 stem m^{-2} for *Spartina*. For *Salicornia*, the increase in flow at <1200 stems m^{-2} was accompanied by a 4-fold increase in turbulence / bed shear stress (Figure 3.5) which resulted in orders of magnitude increase in sediment erodibility compared to higher stem densities (2400 to 4000 stems m^{-2}) and even 5-fold higher than bare sediment (Figure 3.6). There was no evidence of increased sedimentation rates in the presence of *Salicornia* or *Spartina* stems and this may also be due to the increased turbulence which hinders settling velocity. However, further research is required to examine whether this is a function of stem density and turbulence.

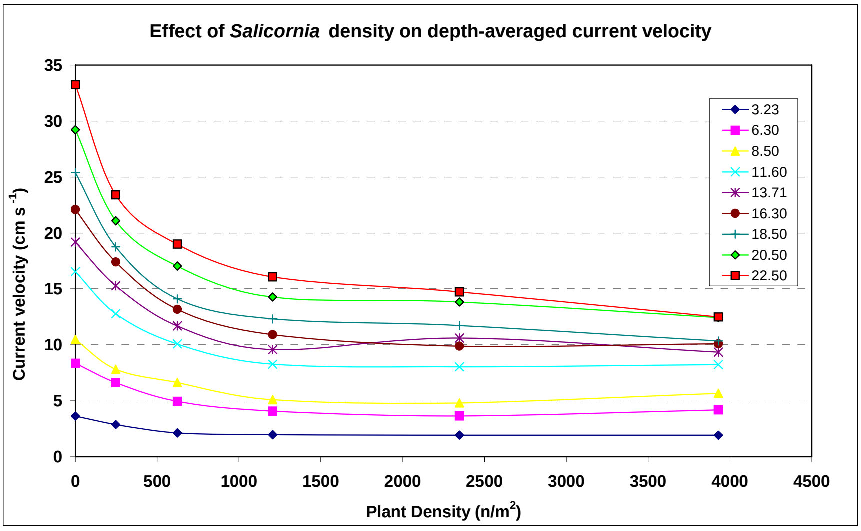


Figure 3.4 Effect of *Salicornia* stem density (n/m^2) on depth-averaged flows (0-10cm) over a range of flume rotation speeds (numbers in caption box are rpm)

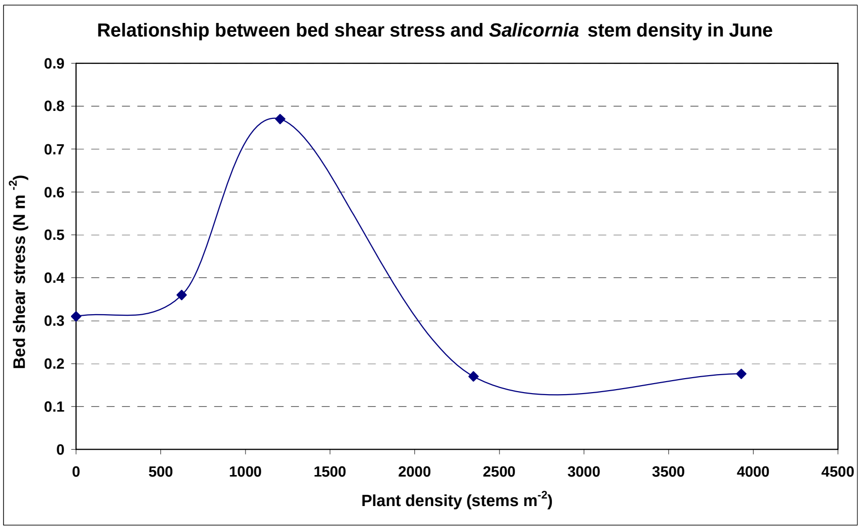


Figure 3.5 Increase in bed shear stress at densities of 1200 stems m^{-2}

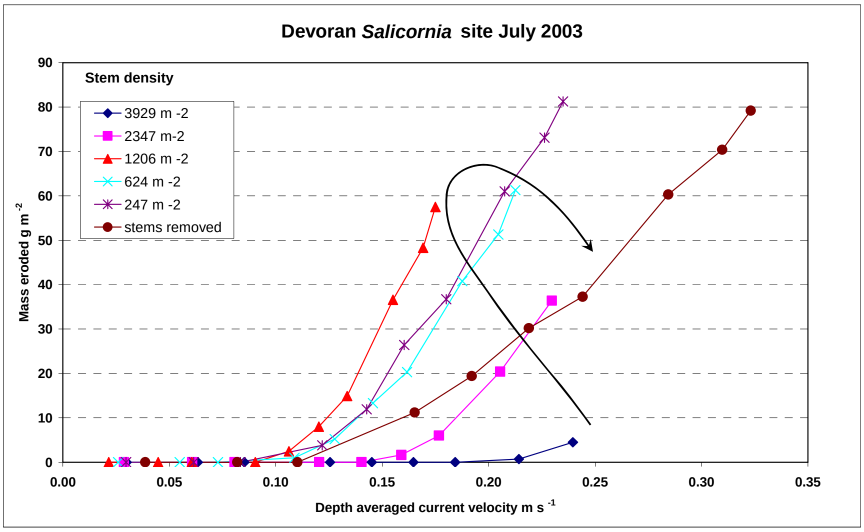


Figure 3.6 Impact of *Salicornia* stem density on sediment erodibility (July 2003) showing highest erosion at a density of 1200 stems m^{-2}

3.2.7 Influence of Enteromorpha on near-bed flows and sediment dynamics

The macroalga, *Enteromorpha* spp., forms extensive algal mats on the mid-shore of many estuaries and is often regarded as a nuisance alga with deleterious ecological consequences (e.g. a reduction in biodiversity). *Enteromorpha* density varies seasonally, growing rapidly during the spring and summer and then dies back during the winter. The growth and persistence of macroalgae in estuaries may be due in part to the positive feedback that it induces. For example, *Enteromorpha* has been shown to reduce near-bed flows, thus reducing sediment resuspension and turbidity in the water column, which increases light penetration, and this in turn enhances its growth potential. Experimental flume studies demonstrated that near-bed flow was reduced by 18% to 56%, and sediment erodibility was reduced from 2- (Figure 3.7) to 10-fold, with increasing *Enteromorpha* density from 10 to 60% (% cover when air exposed). The presence of *Enteromorpha* also significantly enhanced sedimentation rates of fine mud by ~50% at 60% cover.

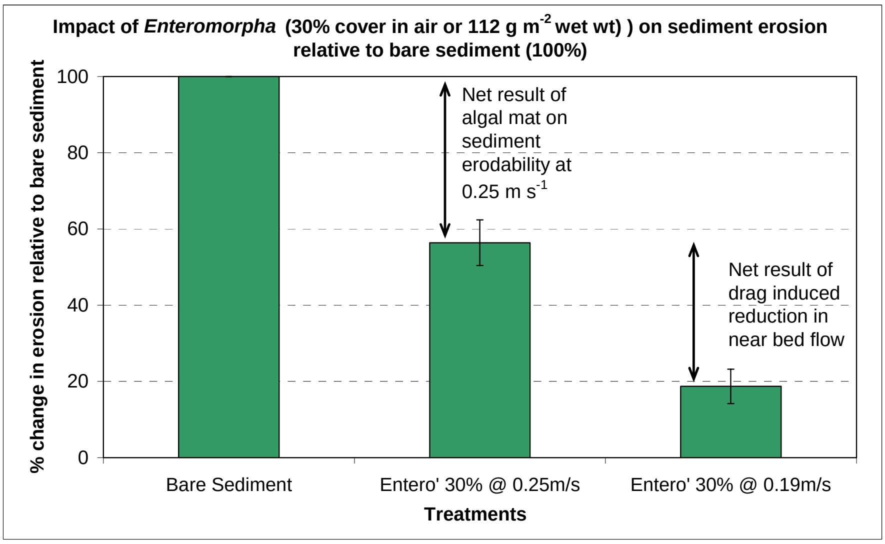


Figure 3.7 Diagram illustrating the impact of *Enteromorpha* (30% cover when air exposed) on sediment erosion relative to bare sediment

Note: Firstly, comparison under similar near-bed flow conditions of 0.25 m s^{-1} showing a 44% reduction in erosion, and secondly accounting for the flow attenuation induced by the macroalgae from 0.25 to 0.19 m s^{-1} and the additional 2-fold reduction in sediment erosion (total reduction = 80%).

3.2.8 Influence of cockle burrowing on sediment erodibility

Cockles (*Cerastoderma edule*) are suspension feeders living in a wide range of intertidal sediments from fine mud to sand. They are buried within the sediment with their short siphons protruding ~ 5mm above the sediment surface. During their active feeding phase they have two behavioural responses that can destabilise the surface sediments (2-3cm depth). Firstly, they move (plough) through the muddy sediment over considerable distances (5-10cm), and secondly they rapidly close (adduct) their valves in order to eject faeces and material collected within their mantle cavity. Many field studies have demonstrated a significant positive correlation between sediment erodibility and cockle density. More recently experimental flume studies have established the density-dependent relationship between cockles and sediment erodibility, thus enabling us to interpret the statistical correlations in field data as a cause-effect relationship (Romano et al, 2003). There was a 4-fold increase in sediment resuspension at a density of 190 individuals m^{-2} (maximum densities recorded in the field:- ~300 m^{-2}) (Figure 3.8).

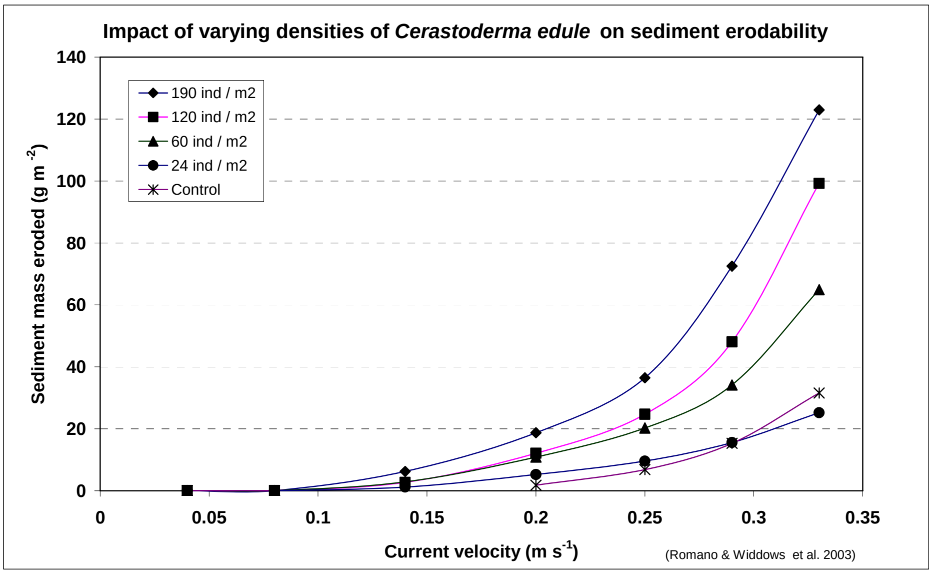


Figure 3.8 Influence of the cockle (*Cerastoderma edule*) density on sediment resuspension in response to increasing current velocities

3.2.9 Influence of mysids on sediment re-suspension

Mysids are one of the few species that are able to exist in the upper estuary at low salinities of 0 to 1ppt. They occur in high density swarms (36,000 to 100,000 m^{-3}) feeding on, re-suspending and disturbing the surface sediments. Recent experimental flume studies have quantified this process of ‘active bio re-suspension’ of sediment at low flows, well below the critical erosion velocity (i.e. at flow speeds of 2 cm s^{-1}), and that the re-suspension is dependent on mysid density (Figure 3.9). The destabilisation of the surface sediment by high density swarms also significantly enhances the total erodibility of the sediment when subjected to higher flows and bed shear stresses. These novel findings suggest that mysids may form an ecologically significant process that contributes to the turbidity maximum zone in the low salinity region of estuaries. Previously, this has been considered the result of purely physical processes.

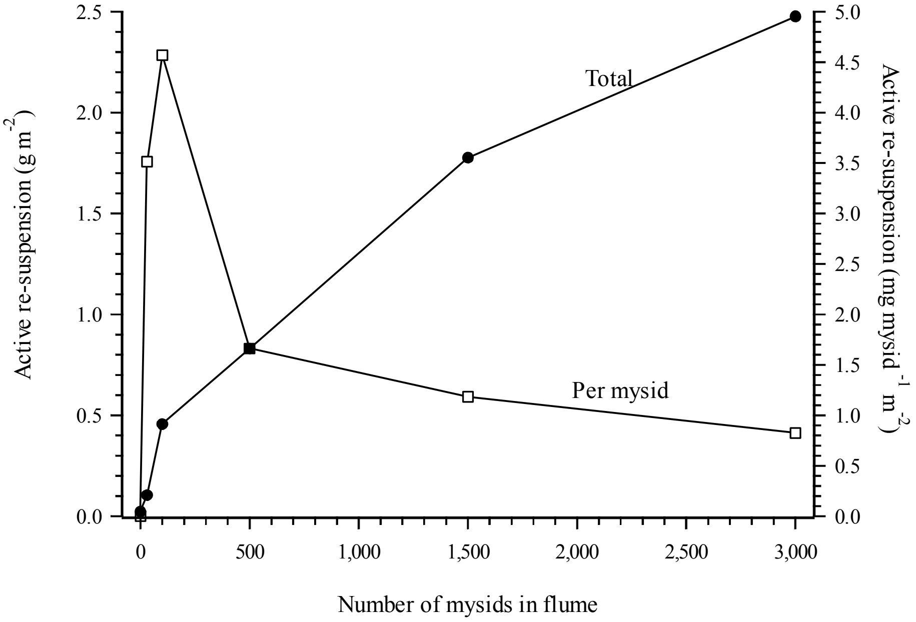


Figure 3.9 Active re-suspension of sediment caused by mysid feeding whilst maintained at a low current speed of 0.02 m s^{-1}. Closed circles – total active re-suspension; open squares – active re-suspension per mysid

3.2.10 Influence of temperature and organic content on biota and sediment stability

Intertidal biota follow seasonal cycles of growth and reproduction but this is not simply temperature dependent. Growth is largely dependent on the availability of nutrients and food supply. Despite invertebrates being poikilothermic (cold-blooded) and unable to regulate their body temperature, they have the ability to adapt to changes in temperature and maintain their metabolic processes and behavioural activities relatively independent of the environmental temperature. However, this thermal adaptation operates only within certain genetically determined limits. For example, polar species are adapted to low temperatures and tropical species to a high range of temperatures. Temperature therefore has a profound effect on the geographical distribution of species and limits its global range. For example, in temperate waters the bioturbating clam *Macoma balthica*, prefers colder environments and requires cold winters for recruitment at high densities on mudflats.

In the UK, the line from the Wash to the Severn represents the species southern limit. South of this line, *Macoma* tends to occur only at low densities, whereas north of this line, *Macoma balthica*, can reach high densities (2000 to 10,000 m^{-2}), particularly following cold winters. At these high densities, *Macoma* has been shown to be a major factor reducing intertidal sediment stability, thus increasing sediment resuspension and transport of sediment up the shore on the spring tides. This results in increased accretion on the saltmarsh. The converse situation occurs in years following mild winters when the mudflats tend to have well developed diatom biofilms and macroalgal mats (*Enteromorpha*), and low *Macoma* abundance. This results in enhanced sediment stability due to bio-stabilisation and causes a reduction in shoreward sediment transport and a 10-fold reduction in accretion on the saltmarsh (Widdows, 2001). Such findings have important implications for the sustainability of our natural coastal defences with global warming and sea level rise.

Global warming is likely to increase intertidal sediment stability but reduce sediment accretion on the saltmarsh. Forecasting changes in sediment dynamics and estuarine morphology requires improved understanding of the role of key biota as ecosystem engineers and their response to global warming.

Field studies examining the relationships between sediment erodibility and sediment properties have found no significant correlation with total organic content of sediment (Widdows et al, 1998, 2000, 2004). In contrast, the majority of field studies demonstrate a significant correlation between sediment erodibility and extracellular polymeric substances (EPS) within the surface sediments, as discussed in Section 3.2.1. These mucus-like carbohydrates, which are produced by micro-organisms such as benthic diatoms, increase the cohesiveness and stability of the sediment (Paterson and Black, 1999).

3.2.11 Modelling of physical-biological interactions

There has been further development of the BIOSED model of biologically mediated sediment transport across a shore-normal intertidal transect (EMPHASYS Consortium, 2000b). Initial model runs focused on the impact of biostabilisers (benthic diatoms) and bio-destabilisers (*Macoma balthica*) on sediment erosion, transport and deposition on the Skeffling mudflat (Spurn Bight, Humber). More recent developments, discussed below, have included:

- Influence of *Enteromorpha* on sediment erosion rate and near bed flows;
- Effects of *Spartina* on wave height and sediment dynamics;
- Methods of modelling intertidal bed morphology over long timescales.

The primary aim of the measurements and modelling were to isolate for estuarine sites the effect of one variable, such as *Spartina* (on muddy sediments; 85% <63µm) and *Enteromorpha* (on sandy sediments; 99.5% >63µm). If the results were applied to mixed (sand-mud) sediment sites some extension of the formulae would be needed.

3.2.12 Influence of *Enteromorpha* on sediment erosion rate from annular flume studies

Data from flume experiments (Romano et al, 2003) with 3 values of percentage cover (*pcover*) by *Enteromorpha* were used to guide construction of an equation for erosion rate. Experiments were performed either with full-length stems (*stemval*=1) or stems cut down to bed level (*stemval*=0). The flume rotation rate (*r*) was raised in increments.

Mass eroded per unit bed area (*q*) was modelled by the equation:

$$\frac{dq}{dt} = \begin{cases} k\left(q_{eq} - q\right) & \text{if } r > rcrit \\ 0 & \text{if } r \le rcrit \end{cases}$$

where $q_{eq} = a.\dfrac{\left(r - rcrit\right)^d}{pcover^b\left(1 + stemval.c.pcover\right)}$ is the maximum mass eroded per unit bed area at constant *r*, *pcover* and *stemval* values and *rcrit* is the critical rotation rate, below which no erosion occurs. There are 5 adjustable parameters: *k, a, b, c, d*. This formula is appropriate over the range of data observed. As rotation rate becomes large, the form must change as erosion changes from type I (erosion limited at constant bed stress) to type II (erosion unlimited at constant bed stress) erosion (Sanford and Maa, 2001). As *pcover* becomes small, the rate of increase of q_{eq} with *pcover* must decrease, to allow the erosion rate for algae-free sediment to be approached smoothly.

The parameters *a* and *b* govern the maximum mass which can be eroded at 67rpm. *a* is simply a multiplicative factor. *b* gives the power dependence on pcover. *c* governs the reduction in maximum mass eroded at 67rpm when stems are present (a large value of *c* will give a large reduction in eroded mass due to stems). *d* and *rcrit* govern the way in which erodible mass at 67rpm is reduced at smaller rotation rates. *k* determines how fast the equilibrium q_{eq} is approached during each period of constant rotation rate.

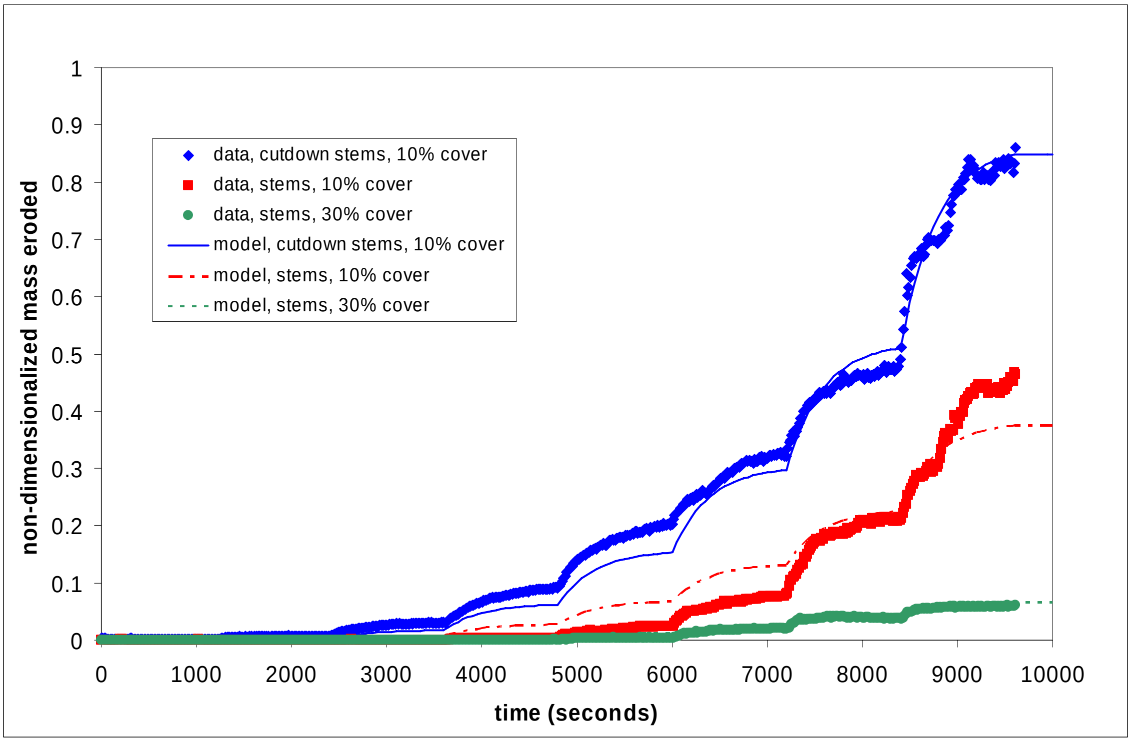


Figure 3.10 Optimized model results and data from PML flume averaged over replicates

Figure 3.10 shows observed results averaged over replicate flume runs for each percentage cover and bare/stems case and the predictive model results using optimised parameters.

Using least squares and using all data, the optimized parameters for the non-dimensionalized equation are:

Optimized Value	a =	0.18143	±	0.09004
Optimized Value	b =	-0.88426	±	0.20486
Optimized Value	c =	12.632	±	4.5408
Optimized Value	d =	2.9533	±	0.55089
Optimized Value	k =	0.0026693	±	0.0039788

The ratio of model Sum of Squares to total Sum of Squares is 0.921.

For a fixed driving force, this formula expresses how erosion changes with percentage cover (for $pcover \geq 10\%$). With plants at full height (about 12cm), erosion varies as $\frac{1}{\left(pcover^{0.88} + 12.6 pcover^{1.88}\right)}$. At low values of pcover, the two terms in the denominator are approximately equal. However, for pcover values greater than about 30%, the second term dominates, and the erosion diminishes as approximately ${}^{1}\!/_{pcover^2}$.

To convert this formula for use in a numerical model, a relationship between flume rotation rate and velocity at a height in or above the canopy must be found. This relationship is expected to vary with percentage cover and canopy height and is discussed below.

Flow resistance due to *Enteromorpha*

The macroalga *Enteromorpha* is attached to the substrate by a small, disc-shaped holdfast. Several filaments branch off a short stalk. The filaments are thin, buoyant, flexible tubes. As water velocity over the bed increases, the filaments bend over in the flow. Romano *et al* (2003) presented experiments carried out on sediment samples with 3 densities of *Enteromorpha*, where velocity was measured at intervals from 1cm to 12cm above the bed in the PML annular flume, with rotation rates between 8rpm and 75rpm.

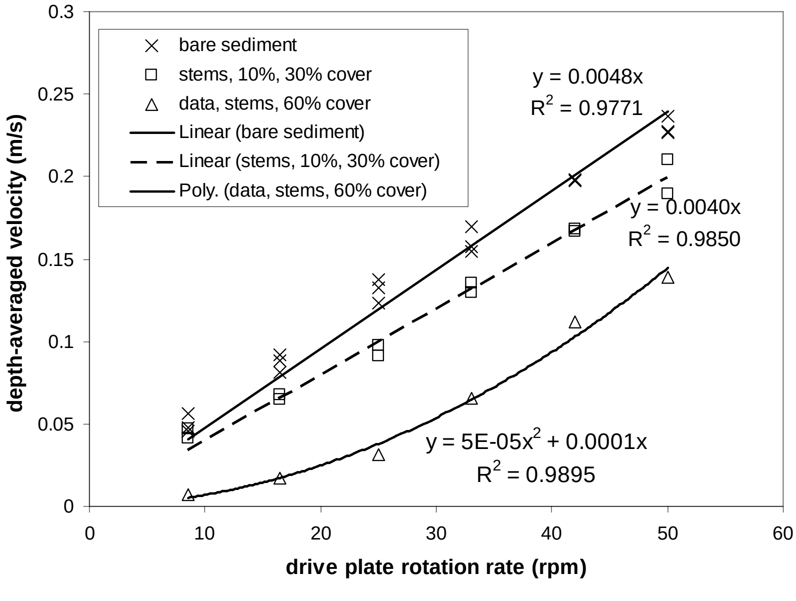


Figure 3.11 Velocity as a function of rotation rate of flume drive plate for bare sediment, sparse cover (10 & 30%) and dense cover (60%)

Figure 3.11 shows the data for bare sediment, and for *Enteromorpha* cover of 10% and 30%, with straight lines (forced to pass through the origin) fitted. The low stem density line gives lower speeds than the bare sediment line, because of drag caused by the stems. Figure 3.11 also shows the data for *Enteromorpha* cover of 60%. A quadratic line provides a better fit to the data than a linear fit due to the enhanced flow attenuation at low rotation rates when the high density stems are vertical in the water column. Flow attenuation is reduced at higher speeds when the stems bend and lie horizontal with the flow.

The case of bare sediment

It is assumed that drag along the sides on the flume is small compared to the drag at the bottom of the flume. For bare sediment, assuming that quadratic friction acts at the bed and at the drive plate, steady values of $\overline{u}$ will be reached when

$$\rho C_{bed}\overline{u}^2 = \rho C_{top} l^2 r^2$$

where ρ=water density, l= length scale for the drive plate, $\overline{u}$ is depth-averaged velocity within the flume, and C_{top}, C_{bed} are dimensionless constant drag coefficients, giving $\overline{u}$ proportional to r.

With *Enteromorpha* present – low stem density

There are two forms of drag exerted on the flow by *Enteromorpha* stems. Skin friction drag is caused by viscous drag along the whole surface area of each frond. It is proportional to $\overline{u}^2$ and to the surface area of fronds within the flume. It is not changed by bending of the stems (unless fronds then touch and shade each other from the flow to a large extent) as in-canopy flow increases. This drag can be modelled by:

$F_{skin} = \rho C_{stem}\overline{u}^2$, with C_{stem} independent of $\overline{u}$.

For low stem densities, this is the largest form of drag due to the *Enteromorpha*. This again gives $\overline{u}$ proportional to r (as observed).

$$\overline{u} = rl\sqrt{\frac{C_{top}}{(C_{bed} + C_{stem})}}$$

With *Enteromorpha* present - high stem density

The second form of drag exerted by the stems on the flow is pressure drag. This is the drag associated with the formation of wakes, and the transfer of mean flow energy into energy of the turbulent wake. This drag is due to the impact of the flow on the upstream side of each frond. The pressure drag has the form

$$F_{pr} = \rho C_{pr}\overline{u}^2$$

where C_{pr} is proportional to the frontal area of the fronds. As $\overline{u}$ increases and the fronds bend over, their frontal area will decrease, reducing the amount of pressure drag. So, C_{pr} is expected to be a function of $\overline{u}$. For a given, moderate in-canopy flow $\overline{u}$, the angle between a frond and the bed can be approximated, balancing the moment of the buoyancy force acting on the frond against the frictional drag acting on the frond. The angle of the fronds then determines the frontal area presented to the flow. For stem angle between about 30° and 60° from the horizontal, this will vary approximately as $1/\overline{u}$. So, the pressure drag will vary as $\overline{u}$. For frond angles of less than 30°, the frontal area becomes progressively smaller, and the pressure drag will diminish, eventually being outweighed by the skin friction drag. So, the $\overline{u}$ vs r line will then give similar behaviour as those for low stem densities. This will occur as r and $\overline{u}$ become large.

For small values of r and $\bar{u}$, the fronds remain close to vertical and frontal area becomes almost constant with small variations of $\bar{u}$. Pressure drag is then roughly proportional to r^2. So, $\bar{u}$ will again vary linearly with r, but with the slope reflecting the large pressure drag (exceeding the small skin friction drag).

For sparse cover, the depth-averaged velocity responds in the same way to changes in forcing as for a bare sediment bed. In contrast, for dense cover the velocity is more responsive to changes in forcing, even though the values of velocity for a given driving force are much smaller than for bare sediment or sparse cover. For sparse cover, the *Enteromorpha* is presenting extra drag to the flow by acting like increased bed area, whereas for dense cover, the *Enteromorpha* acts like a permeable barrier where the height of the barrier decreases as flow increases.

This work does not cover wave action because the experiments, which are good at isolating effects of *Enteromorpha* cover on erosion, used steady currents. In many of the estuarine areas where the biological measurements have been made, the sites are sheltered and experience low wave energy. Changes which might enable erosion by waves to be studied are being investigated outside of EstProc.

3.2.13 Effects of *Spartina* in a high-shore model with waves

Two models have been constructed to investigate possible effects of *Spartina* marsh on high-shore sediment movement. They are aligned onshore-offshore and are applied for single tides. Saltmarsh occupies the top 50m of the shore profile. Deposition is dependent on the difference between bed stress and a critical deposition threshold of 0.11 $\mathrm{Nm^{-2}}$. We have made the assumption that maximum erosion at a particular bed stress varies with excess bed stress above a critical erosion threshold of 0.3 $\mathrm{Nm^{-2}}$. The rate of erosion is determined by the difference between sediment eroded so far and the maximum which can be eroded at that bed stress. Bed stress is calculated by combining stress due to waves and currents, following Soulsby (2000) (also: Whitehouse et al, 2000). A single frequency wavetrain is imposed.

In the first model, wave height is given by:

$$H = \min(H_i, a \times h_e)$$

where H_i is the height of the incident wave where it is not restricted by water depth, a is a factor (set to 0.8 in this model) which governs how quickly wave height decays as effective water depth decreases, and h_e is the effective water depth, which is equal to the water depth – *Spartina* stem height. So, as waves approach the shore, the wave height remains constant until

$$h_e = \frac{H_i}{a}$$

Shoreward of this point, the wave height decreases as a proportion of water depth. Offshore of this point, bed stress due to waves decreases as depth increases.

Figure 3.12 shows the change in bed level in the first model after one tide, with incident waves of height 20cm, and *Spartina* stem height taking values from 0 to 15cm. At a stem height of 10cm, the reduced erosion in the marsh balances deposition. At a stem height of 15cm, deposition outweighs erosion in the marsh. For lower stem heights, erosion occurs across the marsh, as it does across the rest of the transect.

In the second model, wave height is limited by a proportion (0.8) of effective water depth but also decreases with distance inshore from the marsh edge. Wave height is made to reduce by a percentage, *q*, of the incident wave height with every metre of distance shorewards from the marsh edge. This gives extinction of the waves at a distance 100/*q* from the marsh edge.

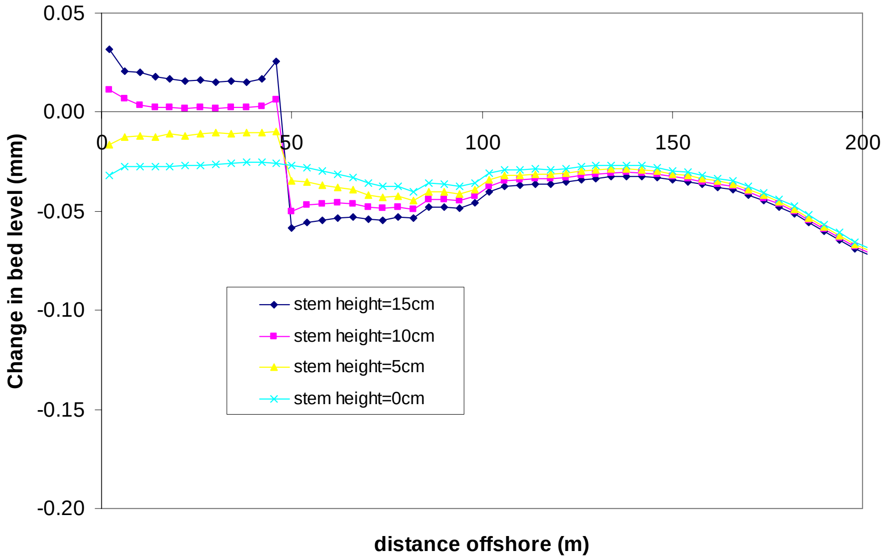


Figure 3.12 Effect of varying stem height of *Spartina* on upper 50m of shore in determining bed level changes after a single tide with wave height of 20cm

Figure 3.13 shows the change in bed level in the second model after one tide for three sets of parameters. The pattern of high-shore deposition is strongly influenced by the rate at which wave height diminishes with distance through the marsh. The incident waves in this example are large (wave height =60cm), so erosion occurs over the marsh, unless *q* is sufficiently high that waves are extinguished completely or unless stem height is large. Deposition then diminishes towards the shore as inundation time decreases.

In shallow water, waves are very effective at eroding sediment. So in saltmarshes even small waves can have a major effect on bed profile evolution. This model allows the consequences of different effects of saltmarsh on wave height to be explored. Reducing wave height according to the depth of clear water above the stems gives erosion or deposition which is almost constant across the width of the saltmarsh. So the erosion or deposition does not alter the slope of the marsh bed but acts to raise or lower it uniformly. However, if wave height also diminishes with distance into the marsh then even large waves can be extinguished completely. In this case, the pattern of erosion and deposition is more variable across the marsh, switching from erosion at the outer edge to deposition further upshore. This will tend to increase the slope of the outer marsh bed. The slope of the highshore bed can be flattened by deposition which decreases as inundation time decreases. These results are for single tides with single sets of wave parameters. Longer, bed-evolving runs with a range of tides and waves need to be made.

In certain situations it might be necessary to include the effect of long-shore wave-induced currents and combine these with the tidal currents. These would need to be included in a parametric form, based on wave height, period and direction, to maintain the morphological update capability in the present model. Alternatively these situations could be predicted in a more extensive 2-dimensional cross-shore model including radiation stresses from oblique breaking waves (e.g. Southgate and Nairn, 1993) or in a gridded numerical model including the same process, for example, such as that proposed for mudflat hydrodynamics by Spearman (2004).

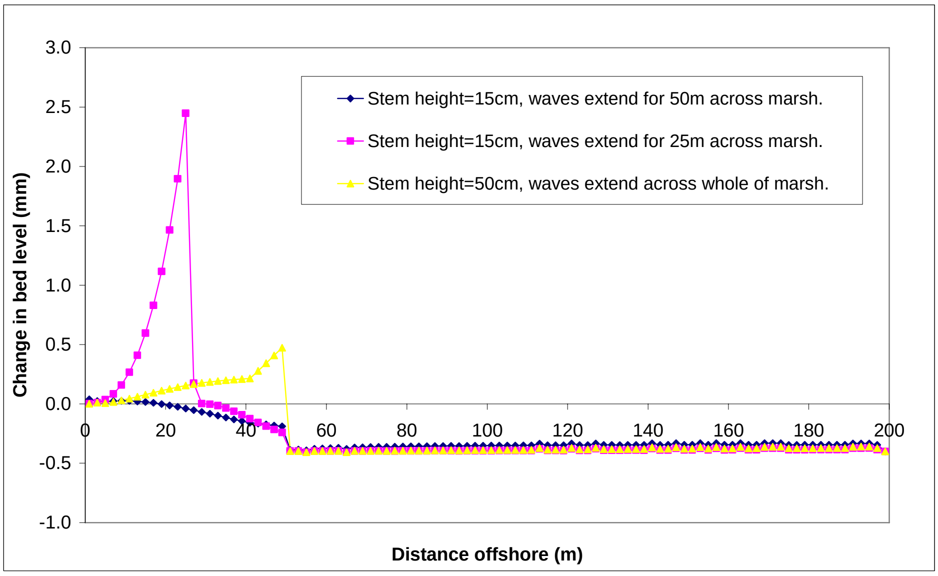


Figure 3.13 Effect of wave height profile and stem height on bed level changes

3.2.14 Modelling bed morphology for an intertidal transect over longer timescales

For two differing transects, the effects of time-varying bioturbators (*Macoma balthica*), stabilisers (benthic diatoms) and external sediment supply were combined using tidal amplitudes for a particular year (1995). The overall contribution to erosion and deposition over the transects was modelled. One transect (based on Skeffling, in the Humber estuary) is broad and shallow-sloping. This leads to high velocities during flooding and drying, and hence there is the potential for large sediment transport within the transect itself. Material eroded during the flood around mid-tide level is advected onshore and can be deposited at high shore levels. The other transect (Leverton, in the Wash) is narrower and steeper, so flooding and ebbing velocities are rarely fast enough to erode sediment. This transect is more influenced by deposition of external suspended sediment. The spatial pattern of deposition depends on the co-occurrence of peaks in offshore sediment supply and tidal amplitude. Four annual patterns of biota were modelled.

At high to mid- shore levels, cycles of erosion and deposition strongly linked to the spring/neap cycle. At lower shore levels, the changes in deposition were instead linked to seasonal changes in offshore sediment supply. Over the broad, shallow-sloping transect, the years with more bioturbators present showed greater mid-shore erosion and high-shore deposition. The pattern of erosion and deposition along the intertidal transect then showed more peaks and troughs due to intertidal redistribution of sediment.

Whereas years with more stabilized sediment showed smooth offshore variation of deposition, due to inundation time decreasing with shore height. The asymptotic nature of the effect of bioturbation on erosion led to smaller differences between years which had widely-spaced, high *Macoma* densities, than between years with different low *Macoma* densities. The association between high *Macoma* densities and low diatom numbers in the given scenarios meant that net stabilizing or destabilizing effects combined for most of the year of simulation time.

3.2.15 Modelling morphology with feedback between flow and bed profile

Results from the BIOSED model (EMPHASYS Consortium, 2000b) are presented, and compared with results from Roberts et al (2000) shown for a single tidal amplitude. The model calculates erosion and deposition at each grid cell during a tide. The net mass eroded or deposited over one tide is converted to a change in bed height. This is multiplied by a factor of 50, to give the change over 50 identical tides, and the bed profile within the model is updated. The bed can move up or down at the seaward boundary of the model, but is constrained to have a zero offshore gradient.

The model has been applied to an intertidal transect, 10500m long. The initial bed profile has a constant slope, with a fall of 8m in height over 10km. Erosion and deposition formulae are chosen to be the same as in Roberts et al (2000) to allow results from the two models to be compared. Bed stress is related to depth-averaged velocity, using a drag coefficient $\tau = \rho C_D u^2$ where water density, ρ=1025 kg m^{-3}, and drag coefficient, C_D = 0.002, and u is depth-averaged velocity. The rate of erosion per unit surface area of bed (g m^{-2} s^{-1}) is $M_e\left(\frac{\tau}{\tau_e}-1\right)$ when $\tau > \tau_e$, or 0 otherwise. If a constant bed stress exceeding τ_e is applied, then erosion will continue at a constant rate. The rate of deposition per unit bed area is $M_d = \frac{w\left(1-\frac{\tau}{\tau_d}\right)}{h}$ when $\tau < \tau_d$, or 0 otherwise h is the water depth (or the drying height depth, 5cm, if h<0.05). The timestep is 60 seconds and the grid cell length is 175m. The critical erosion stress is 0.2 N m^{-2}, the critical deposition stress is 0.1 N m^{-2}.

Adjustment to equilibrium is quicker when the profile is mainly being eroded, and slower when deposition is required to raise the bed level. The BIOSED model, which uses a level sea surface and conservation of volume to calculate velocity, and consequently cannot produce inertial effects or flood-ebb asymmetry, nevertheless manages to give reasonable agreement with the changes in bed profile seen in the Roberts et al model. Differences in the final profiles produced are much smaller than the total change in profile which has occurred from initial to final bed level.

Four runs were made with external SPM concentration fixed at 100 mg l^{-3}, and tidal range of 2m, 4m, 6m and 8m (shown in Figure 3.14). Final bed profiles were plotted together with results from Roberts et al (2000). The agreement is worst for the smallest (2m) tidal range. This may well be due to a difference in the way suspended sediment below the low water mark is handled in the two models. In BIOSED, suspended sediment is only set to the external value at the open boundary (x=10500 m). In the run with a tide range of 2m, as the bed evolves and large deposition occurs, the low water mark moves shorewards. If suspended sediment were set to the external value for all parts of the transect below low water mark, then much more sediment would be available for deposition at each tide. This would move the equilibrium profile closer to that given in Roberts et al (2000).

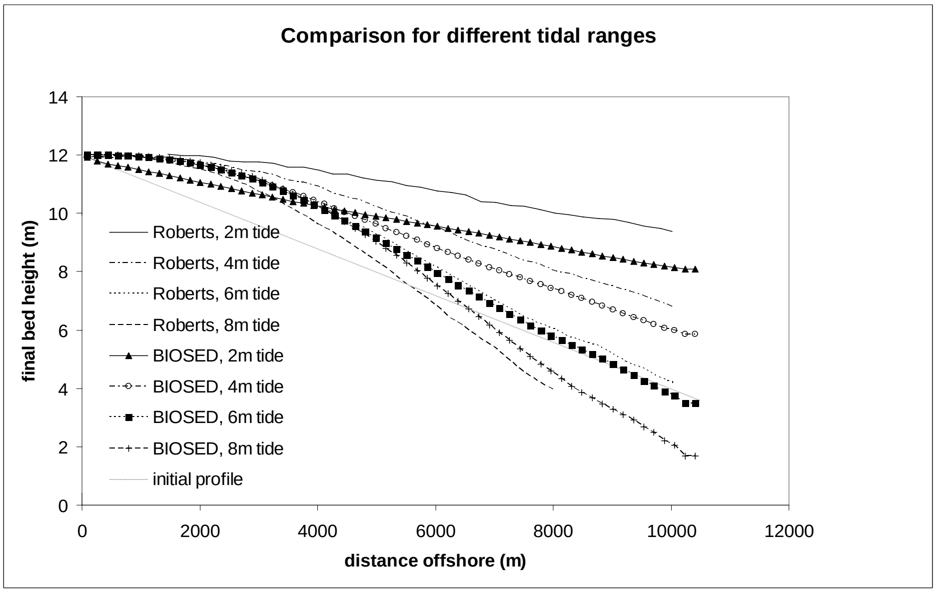


Figure 3.14 Comparison of BIOSED model and Roberts et al (2000) model showing final bed profile in response to 50 identical tides with tidal ranges from 2m to 4m and an external SPM concentration of 100 mg l^{-1}

3.2.16 Review of link between hydrodynamics and faunal assemblages

To extend the process based understanding a review by Bolam (2003) has attempted to identify the relationship between hydrodynamics and faunal assemblages and key species in estuarine environments. If a predictive capability of macrofaunal assemblages (given a set of hydrodynamic conditions) exists, this would facilitate their incorporation into estuarine process and morphological models.

There is no doubt that at the estuarine scale, predictable differences in macrofaunal assemblages occur from the wide, wave-dominated, well-sorted lower reaches of an estuary, to the narrow-channelled, tidally-dominated, poorly-sorted sediments of the upper estuary (Goss-Custard, 2000). The large differences in salinity between these two extremes is responsible for the largest and most predictable differences in community composition (Attrill and Rundle, 2002), while faunal differences resulting from hydrodynamic differences are still discernible. The sandier, wave-dominated outer reaches are relatively species-rich, represented by the estuarine invasion of marine species. The water movements in the upper reaches are very different: tidal forces are funnelled and meet the opposing freshwater flow to create complex water movements. These systems are in entropy, species richness is poor and relatively predictable. This is exemplified in fluid mud environments where few species are adapted to live (Diaz and Boesch, 1977). However, between these two extremes, predictability of macrofaunal assemblages is poor, and we rely on correlations with static sediment variables.

Correlations between grain size and species distributions have been made leading to generalisations of distinct associations between species and/or communities and specific sediment types (Snelgrove and Butman, 1994). From the intertidal zone to the subtidal, sands, silts and clays, these sediments are inhabited by a variety of marine benthic organisms which display a range of adaptations to deposition and erosion of the bed (Miller et al, 2002).

The review has indicated that there is an underlying relationship between sediment granulometry, a surrogate measure for hydrodynamic conditions in most studies, and estuarine macrofaunal assemblage at the estuarine scale. For three estuaries documented in the review; the Severn, the Humber and the Forth, faunal assemblages based on similarity matrices were more-or-less associated with distinctive sediment types. For the Severn Estuary and Bristol Channel, this was taken further by Warwick and Uncles (1980) who found that community type was correlated with tidal stress. This opens up the possibility of predicting macrofaunal distributions from hydrodynamic models.

Our predictions from large-scale models of distributions rely mostly on inferences drawn from correlations between easily measured parameters and the patterns of abundance rather than direct tests of the factors causing the patterns (Peterson, 1977; Snelgrove and Butman, 1994; Constable, 1999). It is evident that the occurrence of a species in a particular habitat is due to not one factor alone but to the complex interaction between particle size, organic and microbial content, hydrodynamic and chemical conditions, and biological interactions (trophic and predator-prey interactions) which makes a habitat suitable for a particular species. Conditions such as these are variable on a spatial and temporal scale and it is therefore not surprising that correlations between fauna and grain size have been weak. Thus a primary question is what parameters, or combinations of parameters, need to be estimated to adequately predict the patterns of abundance of biota in relation to physical factors. This will require tests of the causal relationships between biota and field conditions and more detailed investigations of dynamic models with faunal structure. While progress could be made following a detailed examination of existing survey information, confidence in the conclusions would be hampered by the lack of standardisation (for example, spatial and temporal scale and sampling device and design) between surveys. A more consistent approach is therefore required with a more explicit aim. This should encompass a number of estuaries with contrasting characteristics. Futhermore, faunal communities should simultaneously be related to static and non-static sediment variables as the present report has highlighted inherent weaknesses in the former.

3.2.17 Role of macrofauna in placement of dredged material

At present, the beneficial placement of maintenance dredged material within the UK is limited to small-scale trials (Bolam, 2004). There are several reasons for this. Firstly, there are concerns over subsequent movement of the material under natural forces (wave and tidal current action) and hence the potential for interference with other uses/users of the area. Secondly, our lack of knowledge of the rate of invertebrate recovery, and how this is affected by other factors, limits our ability to predict the effects of sediment placement on bird and fish populations. This is particularly important as the majority of 'beneficial use' schemes are in estuarine intertidal habitats, areas important for sustaining such populations. However, these two issues are inter-related: macrofaunal invertebrates have demonstrable effects on sediment stability and it follows that factors affecting their recolonization may indirectly affect the fate of the recharged material.

In the review paper by Bolam (2004) an attempt was made to predict the role of macrofaunal organisms in sediment (de)stabilization processes following the intertidal placement of fine-grained material, or beneficial use schemes. They found, using examples from the UK and US that recovery:

- Starts within a short time following recharge;
- Occurs via a gradual return of the species within the ambient community;
- Is more-or-less consistent between schemes; and
- Leads to a net sediment destabilization.

These results imply that biological destabilization processes can, and should, be incorporated into models based on physical parameters. However, indirect effects and seasonal variations make estimations of these effects inherently complex indicating the need for examination of multiple scenarios if a modelling approach is to be used.

3.2.18 Distribution of meiofauna in estuaries

Information on the distribution of meiofauna[4] in estuaries has been acquired from medium- to large-scale studies involving various benthic habitats ranging from near-freshwater to marine and from pure silts to fine-sandy and gravelly bottoms (Schratzberger, 2004). The main factors governing the distribution of generally nematode-dominated estuarine meiofauna communities appears to be (e.g. Warwick, 1971; Soetaert et al, 1995; Tita et al, 2002):

- Salinity; Meiobenthic density and diversity has been shown to generally increase with increasing salinity.
- The granulometric composition of the sediment with its associated variation in organic content;
- The degree to which the sediment retains water during low tide; and,
- Exposure time during low tide.

Warwick and Gee (1984) emphasised the potential importance of biological interactions between species, both within meiofauna and between meio- and macrofaunal in structuring estuarine meiofauna communities. They found that meiofauna species abundance and diversity patterns in the lower, middle and upper reaches of the Tamar estuary, UK did **not** follow the expected trends in relation to salinity. Lowest diversity was found at the middle rather than the upper site. The authors presented circumstantial evidence suggesting that intense macrofaunal predation and disturbance together with more pronounced environmental fluctuations at the upper site kept the meiofauna community in a non-equilibrium successional state, characterised by a relatively high species diversity. The absence of such population-reduction mechanisms at the middle site, in contrast, led to a more stable climax community and resulted in lower diversity.

In contrast to macrofauna, the role of meiofauna as bioturbators and sediment stabilisers has received little attention. There are three main activities of meiofauna which may bioturbate and thus destabilise sediments directly. These are:

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[4] Animals ranging in size from about 0.1mm to 1mm living within the sediment. Meiofauna is the transition size class between micro and macrofauna.

- Feeding (including locomotion to find food);
- Burrow construction; and,
- Migrations related to tidal or diurnal cycles (Reichelt, 1991).

Aller and Aller (1992) concluded that the effect of meiofauna on solute transport and other destabilising processes are small in comparison with macrofauna and are generally confined to superficial oxidised sediments.

The few documented studies are based on direct observations of live meiofaunal organisms in the laboratory. Cullen (1973) described the activity of various meiofaunal taxa from the shallow water deposits of the Bristol Channel, UK. Ostracods were seen burrowing down to at least 4mm into the sediment, jostling aside sediment grains several times their own size with a vigorous, jerky motion and disrupting the sediment fabric within their immediate vicinity. Meiobenthic copepods exhibited a similar behaviour but their capacity for burrowing and movement of sediment particles varied according to their size and vigour.

Several meiofaunal species occupying muddy, estuarine sediments build and inhabit mucus tubes. The harpacticoid copepod *Pseudostenhelia wellsi*, for example, constructs a maze of horizontal and vertical tubes throughout the top 4mm of the sediment. The tubes are constructed from a matrix of small sediment particles and detritus bound together with an acid mucopolysaccharide (mucin). Many tubes extend laterally to form an infaunal network that markedly transforms the free surface sediment to a cohesive mucus-sediment mat (Chandler and Fleeger, 1984). Various activities have been described for estuarine nematodes. Some species rapidly establish an intricate, closely spaced network of thread-like interangular burrows within the surface layer of freshly placed sediment which is reinforced by mucus secretions (Cullen, 1973) and free-living marine nematodes of the genus *Ptycholaimellus* build membranous tubes from detritus bound by released mucus (Nehring et al, 1990).

De Deckere et al (2001) described the net effect of the estuarine meio- and macrofauna community on the sediment stability of muddy sediments at the Skeffling mudflat in the Humber estuary, UK after four days treatment of the sediment with an insecticide. The decrease of meio- and macrofauna densities in the treated sediments resulted in an increase of the critical erosion threshold of the sediment by more than 300 %, indicating a net destabilising effect of the whole benthic infaunal community but it was not possible to compare the degree of destabilisation effected by each group.

4. REVIEW OF EXAMPLE APPLICATIONS

This section of the report describes how the improved understanding, algorithms and expertise has been implemented in estuarine modelling applications.

4.1 The Mersey estuary

Lane (2004) examined the Mersey estuary which is one of three estuaries situated within a 50-km stretch of coast in Liverpool Bay (Figure 4.1). The estuaries are each exposed to similar conditions of macro-tides, storm surges and swell. While their bathymetries are of comparable size, their shapes are completely different (bay, inlet and funnel), as are their surficial sediments distributions. Results for the specific morphological developments were compared with generalized theories for the nature and rate of estuarine adjustments. Selected results for the Mersey are presented here and results for the contrasting estuaries of the Dee and the Ribble have been presented in the paper by Lane (2004).

Using a 3-D model that incorporates wave stirring and wave-current interaction (Soulsby and Clarke, 2004), the stability of the present hydrodynamic-sediment transport regimes was explored by looking at the roles of intervention (e.g., reclamation and dredging), wave exposure, marine sediment supply and rise in mean sea level (msl). Their likely future morphologies were also investigated based on scenarios of changes in msl, storminess (waves and surges) and river flows.

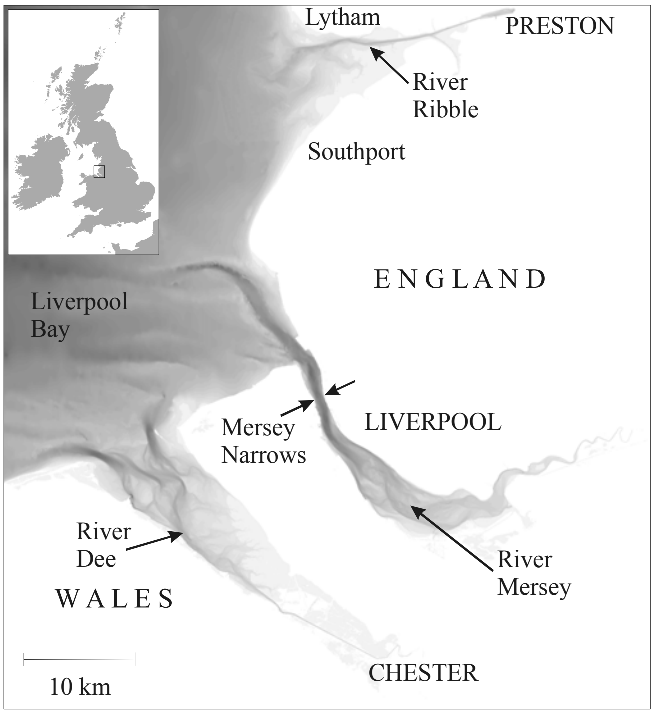


Figure 4.1 Location of the Mersey estuary studied by Lane (2004)

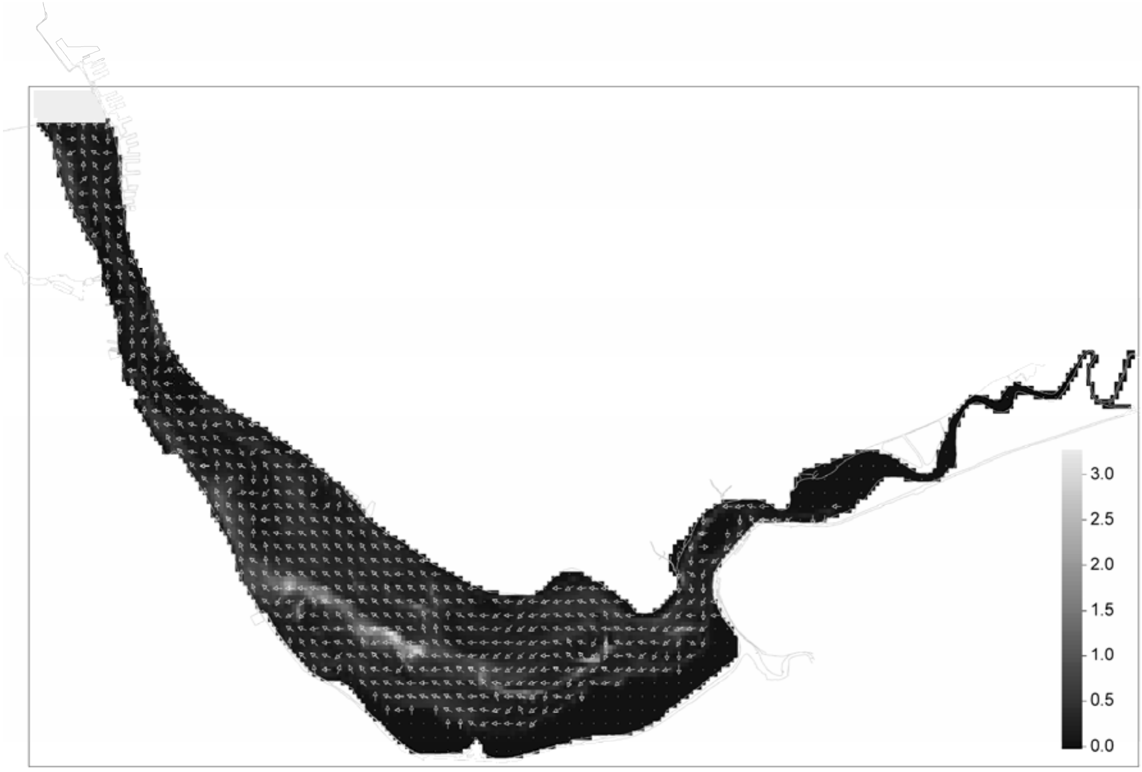
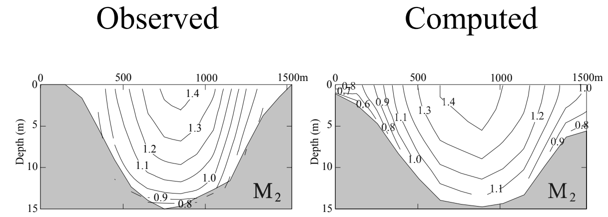


Figure 4.2 Residual currents in the Mersey Estuary near the bed from the high resolution 3-D model (in cm s^{-1})


Observed

Computed

Figure 4.3 Observed and computed M_2 current amplitudes across the Mersey Narrows in July 1992

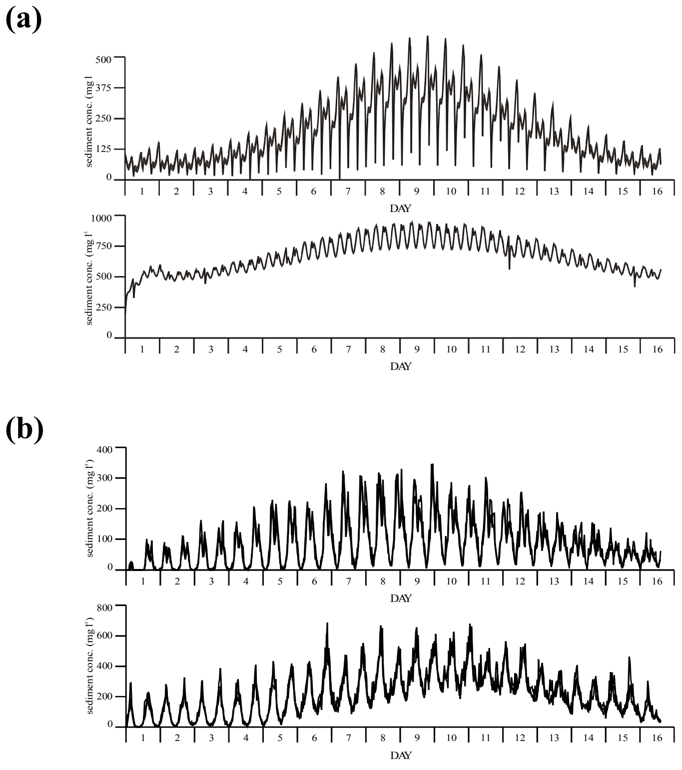


Figure 4.4 Suspended sediment concentrations in the Mersey Narrows from the (a) 1-D model, and (b) 3-D model for settling velocities w_s = 0.005 m s^{-1} (upper) and w_s = 0.0005 m s^{-1} (lower)

Close to the mouth of the estuary, the Mersey Narrows (Figure 4.1) is approximately 1.5 km wide with a mean depth of 20 m, and tidal currents through this section can exceed 2 m s^{-1}. This deep entrance channel, important for shipping, extends outside of the estuary and is kept in place by training walls. The inner estuary is much broader than at the mouth, and consists of mud and sandbanks with highly mobile low water channels. Freshwater flow into the Mersey Estuary, Q_f, varies from 25 to 200 m^3 s^{-1} with a mean flow ratio (Q_f × 12.42 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. Historically, the Mersey has been seriously polluted by industrial discharges and adjacent sea dumping. An ongoing comprehensive program has improved water quality in the river.

Tidal and other currents and bedload transport A range of studies have been carried out over many years for different purposes and using different approaches. Earlier field and physical model studies reported by Price and Kendrick (1963) had led to the conclusion that sediment transport at the bed was landwards into the estuary controlled by the longitudinal salinity distribution in the estuary. More recently, for example, Prandle et al (1990) described some earlier attempts at monitoring currents in this estuary using electromagnetic current meters mounted on a floating buoy. In a subsequent exercise, ADCP, electromagnetic and mechanical current meters were mounted on low-profile frames across a section of the estuary. Additional ADCP transects across the Narrows were made continuously over a 15-day spring-neap cycle. These towed ADCP data, once subject to appropriate transformation to an appropriate geographic reference frame, provided detailed 3-D spatial patterns of current ellipse distributions for the major tidal constituents.

In the EMPHASYS project, Spearman et al (2000) carried out 2-D and 3-D numerical modelling of flows and sediment transport in the Mersey, the 2-D model without salinity effects and the 3-D model with varying density. The 2-D results indicated a net seawards residual current whereas the 3-D model was able to simulate a net landwards residual current, similar to that referred to by Price and Kendrick. The results for residual currents and residual sand transport effects were compared. The sand transport patterns show significant differences when compared with the near bed residual current. This is because the direction of sand transport, especially bedload, is dominated by the higher peak current speed on the flooding tide.

In EstProc simulations of the whole-estuary near-bed residual currents were produced from a 3-D numerical model by Lane and Prandle (Figure 4.2) as part of a simulation of suspended sediments. This extends the earlier work on bedload referred to above and is discussed below in the section on suspended sediments.

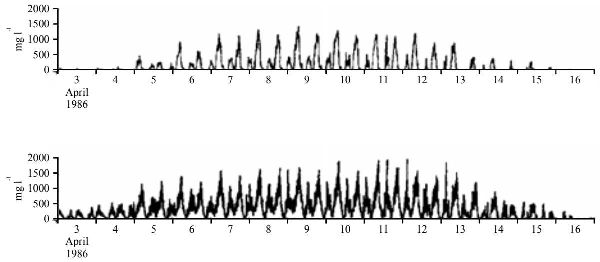


Figure 4.5 Observed suspended sediment concentrations in the Mersey Narrows at surface (above), and mid-depth (below)

Cross-sectional distribution Using a 3-D hydrodynamic model with a 100-m rectangular grid and 15 (sigma-coordinate) layers, the following results were obtained. The M_2 constituent (Figure 4.3) dominates the time series at the monitoring transect, having maximum amplitude of 1.5 m s^{-1}, and is almost rectilinear. 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. In the vertical profiles of the axial component of the above current ellipses along the transect line, the largest M_2 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 localized response to depth variations.

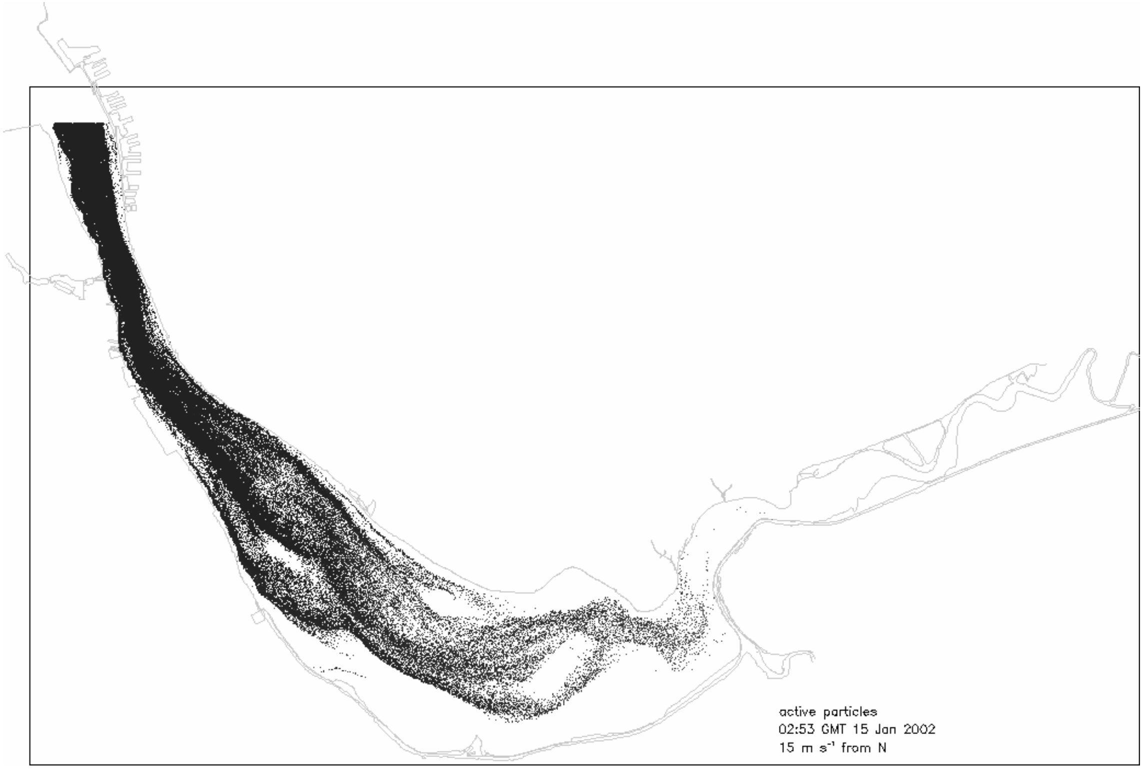


Figure 4.6 'Active' particles represent suspended sediments in the 3-D random-walk model. This model includes the effects of bed stresses due to fetch-limited wind-waves, which enhances the erosion of deposited particles

Suspended sediments Work on the bedload transport referred to earlier in this section was extended by Lane and Prandle who reported a specific model test on the influence of salinity gradients on suspended sediments. The results of adding salinity-related residual currents, indicated little change to the sediment regime relative to a Base-Line simulation. However, it is important to note that this result is peculiar to the seaward section of the Mersey and is not applicable to estuaries in general.

Figure 4.4 shows suspended sediment time series from models at the MIDAS (Mersey Inshore Data Acquisition Station) location in the Narrows. Observations of suspended sediment were made by the Environment Agency (NW) at the same location (Figure 4.5) (National Rivers Authority, 1995); analyses of these data are described by Prandle et al (1990). Time series of suspended sediments from a model for fall velocities, w_s, of 0.005 m s^{-1} (fine sand) and 0.0005 m s^{-1} (silt) are comparable with those in a recent study (Hill et al, 2003), which suggests a median fall velocity $w_s = 0.003$ m s^{-1}.

The 3-D random-walk model results (Figure 4.6) assume unlimited supplies originating exclusively from the mouth of the estuary, and can produce concurrent sediment import and export (Figure 4.7). Axial time series of suspended sediment indicate sharp initial peaks following flow reversal.

Concentrations of fine and coarse sediments depend on sediment supply (marine only here), consolidation, flocculation, bioturbation, a wide spectrum of w_s (i.e., particle types) together with feedback between sediment motions, bed forms and overlying dynamics. While this wide range of parameters may allow seemingly close reproduction of specific concentration time series, the likelihood of broader scale, long-term, accurate simulation of suspended sediment is much less certain. Moreover, suspended sediment concentrations depend on recent chronology providing erodible surficial sediments.

Uncertainties in simulating bathymetric evolution evidently depend on the long term temporal integration of spatial gradients in relative erosion-deposition budgets. Nonetheless, 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. Indications of such budgets illustrate how detailed processes within these models can be examined. Although not discussed here, the net quantities of suspended sediment entering the Mersey and the rate and spatial patterns of deposition (for $w_S = 0.005 \text{ m s}^{-1}$) are consistent with observations.

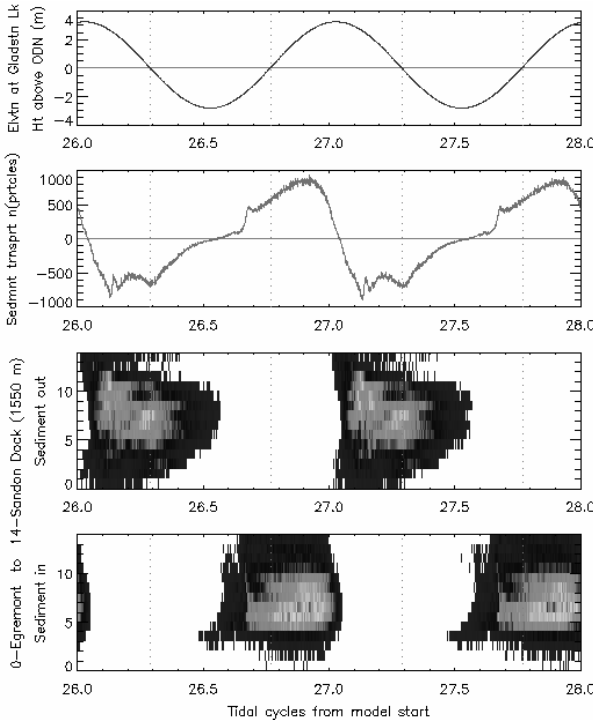


Figure 4.7 The top panel shows the tidal elevation, the second panel shows the number of particles crossing the Narrows (representing suspended sediment transport during the tidal cycle). The remaining diagrams show the spatial variation of particles crossing the line, moving upstream (in) and downstream (out)

4.2 Humber estuary

A study was carried out on the processes that govern the net transport of fine sediment in the mouth of estuaries and tidal basins in general, and of the Humber mouth in particular (Winterwerp, 2004). These processes have been identified on the basis of literature surveys and further analysis of data and numerical modelling results. From these analyses it is concluded that:

- The net sediment import into estuaries and tidal lagoons is largely governed by channel-shoal interactions. Moreover it is concluded that the water-bed exchange processes on these intertidal areas is much larger than commonly predicted with the current class of engineering models for cohesive sediment predictions.
- Further distribution of the fine sediments within estuaries and tidal lagoons is governed by temporal variations in driving forces and biological activity.

These analyses have partly been substantiated further through a sensitivity study with a 2Dh and 3D numerical model of the Humber estuary. All simulations yielded net import of fine sediment. It was concluded that:

1. Within the inner part of the Humber estuary, overtides are locally generated. The resulting asymmetry causes a net up-estuary transport of fine sediment.
2. The tidal asymmetry in the outer part of the estuary is sensitive to the tidal constituents prescribed at the model boundaries. When the 8 major constituents are incorporated, the asymmetry in peak velocity predicts ebb-dominant conditions in the outer estuary, whereas the asymmetry in slack water period predicts flood-dominant conditions.
3. Gravitational circulation increases the net import of fine sediment into the estuary by about 10 %. However, further into the estuary, the effect of gravitational circulation is much larger, and increases net transport rates by 60 %.
4. Intertidal trapping contributes largely to the net import of fine sediment. This contribution is very sensitive to for instance local (re-)erosion by waves. A moderate increase in wave-induced bed shear stresses, simulated through an increase in skin friction coefficient, yielded a considerable decrease in net sediment import. However, sediment transports further into the estuary increased considerably. See Figure 4.8 as an example.

The influence of gravitational circulation was included through algorithm EP21 in Reference TR3.

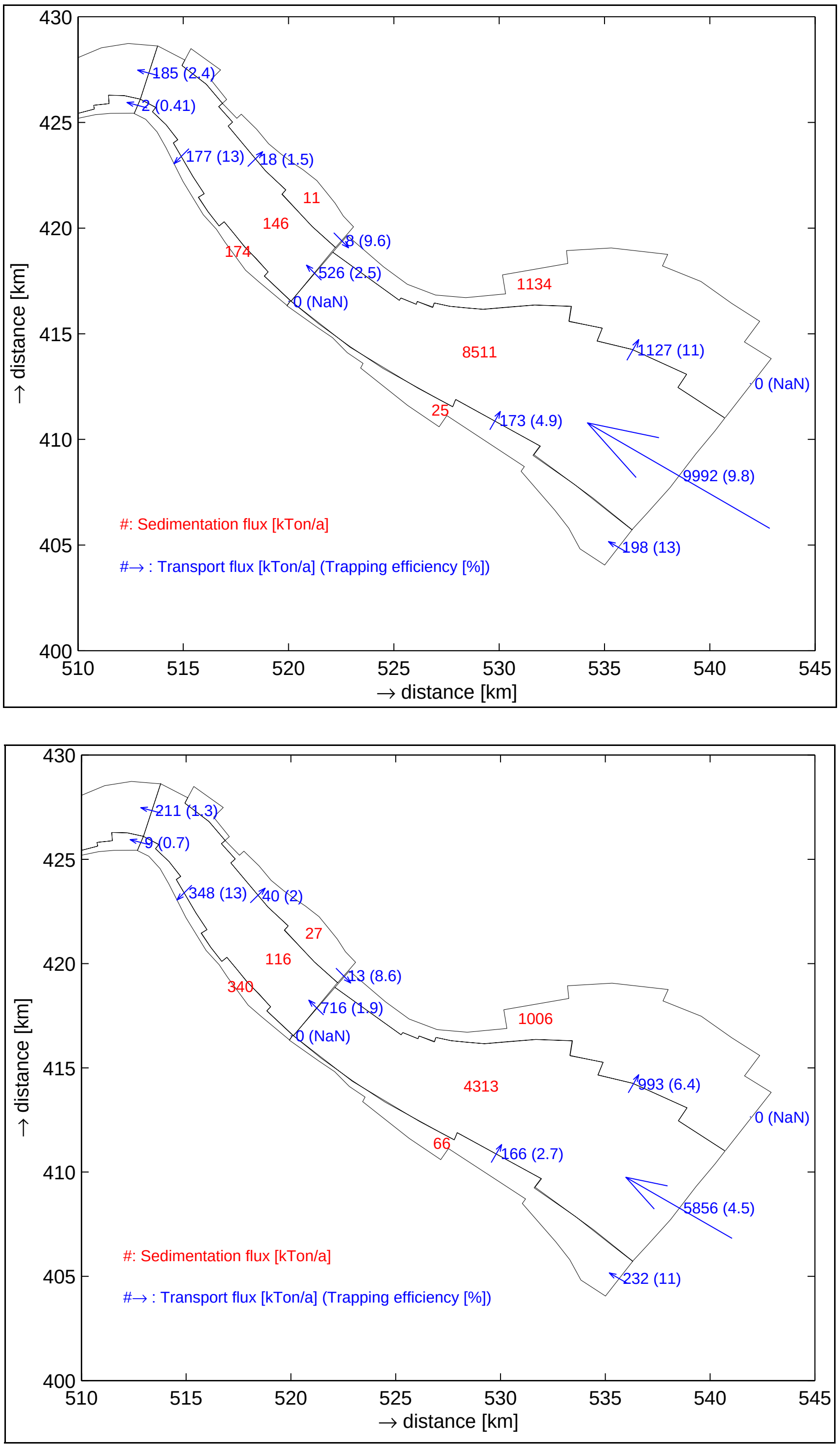


Figure 4.8 **Net fine sediment transport in Humber mouth computed with 2Dh model with smooth bed (k_s = 1 mm, upper panel) and rough bed (k_s = 10 mm, lower panel)**

4.3 Implementation of EstProc algorithm for settling velocity in an estuarine numerical model of the Thames estuary

Work was done to implement the Manning (2004) algorithm for the settling velocity of mud into a 3D computational model of estuarine hydraulics and sediment transport (TELEMAC3D, developed by EDF-LNHE). For these studies an existing model of a length of the Lower Thames estuary was chosen (Figure 4.9). This model was of interest because it had already been used for comparison of simulated sediment distribution with detailed sediment concentration measurements using the ADCP acoustic backscatter method Sediview.

The model results with the Manning algorithm included were compared to runs with (1) a constant settling velocity of 0.5 mm/s and (2) settling velocity based on a simple linear multiplier of concentration and with the above mentioned observations (Baugh, 2004). The results are presented in Figure 4.10.

The main conclusions of the implementation exercise were:

- The predicted pattern of sediment concentrations in a tidal situation is dependant on the settling velocity assumption.
- It is feasible to implement the new and more complex relationship between settling velocity and concentration in a 3D computational model of estuarine hydraulics, without producing any significant increase in model run times or reducing model stability. This was raised as a potential drawback of including new algorithms in Section 3.1.1, but in this case there was no negative impact on the model run time or stability.
- The use of the algorithm improved the reproduction of the observed distribution of suspended concentration both in the vertical and horizontal directions compared to the other simulations.
- The application of the algorithm to the Thames suggests that the algorithm is generally applicable to estuarine mud transport modelling. The large amount of data from three estuaries, not including the Thames, used in the algorithm establishment means that it represents the best presently available method for simulating settling velocity and should be used routinely. The sensitivity of predictions made with this algorithm should be evaluated and, as with any modelling exercise, validation data of the predictions will be required.

From this implementation exercise it has been shown the new method by Manning provides a physically based approach to predicting sediment settling velocity. It is, as stated above, not more computationally expensive to use the new approach but it is more complex to code than a relationship proportional to concentration. The inclusion of effects of salinity and pollutants would be an additional refinement. The simpler fall velocity proportional to concentration approach requires *in situ* data to calibrate it for the specific estuary – this approach lumps everything into a coefficient of proportionality and a power (which may be 1, i.e. linear). What is clear is that whichever method is used then some *in situ* data is required to set coefficients or validate the method. The new method gives more scope for exploration of the key parameters.

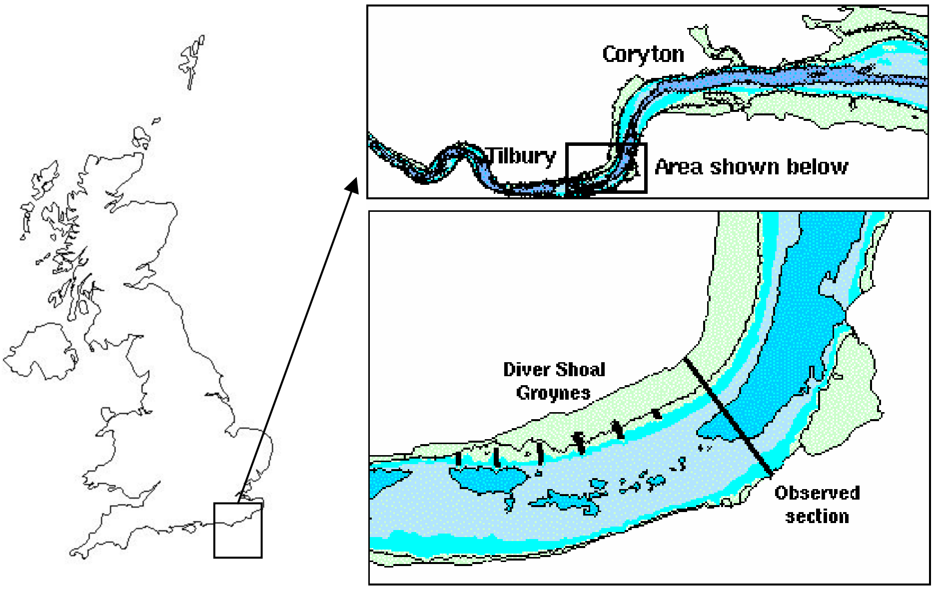


Figure 4.9 Figure showing location of study area in Thames modelling

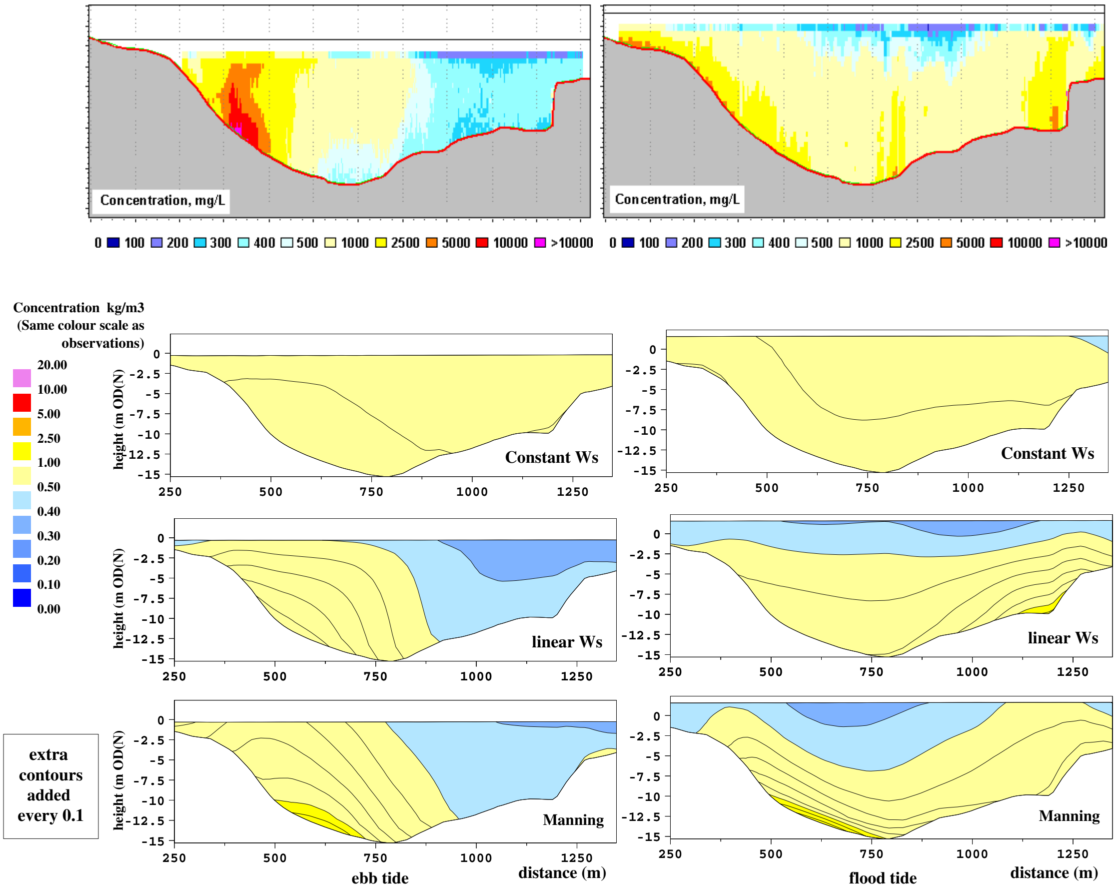


Figure 4.10 Effect of including the new EstProc representation (Manning) of settling velocity on the cross section distribution of mud concentration. The top two panels are the observed concentration field (units: mgL^{-1}) and the bottom six panels are the computed concentration field (units: kgm^{-3}) with the three different settling velocity models. [note: 1 kgm^{-3} = 1000 mgL^{-1}]

4.4 Inclusion of EstProc algorithms for modelling mud transport on tidal flats into a 3d mudflat model

As part of the EstProc a number of algorithms have been developed relating to tidal mud flat processes (EstProc Consortium, 2004a). This section summarises some of the application, relevance, and sensitivity issues surrounding the algorithms relevant to mudflats developed. This work has been carried out in order to kickstart the examination of their practical usefulness and provide some value-added algorithms to the end-user as a result.

The methodology chosen in the study has been to model the suspended sediment (mud) transport for a typical mudflat scenario from the simplest basis and to add complexity (i.e. add the algorithms developed in the EstProc Project) one by one. This process allowed some identification of the issues of applicability, relevance, data and sensitivity. In addition, to allow the effect of the algorithms to be evaluated in the context of applied modelling, the sensitivity of the model results to using different numerical approaches such as 2D/3D modelling and the number of 3D layers used was also examined.
The conclusions of the study were that the inclusion of the Winterwerp algorithm involving simultaneous erosion and deposition *in combination with* a reliable estimate of settling velocity (such as the Manning algorithm) had the largest impact when modelling the erosion arising from more significant wave action. For smaller waves, where suspended sediment concentrations induced by wave action are lower, numerical considerations such as choice of 2D or 3D model and the number of layers included in the latter, appeared to be the most significant factors on the prediction of erosion on mudflats, although varying the sediment erosion parameters, as affected for instance by biology, also had a very significant impact on the resulting prediction of erosion (illustrated in Figure 4.11 below).

The report by Spearman (2004) provides more details and results than are summarised here.

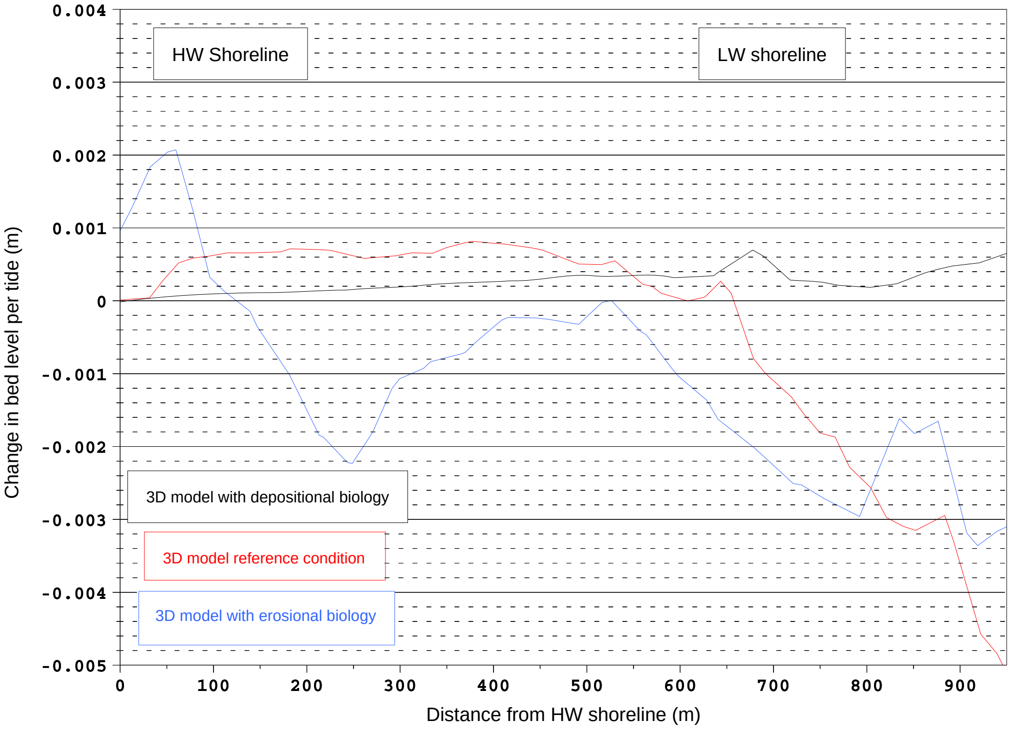


Figure 4.11 Comparison of predicted erosion on the mudflat profile for different biological scenarios: (Depositional biology: high population of Microphytobenthos, Erosional biology: high population of *Macoma*)

5. RESEARCH RECOMMENDATIONS

EstProc produced user-oriented algorithms describing hydrodynamic, sedimentary and biological processes in estuaries and their interactions (EstProc Consortium, 2004a). These were presented for stand-alone use in desk study application and for ready inclusion in computational models, as indicated in the present report. EstProc also produced a range of process concepts and less well developed algorithms reflecting a higher level of uncertainty or lack of information in particular areas. One strand of these research recommendations is to take the existing outputs at this level and develop them to working algorithms for implementation in models. The biological influences are now better understood but more integration of the hydrobiosedimentary elements is needed to allow regular implementation of biological effects. There are also some regional studies that need to be tackled which will demonstrate how the hydrobiosedimentary process parameters apply in the estuaries of England and Wales.

Following on from the recommendations of the EMPHASYS Consortium (2000a) the basic headings of data collection, monitoring and research, including model development, is adopted. On the modelling front the process work continues to bolster the capabilities of models predicting processes but also continues to develop the existing links across to ERP2 Broad Scale Modelling projects on hybrid morphological modelling. Phase 2, of which EstProc was a part, comprised the improvement and combination of the best methods, together with new fundamental research. The next levels of development are within a continuation of Phase 2 and also Phase 3, which comprises the development of new, cross-fertilized methods based on the results of the fundamental research from Phase 2.

On the modelling front process work is needed to continue to bolster the capabilities of models predicting processes, but also continues to develop the existing links across to ERP2 Broad Scale Modelling projects on hybrid morphological modelling.

There is also continuing work which needs to be integrated into EstProc and developed forwards to help solve outstanding problems and provide a robust set of procedures for answering awkward practical problems.

The main issues to address are:

- Development of additional process concepts already developed within EstProc (FD1905) up to the level of working algorithms for feed to Broad scale modelling / Engineering projects (FD2107 and FD2117);
- Wider application of existing (FD1905) and new algorithms within 'bottom-up' process models; and,
- Framework for assessing relevance of algorithms at regional scale and links to existing national databases to ensure maximum interoperability at time of delivering [5]ERP EIAS and EMS.

The outputs will be improved techniques, demonstration of uptake in operational models, generic/regional indicators. It will place the research in the context of existing

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[5] Estuaries Research Programme Environmental Impact Assessment System and Estuary Management System

data initiatives and frameworks and build directly towards the ERP EIAS and EMS to be developed within ERP.

It will support process studies for engineering projects such as the response to 'managed realignment' of the coastline, modelling and exploitation of marine data interoperability to support the statutory requirements of the Water Framework Directive, and extended investigation of Global Climate Change scenarios.

The project can only make recommendations – it is up to the funders programmes to be able to take this forward. Thus there is a continuing risk that new research on estuaries will fall into a gulf between research council funding on rivers, coasts and shelf and the end-user focus of the Defra/EA programmes.

5.1 Broad approach

The proposed research takes three main strands as outlined above. The first and second strands keep the momentum of the current EstProc project and parallel initiatives to extend the science achievements. To take advantage of the recent advances the ongoing research needs to include the following approaches:

- Mining and analysis of existing datasets to develop algorithms. There will be a need for some new process studies data to develop, extend, calibrate and validate the existing algorithms; and,
- Methodology development and process modelling on contrasting ERP designated estuaries to demonstrate implementation of algorithms extending the range of scenarios that can be modelled and the impact of their inclusion on predictive capability.

There are a number of important areas which can be advanced with the further R&D, these include:

1. Incorporation of vegetation and biota into models. Further quantification on the feedback between vegetation and sediments using modelling and data mining of existing datasets;
2. Generalisation of the behaviour of real estuarine sediments building on the geotechnical and hydraulic insights generated within EstProc;
3. Measurements for validation of sediment transport process models including long-term monitoring of tides, waves, river flows, sediment and salinity concentration;
4. Developing sediment budget analysis and framework determining the relative roles of biology, waves, tidal asymmetry, accumulation of sediments and the role of benthos/vegetation [extends the work proposed for FD2116 which is essentially a review of presently available methods within a consistent framework];
5. Improving the understanding of the interaction of tidal flats and channels. A better understanding of the exchange processes, magnitude and timing of sediment exchanges is needed including assessing the role of river discharge and weather and tidal harmonics generated within the estuary. This can be achieved using data analysis and process modelling from contrasting estuaries.
6. Extending the existing estuary sediment floc database to allow prediction in saline conditions throughout the estuary and out to the sea. Determining the role of biology and biochemical properties in floc and bed properties through further laboratory and *in-situ* measurements.

7. Application of process models within contrasting selected estuaries to investigate the applicability of the algorithms. This will need to consider event sequencing and probabilistic approaches, and further development of and implementation of ensemble techniques for process modelling.

The third strand extends the uptake of EstProc into application methods and interpretation. This brings together the improved process understanding with ongoing monitoring initiatives and includes empirical approaches, including a high level screening of the key hydrobiosedimentary parameters expected to be significant.

1. Combination of existing hydrodynamic, sedimentary and biological parameters using GIS based techniques operating at the estuary level, and building on existing databases including EMPHASYS-ERP uptake, Futurecoast, JNCC, EA/Defra, BGS. The relative role of riverine sources, coastal sources, and internal erosion in the estuary to topographic change should become apparent in this.
2. Schematic mapping out of zones of particular 'bioengineer' organisms to establish range of influence around coast of England and Wales. An example of the approach could be development of categories of tidal response building on EC INTRMUD concept of spring low water timing in daylight hours, as well as and the budgetary analysis at regional scale done in FUTURECOAST.
3. Generalisation of estuarine suspended sediment concentrations and threshold values leading to relationships between physical effects and biological parameters. Predictions of patterns of biota in estuaries in relation to physical factors will be facilitated by further research on what parameters, or combinations, need to be measured or estimated.

It is expected that demonstrable progress can be made on a substantial portion of the above within a 3-year carefully structured programme of work. The work can be completed by an appropriate consortium building on the significant expertise contained within the EstProc consortium (www.estproc.net) and other research initiatives on process and data initiatives and frameworks. An appropriate consortium or managed network of smaller projects should be drawn together to deliver the research;

Some of the work may link into other work funded under Defra/EA Broadscale Modelling Theme and into Research Council programmes (e.g. building on NERC FREE – Flood Risk in Extreme Events) and other research council grants. The Defra/EA R&D programme needs to facilitate the completion of the necessary process work to ensure that it is not overlooked. It will map out and add value to those marine data initiatives and frameworks being operated within the UK for river, estuarine and coastal areas that are relevant to the screening and application of the EstProc process algorithms.

5.2 Supporting initiatives

The above research needs to be supported by implementation of up-to-date and novel technology. This should include:

- Further development of remote sensing approaches, e.g. building on repeat airborne imaging spectrometry, ground-truthed with field spectra, which has been used to establish patterns of suspended sediment dynamics on rising tidal stages at the managed re-alignment site at Tollesbury. Development and generalisation of existing analytical vertical sediment profile algorithms to provide full water depth predictive capability from remotely sensed data;

- Measurement techniques for short term (hours / days) and long term (months / years) changes in intertidal sediment levels. This is essential information for the validation of the next generation of models of estuarine sediment dynamics and morphology. For example, this may be achieved by deploying a new sediment level sensor under development by PML.
- Establishment of a quantitative criterion-based framework for evaluation of model calibration and performance, building on existing approaches, that is appropriate to estuary modellers and end users of the results.

There are a number of initiatives that are appropriate for possible Research Council funding. These would increase the general level of understanding, assist the development of new conceptual approaches, and improve interpretation of models. These include further investigation, quantification and determination of:

- The effects of waves on levels of turbidity within estuaries – their potential influence on the turbidity maximum and on intertidal, mudbank morphology;
- The effect of waves and tidal currents on sediment erosion and deposition in shallow estuaries with the aim of establishing the relative importance of intermittent vs persistent events (i.e. waves vs tidal cycles);
- The importance of the initial flooding and final ebbing over mudflats (i.e. shallow water depth of <10cm) in transporting sediment. Investigations into the importance of drainage from intertidal areas in transporting sediments;
- The impact of a wider range of key biota (than studied in EstProc) on intertidal sediment dynamics and assessing their role as ecosystem engineers on the estuarine mudflats;
- Benthic structure and function along estuarine gradients of declining biodiversity to test hypothesis that there is less replication of ecological function in the low diversity region and therefore more vulnerable to loss of key species;
- The importance of biota in remobilising historically contaminated sediments (bioturbators) or sequestering contaminants (biostabilisation), and the impact of contaminant remobilisation on water quality;
- The influence of a wider range of intertidal biota on flow, erosion and deposition (e.g. *Salicornia*, Mussels), particularly the combination of biostabilisers and destabilisers occurring on intertidal mudflats;
- Incorporation of algorithms for bioengineering of sediments and flow into models of long term changes in estuarine morphology involving feedback between tidal currents and bathymetry. For example to more widely assess the impact of biota on equilibrium shore profiles;
- Detailed measurements of cross-estuary subtidal and intertidal water and sediment properties (e.g. calibrated mini-flumes) to investigate the water-sediment dynamics of mudbank and mudflat morphology;
- Measure turbulence (ADV + other instruments) within freshwater-saltwater interface to examine influence of stability on turbidity maximum and salt intrusion;
- Utilise remote sensing data to examine estuarine turbidity; and,
- Continue to classify turbidity and salinity in contrasting estuaries.

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Appendix 2

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