ESTUARY PROCESS RESEARCH PROJECT LINKING HYDRODYNAMICS, SEDIMENTS AND BIOLOGY (*ESTPROC*)

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ABSTRACT
This paper discusses a major research project on estuarine processes within the DEFRA/EA R&D framework of Fluvial, Estuarine and Coastal Processes. The ***EstProc*** project brings together a multi-disciplinary team to undertake innovative research on estuarine hydrodynamics, sediments and biology and their interactions. The 3 year research project is being undertaken by a project team comprising 11 partners drawn from the UK and Netherlands. The paper describes the objectives and the agreed approach to the research and summarises some of the thinking at the mid-point of the project. More information about the project is available from the web site http://www.estproc.net/ .

INTRODUCING THE PROJECT
The DEFRA funded Estuary Process Research project (EstProc) was initiated in December 2001 and has the following stated objectives:

- Innovative and fundamental research in estuarine hydrodynamics, sediments and biological interactions (hydrobiosedimentary); and,
- Improved underpinning knowledge and sound scientific results for the estuary research community and end users of the tools and methods used.

The specific scientific objectives of the project are categorised under Hydrodynamics, Sedimentary Processes and Interactions between Biological and Sedimentary Processes. The research aims to improve knowledge relating to the calculation of water flows and the sediment stirring and transporting mechanisms, which can be incorporated into modelling tools and design methodologies improving their performance. In turn the knowledge about the interaction between the biota, the waves, currents and the sediments will be developed. The outcomes from this hydrobiosedimentary research will contribute to the estuarine knowledge base and yield improvements in existing predictive tools for understanding the movement of water and sediments in estuarine environments. These outcomes are directly relevant to the prediction of morphology change and water quality and the long-term goal of developing an Estuary Impact Assessment System. The project recognises the prioritisation of research (French and Townend, 2001) arising from the EMPHASYS project (EMPHASYS Consortium, 2000). These are the topics where greatest advances can be made, and where the present predictive capabilities are most limited.

A multidisciplinary approach has been applied to achieve the objectives because real advances can be made from an integrated team effort. This allows focusing on specific problems where the disciplines interact and to capture significant feedback between the various processes. All estuarine processes include important elements of all 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 input of biologists and sedimentologists is necessary at all stages of an investigation to ensure that these factors and their limits are properly defined. The activities within the project are detailed in the Inception Report (HR Wallingford, 2002).

Some key integrating objectives have been defined which will keep the project focussed:

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[1] The EstProc Research is carried out by: HR Wallingford Ltd; 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, NL; Plymouth Marine Laboratory; University of Cambridge, Cambridge Coastal Research Unit; University of Southampton, School of Ocean and Earth Sciences; Digital Hydraulics Holland B.V., NL; and, Centre for Environment, Fisheries and Aquaculture Science.

- **Tidal flat sedimentation** – a key environment in which the research results must be demonstrated to operate in a harmonious fashion;
- **Mudflat-saltmarsh interactions** – a key area of the estuary fringe for fluxes of water and sediment, and a role as high water storage;
- **Integrated morphological modelling** – a key tool for implementing the new research findings and assessing their suitability in the subtidal and intertidal reaches of estuaries;
- **Estuary wide modelling** – recognising the importance of being able to model fluxes of water, sediment and wave energy across the whole estuary;
- **Modeller/process scientist interaction** – the benefits of numerical modellers and process scientists, those people trying to understand the fundamental processes in the laboratory and the field are recognised; and,
- **Data** – interrogation of existing datasets; this is a recurring theme throughout the research.

The paper proceeds to discuss various of these aspects, to outline the current thinking of the research team at around the mid-point of the project (March 2003), and to summarise the expected outputs.

THE TIDAL FLAT ENVIRONMENT AS A VEHICLE FOR INTEGRATING THE RESEARCH

The benefits to estuary managers of the new and innovative research within the EstProc project will be identified both in terms of improved knowledge and in the provision of tools (models and methods) with more accurate component parts representing the physical processes in hydrobiosedimentary interactions.

One key area where the biggest gains can be made is in the understanding and representation of processes on tidal flats. The broad inter-tidal zones fringing the meso- and macro-tidal coastlines of many countries in mid-latitude form an integral and important part of estuarine and coastal systems. These areas comprise extensive low-slope flats, often associated with a shore-connected marsh system. The transportation of sediment is a ubiquitous feature of these muddy and extensive environments. The formation and destruction of floc aggregates from fine-grained sediments and their transport across tidal mudflats provides the mechanism through which sediment is exchanged between the high shore region and the sub-tidal zone. There remain significant gaps in knowledge. The hydrodynamic-biological-sedimentary processes visibly interact and it forms a fertile location for research into those areas which require further attention and multidisciplinary integrated assessment within EstProc.

A complete and detailed description of these processes in one numerical model is not yet feasible, and would also require large computational efforts. Therefore, a parameterised approach is more appropriate, the results of which will yield algorithms to be implemented in engineering tools. An obvious approach is to start with an equilibrium analysis of the various descriptions and such work is being undertaken in the project.

THE BENEFITS FROM MODELLERS WORKING WITH PROCESS SCIENTISTS

In EstProc one of the identified objectives is to facilitate the multidisciplinary interaction between field/lab researchers and modellers[2] to better enable the overall objective of providing improved but relevant science for the end-user. The potential benefits of this interaction are high as small-scale processes in biology and sediment behaviour are likely to significantly influence the larger scale sediment transport, tidal currents and waves as well as each other. It is clear from the exchanges so far within the project between process scientists and modelling scientists that this has facilitated the tailoring of research output for modelling purposes and enhanced the confidence of modellers in using currently available research data. 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.

When considering the addition of complexity (whether “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?;

[2] Both represented in the project

- Is the data contemporary?;
- Is the data/algorithm site-specific?; and,
- Is the effect of including the data/algorithm significantly beneficial when compared to the uncertainty already contained within the model?

The first four of these questions are more or less common sense (although frequently overlooked) but the last question is fundamental when trying to move from a process-based understanding to inclusion of a specific mechanism in an estuary model.

INTEGRATED HYDROBIOSEDIMENTARY MODELLING SUPPORTING MORPHOLOGICAL MODELS

Models which predict morphological change are a logical end point for all the research on estuarine processes. It is important therefore to ensure that knowledge and algorithms developed within the project fit within a conceptual framework that can be used within actual model systems for predicting estuary hydrodynamics, sediment transport and morphological change. The challenges are not insignificant.

A first important aspect of such a framework is to group processes according to the time-scale under consideration, and to decide on the smallest time- and length scales that needs to be resolved within the simulation system. For estuaries, the smallest timescale to resolve is that of the tide and short-term events and the smallest length scale that can be resolved in a practical sense is the scale of the major channels and shoals and that of man-made structures. In Figure 1, the group of processes acting together on this scale is depicted in the central area of 'Intra-tidal, intra-event processes'. These processes interact in so many ways that a tight coupling at the level of the flow model time step is necessary.

The lower block in Figure 1 deals with the dynamic updating of the bathymetry, the bed composition and the vegetation at the morphological timescale. This timescale may be short in some cases, for instance during storm events. In such cases the 'Upscaling' may be left out, and the three processes in this box may be coupled directly to the processes in the central box. When the morphological timescales or the timescales of interest are much longer, some upscaling techniques are required, such as using a (neap-spring) tide-averaged approach, a technique known as an 'elongated tide', or simplified updating techniques applied to the averaged sediment transport.

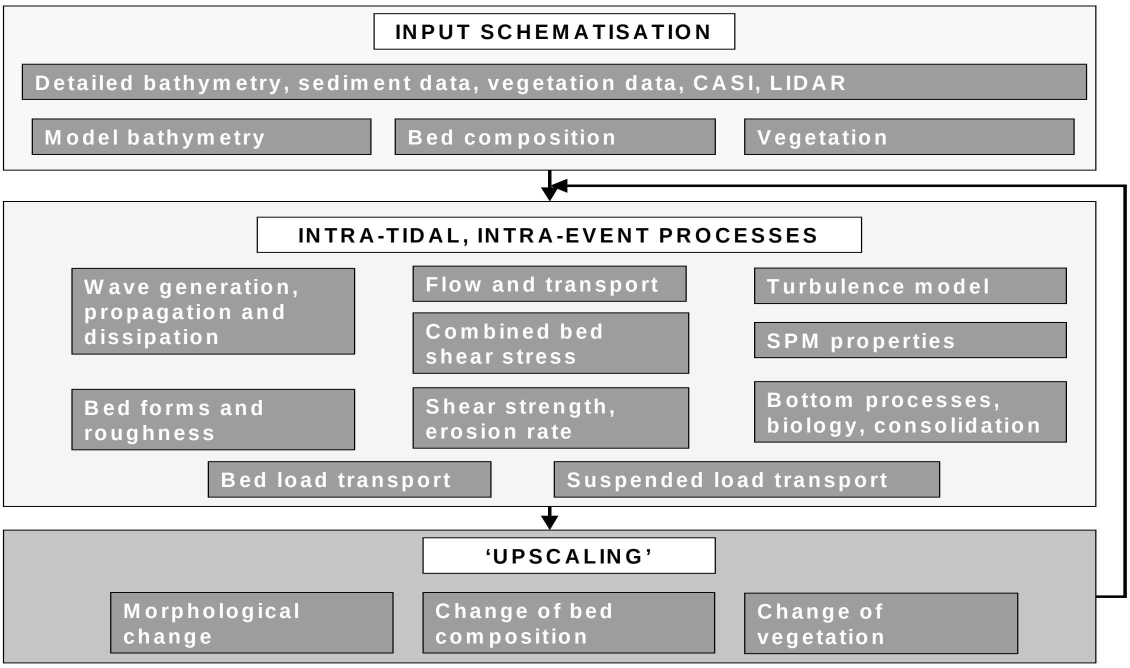

Figure 1 Integrated hydrobiosedimentary modelling approach

An appropriate input schematisation must be prepared in the topmost block of the diagram to feed through in a way that can support the choice made for the lower block. The input definitions to this block are usually carried out off-line, and deal with the representation of the estuary wide bathymetry including dendritic gully structures, the selection of representative tides, and wind and wave conditions.

The practical implementation of results from the research will concentrate on the following items:

- Testing algorithms within existing model environments such as Telemac (e.g. Stour-Orwell model) and Delft3D (e.g. Humber model);
- Investigating the interactions between processes and assessing their combined behaviour;
- Testing the influence of individual process refinements on the overall morphological behaviour of selected estuaries, for which morphological models are available to the research team; and,
- Provide recommendations for building or improving integrated model systems based on the experience gained within the project.

ESTUARY WIDE MODELLING

Estuaries are complex and important areas where changes made by man have in many cases modified significantly the natural systems. It is apparent that a change in one area will have impacts elsewhere within the system through a chain of 'change and response'. There is a continuum of change, with the governing processes altering in emphasis and importance both in time and in space. It is possible to consider three main estuarine environments (Figure 2) – subtidal reaches of the estuary, intertidal sand and mudflats, and fringing saltmarsh – discussed above. Advances in understanding the interconnections between them is being achieved through exchanges of knowledge, and use of data for particular estuaries, e.g. the Humber where there is a large multidisciplinary dataset already available. Where appropriate existing wave-current-sediment process models are being adapted as necessary and used to test algorithms and explore the sensitivity and relative importance of particular processes or interactions. Exploration of modelling concepts will be carried out by the project team, and through the application of simple models EstProc will assess the role of particular factors.

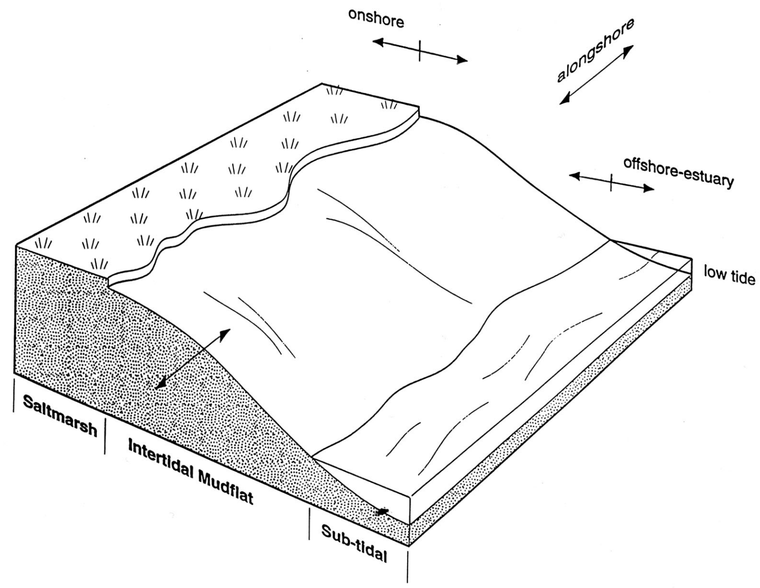

Figure 2 The estuary fringe

For many practical applications it is necessary to predict the spatial distributions of both currents and waves in the estuary, not only in the deeper channels but also, as mentioned above, over the shallow banks and intertidal areas. Local wave generation can be important and dependent on fetch lengths which can vary considerably with the tidal level. The influences of shallow intertidal areas and the variations in marsh morphology/geometry and vegetation composition on wave and current energy dissipation need further assessment. Processes acting in these areas exert an important influence on sediment transport in the whole estuary. Improved methods for the determination of surface roughness and energy dissipation on intertidal surfaces are required taking account of processes acting at different scales. Specific process studies will address these issues and assessments will be made using computational models for waves and tidal currents appropriate to the estuary-wide scale.

The numerical wave model SWAN has been applied widely in coastal and estuarine areas. In general the results for significant wave height H_s are good, those for wave period a little less so and the shape of the spectrum is still unsatisfactory. Within EstProc SWAN needs to be validated for some British estuaries.

The outcome of the research will be improved knowledge, understanding and improved predictive algorithms for application by estuary modellers (i.e. to improve the 'bottom-up' model category defined in Phase 1 of the Estuaries Research Programme). The sources of uncertainty will be considered and the relevance of the different processes at longer timescales and the role of extreme events will be assessed. The research directly underpins improvements in assessing and managing risk.

Wave propagation, dissipation, role of vegetation including morphology of high water zones
Over the last decade at the estuary scale there has developed a greater awareness of the potential role of wind-waves within estuaries and ideas on how they may drive morphological change. There are now some wave-tide datasets for certain estuaries that will help calibrate models of wave activity, and wave - tide interactions within estuaries. The more extensive datasets show oscillations between periods of rapid mudflat accretion and saltmarsh progradation and periods of mudflat lowering and saltmarsh retreat. The linkages between changes in wind-wave climate and changes in the position of intertidal mudflats and saltmarshes will be examined in the project.

Recent research has shown that saltmarshes are extremely efficient dissipaters of incident wave energy under 'normal' energy conditions; current work is focussed on better establishing the 'distance from marsh edge' pattern to dissipation under different marsh edge and surface morphologies. Further integration of existing datasets is needed to better define how dissipation is influenced by variations in marsh position in the tidal frame, marsh surface morphology and geometry, saltmarsh floristics and community structure (and its annual variability) and marsh seaward edge characteristics. There is also a need to define the hydrodynamic thresholds between the efficient dissipation of wave energy by vegetated surfaces, and the efficient binding and retention of intertidal sediments by plants and their root systems, and the break up and erosion of vegetated surfaces and the release of sediments as these thresholds are overcome. These issues also link into the large scale estuary responses to wind-wave regime change, and the role of extreme wave and water level conditions in estuaries.

Research leading to the improved specification of surface roughness, and the better parameterisation of the structural characteristics of low vegetation canopies, will be made for modelling applications.

Dendritic channel models
The term dendritic refers to a 'tree-like' channel branching network, as found on intertidal areas and saltmarsh systems within estuaries. Such features are formed by tidal run-off and can have up to four levels of branching involving several kilometres of channel length. In estuaries where a significant proportion of the intertidal area includes such channels, it has become increasingly important that they must be represented in numerical models. Many existing modelling techniques are unable to resolve the channels without increasing model run-times. Hence an alternative approach is required to reproduce discharge and storage within these channels.

The first step in developing a procedure has been to characterise the form of the channels. Over recent years there have been increased applications of the LiDAR remote land survey technique; for example, in the Humber Estuary there is complete coverage of intertidal areas with elevations typically quoted to 200 millimetres or better.

The next step involves the calculation of discharge and storage characteristics for the channel network. One method that has been tried is to produce realistic flow through grid cells by characterising the sub-grid bathymetry as a simple channel flowing between grid-nodes. An alternative approach uses a detailed hydrodynamic model of the channel network to obtain a time-dependent discharge relationship. This result could then be parameterised for use in the coarser, estuary model with the discharge in the dendritic channels represented by a series of sink / source terms. The merits of both approaches are being assessed in the project. Trials for interfacing the resulting algorithms into numerical models will be undertaken using case study data sets from the SE of England where previous modelling has attempted to resolve sub-grid scale processes.

Role of extreme events and rapid change scenarios
An improved understanding of extreme events in estuaries requires interrogation and analyses of data records for estuary hydrodynamics and morphology to assess the impact on flow, wave and sediment transport. An analysis of existing long-term datasets of water levels and waves will be undertaken in terms of joint-probability of occurrence. The inclusion of river discharge is important because extreme fluvial events can produce a shift in the estuary dynamics which in turn influences the sediment transport regime and sedimentation patterns, possibly generating effects that persist for some considerable time. In addition it may be possible to undertake some scenario modelling and the role of estuary storage in extreme extents will be investigated.

The models and methodologies developed will seek to account for uncertainty in:
(i) the model algorithms;
(ii) the associated empirical/parameterised coefficients;
(iii) the 'forcing' agents and event structure; and,
(v) potential anthropogenic impacts.

The impact of large tides and high runoff conditions on water levels, salinity, currents and suspended fine sediment concentrations and transport for selected data sets will be examined. However, analysis will be limited to the few examples of long-term measurements in estuaries that simultaneously capture the behaviour of velocity, salinity and suspended solids during extreme water levels (such as might arise due to large spring tides in combination with high runoff events).

The effect of sudden changes to estuary form and shape on salinity distribution and water / sediment circulation patterns will be investigated both from theoretical aspects and via analyses of data and modelling of specific estuaries (Tamar, Humber, Mersey). The rapid change of saltmarsh 'leading edge' will be investigated and the determination of thresholds to marsh edge erosion and retreat will be established through comparison of tide -wave datasets with repeat surveys of marsh edge morphology.

SEDIMENTARY PROCESSES

Parameterising sediment processes in estuarine system models
The hydrodynamic processes of interest include, but are not limited to, variations in currents, water levels, temperature and salinity distribution and the generation, and propagation of waves. In addition, improving wave modelling in estuaries and developing methods of impact prediction for extreme events on morphology and hydrodynamics are considered to be of paramount importance. Ideally, the methodologies generated should incorporate some capacity to propagate uncertainty (e.g. data, model, process and statistical uncertainties). The models and methodologies should also be shown to be calibrated and validated where possible (i.e. subject to the availability of suitable data).

In estuary models, taking the example here of models predicting mud transport, the mud is often defined by as few as four input parameters:
- threshold shear stress for erosion τ_e;
- erosion rate constant m_e;
- threshold shear stress for deposition τ_d; and,
- settling velocity w_s.

More sophisticated models may introduce extra parameters to describe the consolidation process (allowing temporally variable thresholds for deposition and erosion), flocculation (allowing temporally variable settling velocity) and fluid mud behaviour (Figure 3). The range of realistic values for these parameters produce changes in sedimentation/erosion that can vary by up to 2 orders of magnitude. In order to produce reliable model predictions the values of the sediment parameters are often calibrated against measured dredging volumes or historical changes in bathymetry as well as observed suspended sediment distributions. The effect of biology and chemistry and other complex processes on sediment are therefore included indirectly and empirically at this stage. Introducing specific biological algorithms into the modelling may potentially increase the accuracy of the modelling. However, the use of more algorithms introduces more parameters into the model possibly increasing rather than reducing uncertainty in the results. Furthermore even if the effect of introducing more complex algorithms is demonstrated to be beneficial, the corresponding increased complexity / run times may outweigh the benefit.

It is often assumed that the increasing speed of computer technology allows the numerical modeller to increase the number of small-scale interactions within his / her model without compromising the requirement for feasible run-times. Whilst this is true it is also accompanied by the competing requirement to include more of the natural variation in natural conditions – waves, tides, freshwater flow – in the assessment of overall change within estuaries so that the number of model simulations required per study is increased. Thus for estuarine assessment a modeller has to balance the benefit from including more small-scale processes for a smaller number of different natural conditions against including less small-scale processes but being able to represent more of the annual range of conditions.

The use of predicted sediment properties may give rise to unrealistic rates of sedimentation where the algorithms are not based on in situ measurements but from laboratory analysis for which artificial (and possibly unrepresentative) mud beds were created. The problem of the validity of laboratory measurements is more acute with cohesive sediment transport. Many of the basic equations used by modellers have been derived in the laboratory.

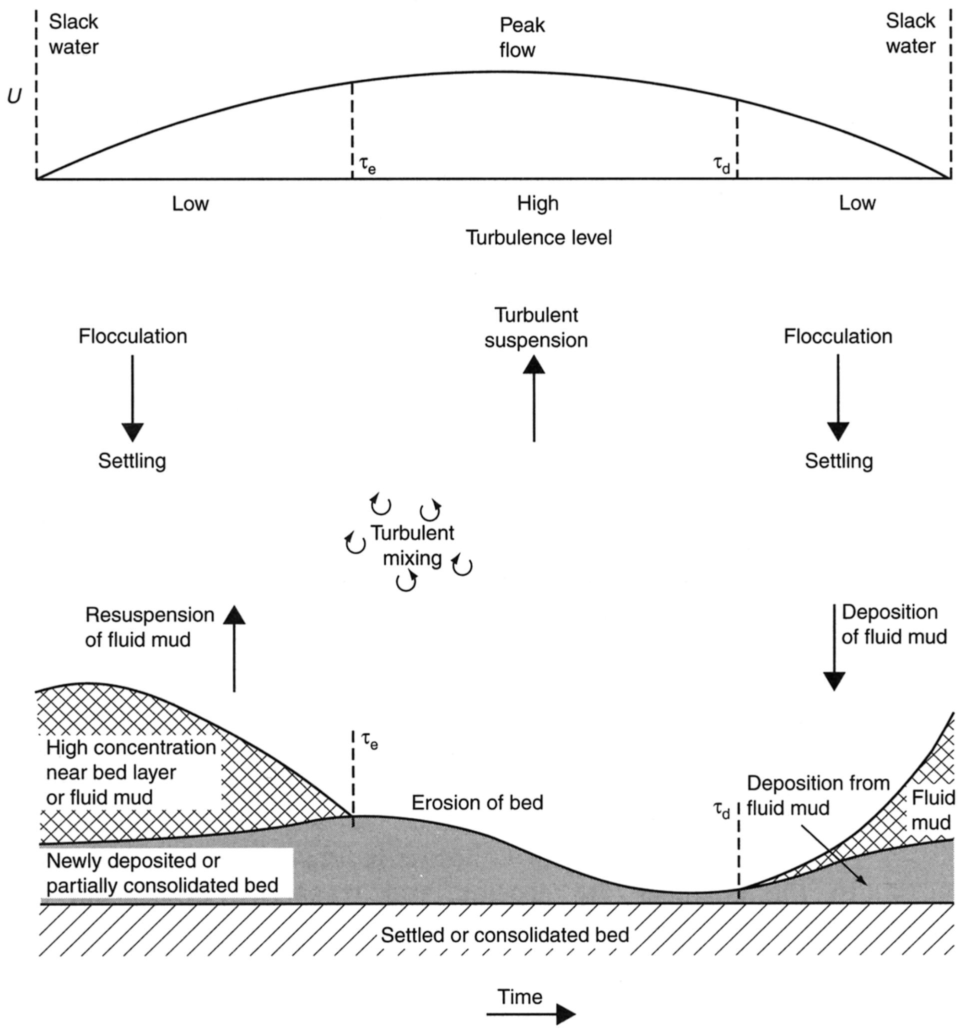

Figure 3 Estuarine tidal flow, sediment transport and bed processes

Process research

There are a large number of theories relating the amount of sediment in transport to the current velocity or discharge of water. Some of the theories are empirical and derived from large numbers of laboratory or controlled field tests, and some are derived from physical principals and validated against flume or field data. Many apply to steady uniform turbulent flow over granular non-cohesive beds and even under controlled conditions there are orders of magnitude difference between predictions using the various theories. In the marine environment with tides and waves the differences between predictions (and data) are also large.

The reasons for the differences and the variance from measurements are well documented, but depend upon:

1. Accurate measurements of the frictional shear stress imposed by the water flow on the bed surface sediment. The total shear stress that the flow exerts partly comprises form drag, i.e. the horizontal pressures on bedforms and biological structures. The relationship between form drag and the physical roughness of the bed has not been well characterised. The addition of waves onto a tidal flow produces a non-linear interaction that is still not well characterised, particularly in shallow water.
2. The thresholds of motion of sandy sediments have been adequately measured for steady uniform flow and under waves. However, when the sediment is cohesive the threshold of motion and the rate of erosion once the threshold is exceeded depend upon many factors, including the biological components. Many sediments are mixed, and are cohesive when they are on the bed, but separate once they are in transport into fine cohesive suspension and a sandy non-cohesive bedload. This sorting affects the patterns of deposition, with the distribution of grain size characteristics containing information on the transport paths, and the source and sink locations.
3. The transport rate depends on the combined profiles of suspended sediment concentration and flow velocity. However, there is a feedback between the two as the sediment affects the turbulence, the velocity profile and the bed shear stress. Also near the bed the highly concentrated sediment layer moving as bed load is difficult to characterise and to measure, as it is only a few centimetres thick at most. With cohesive sediment this concentrated near-bed layer causes drag reduction, and can flow under gravity as a density current.
4. Deposition from the flow depends upon the settling velocity of grains within the suspension. For sand this is well known, primarily being a function of grain size and density, but for muddy sediment the process of flocculation causes the settling velocity to be a function of suspended sediment concentration, shear stress, salinity and biological factors.

There are two approaches to overcoming the above problems. One is to obtain sufficient measurements to enable empirical predictions, and the other is to obtain a better understanding of the physical principals in order to develop generalised formulae. In the project a combination of the two approaches has been adopted, whereby extensive measurements are being analysed to produce empirical formulae and these will be used in physics based numerical modelling to explore and refine more rigorous concepts. For instance, observations of velocity and concentration profiles can be used to obtain best-fit curves that, together with theory, can be used to determine relationships for vertical parameterisation of fluxes of sediment. As far as predictive estuarine morphological modelling is concerned, there are several crucial topics where the research planned in EstProc can make useful advances without the need for large field experiments.

Bed shear stresses

The detailed physics of flow and the interaction with the bed of the estuary are controlled by the small-scale process interactions. Some specific initiatives are underway to improve the representation of bed shear stresses, the primary input for many sediment transport predictive equations. The development and incorporation of wave-tide-turbulence-sediment-bed feature algorithms in models is required to enable accurate prediction of the erosion and deposition of sediment in estuaries. Moreover, advances in hydrodynamics need to accommodate similar advances in sediment studies, including fluid mud and mixed sediments (mud and sand mixtures) and influences of biological processes and vegetation on shear stress.

Existing parameterised expressions for determining the bed shear stress due to waves, currents and combined waves and currents on mud and sand beds will be extended for the specific case of wave current interaction over (shallow) inter-tidal areas. Here the effective bed roughness coefficient may change continuously due to the presence of recently deposited/mobilised bed sediments. These involve modelling and an analytical study closely linked to existing observational data (flume and field). Extensive use is being made of recent measurements from large-scale flumes and from inter-tidal field studies in various European MAST programmes. Advances in the representation of these detailed processes need to be integrated in the whole estuarine models. This work will link in with the development of single-point and estuary cross section process models and a wave-current bed stress algorithm for inter tidal regions. Where possible the new algorithms will be validated against other field measurements to demonstrate their applicability.

The initiation and transport of mixed sediments
Many estuarine sediments comprise a mixture of different particle sizes and because of the interaction between these different fractions the mixture behaves in a different way than the constituent parts. This is especially true of mixtures of (cohesionless) sand when it is mixed with an amount of cohesive mud or clay particles.

Natural sediments are often layered, and contain varying amounts of biological organisms and secretions, which further affect the erosion behaviour. Sand increases the binding between the clay particles and results in a more compact and dense matrix, which is then more resistant to erosion. For underconsolidated muds adding sand to mud increases its erosion resistance (thus increasing τ_e) because of the increased bed density and influence on consolidation rates. Small amounts of clay added to a sand can significantly increase its erosion resistance. The addition of mud to a sand creates a cagework structure around the sand grains trapping the sand within a clay aggregate envelope. Deposits of sand within mud increase the bed density via compaction because of the following: increased self-weight consolidation; increased drainage; and, higher solids fraction within the sediment due to larger sand grains.

Complexity of the sediment transport process is also increased when mixtures of sand and coarser sand/gravel (and shell) are found together. The threshold of sediment movement is again a key parameter as the concept of threshold is used widely, in qualitative and quantitative descriptions of sediment dynamics. In a bed of mixed grains there will be exposed particles, the most unstable grains, that will move and relocate themselves to more streamlined or sheltered positions. Therefore, short exposures to sub-threshold velocities increase the resistance of a sediment bed by armouring. The time varying nature of tidal flows may contribute to this process. The sensitivity of models to the definition of threshold conditions requires careful consideration of the effects of these controlling variables when attempting predictions.

There are a currently number of techniques that are used for predicting the transport paths of sediment, and the source and sink locations, based on the distributions of grain size and sorting. Comparison using common data sets and modelled results will help understand which technique may be the most satisfactory, and this may be helpful in understanding the factors important in controlling the transport. In the project various concepts and theories are being tested in regional numerical models and the results compared with data on bed surface grain size distributions.

Estuarine sediment dynamics
The locations of an estuary's turbidity maximum, mud reaches and fluid mud, as well as its distributions of mudflat biota, are all influenced by the extent of salinity intrusion. Short term and long term changes in fluvial discharges, which greatly influence estuarine salinity, therefore affect all of these variables. Existing data sets will be used to study and extract relationships between the influences of weather, runoff, tides and tidal velocities on estuarine salt intrusion, suspended sediment transport and mudbank migration. The interpretations will be generalised and used to improve models of these processes.

Supporting work uses velocity and suspended sediment concentration profiles measured under different conditions to develop and test parameterisations of sediment transport profiles, and compare them with theory. This will need to incorporate specification of the bed load and suspended load transport, as well as the different turbulent structures in the flow.

In very turbid (fluid mud) estuaries the concentration, distribution and transport of fine sediment all vary within a tide and over a spring-neap cycle. Fluid mud can accumulate on the bed during neap tides, especially in localised deeper regions, and then be dispersed during spring tides. Existing data will be analysed to provide a picture of how high concentration suspensions of fine sediment are transported during a tidal cycle and how conditions change over a spring-neap and annual cycle. ADCP measurements of tidal currents together with those for salinity and suspended solids, acquired over estuarine intertidal areas, will be used to interpret and parameterise the linkages between estuarine tidal velocities, sediment transport and intertidal mudflat morphology. Other data will be used to determine the influence of strongly asymmetric (including bore-like) flows on suspended sediment (especially fluid mud) transport and the potential consequences for intertidal morphology.

Sediment fluxes

For the purpose of predicting sediment movement, the determination of the various spatial and temporal mass fluxes are of significant. One particularly problematic area is the modelling and mathematical description of the vertical mass settling flux of sediment, which becomes the depositional flux near to slack water. This is the product of the concentration and the settling velocity. For non-cohesive sediment this is relatively simple as the settling velocity is proportional to the particle size. Muds on the other hand are composed of both clay mineral platelets and different types of biological matter, at various stages of decomposition, and they have the potential to flocculate in to larger aggregates called flocs. These flocs demonstrate a lower effective density, but faster settling velocities than the individual cohesive particles (~ 1-5 microns).

During spring tidal conditions macroflocs (>160 microns) can typically reach 1-2 mm in diameter. These flocs demonstrate settling velocities of up to 20 mms^{-1}, but their effective densities are generally less than 50 kgm^{-3}, which means they would be prone to break-up when settling through a region of high turbulent shear. The flocculation process and resulting floc characteristics are a function of:

- sediment concentration, salinity, mineralogy, chemical composition, organic matter content (especially the sticky carbohydrates), and the physical mechanisms which bring the cohesive particles into contact, such as velocity gradients produced in the water column.

It is also generally agreed that increases in concentration encourage floc growth, however significantly high levels of turbulence which occur during a tidal cycle may create disruption and pull the constituent components of a floc apart. Site-specific information of spectra of floc characteristics and data on flow dynamics, collected simultaneously, is a prerequisite for developing accurate algorithms for implementation in predictive models. Examples of such data sets have been obtained previously for the Tamar and Gironde estuaries during the EC MAST III COSINUS and EC TMR SWAMIEE projects, respectively. To facilitate comparisons between in-situ results and the controlled environment of the laboratory, additional floc data sets are available on the vertical distributions of suspended sediment and floc sizes in turbid estuaries. These data are being interpreted and used to model the vertical structure of fine suspended sediment and its exchanges with the bed.

Complementary time-series measurements of vertical processes in fluid mud areas that extend over tidal cycles are available. These will be used to provide information on the formation and entrainment of fluid mud layers under the effect of bed shear stresses. The measurements include single tidal cycles of vertical profiles at various times of the year and provide important data on the seasonal variability of suspended sediment distributions. These data are being compiled in a standard way in order to produce a complete set that can be statistically analysed. From this a number of algorithms will be produced relating floc characteristics to concentration, shear, salinity, and as far as possible, biological factors. These algorithms will be tested in the numerical models.

ASSESSMENT OF THE IMPACT OF BIOLOGICAL PROCESS PARAMETERS

During the past ten years, multidisciplinary studies have provided quantitative evidence of the functional role of biota in estuarine sediment dynamics. The impact of biota on the erosion, transport and deposition of intertidal sediments (both cohesive and non-cohesive) is achieved through a number of different processes, which can either be considered ‘stabilising’ or ‘destabilising’. The mechanisms enhancing stability or net accretion include:

- sediment armouring, biofiltration / biodeposition, enhanced cohesion via secretion of extracellular polymeric substances, filamentous binding, reduction in near-bed flows and the induction of skimming flow effects in the overlying water.

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

- burrowing, bioturbation of surficial sediment, grazing on biostabilisers, faecal pelletisation of sediment, enhanced buoyancy of biofilms (by O_2 bubbles), and increased near-bed turbulence by means of increased bed roughness.

Some of the key intertidal biota directly influencing sediment stability include:

- seagrass, mussel and oyster beds (biogenic reefs), deposit feeding clams, benthic microalgae, macroalgae, and various saltmarsh plants. Other species can act indirectly through their feeding impact on 'bio-stabilisers' (grazers such as molluscs, polychaetes, crustaceans) and on 'bio-destabilisers' (predators such as birds and fish).

The quantitative data derived from both experimental and multivariate approaches has led to an improved understanding and modelling of the physical and biogeochemical factors influencing sediment dynamics in estuaries. These field and laboratory studies have largely focused on:

1. Measurement of critical erosion threshold, erosion rate and deposition rate in relation to natural benthic communities, as well as key biota (establishing density-dependent relationships), using annular flumes and other erosion devices.
2. Field measurement of near-bed current velocities, vertical profiles and SPM experienced by biota at different tidal heights and at a range of sites, for comparison with the flume data.

To date these studies have demonstrated that biota can alter sediment erodibility by more than two orders of magnitude and this varies spatially and temporally. Spatial variation in sediment erosion potential is largely dependent on the changes in biota and sediment properties with shore height, whereas temporal variation is both seasonal and inter-annual. A bibliography of bio-sedimentary processes has been published on the project website.

Much information currently exists and the project is pursuing the considerable scope for improvement to, and quantification of, our understanding of the role of intertidal biota in sediment dynamics using this information. This in turn should lead to the improvement of benthic boundary layer algorithms and the parameterisation of existing models to include relevant biological effects. A full consideration of the processes associated with major flora and fauna and the methods of incorporating these processes into models is an essential step in improving the utility of sediment transport / morphological models to predict change within estuaries.

Effects of physical conditions on biology

The previous section describe the influence of biota on saltmarsh-mudflat systems, however, from a broader environmental management point of view, the ecological effects of changes in sediment environments in response to human activities are equally important. Such effects are significant from a conservation perspective and because of their potential to interact with sedimentological changes.

The anthropogenic causes of changes to estuarine sediments include:

1. Dredging to expose, for example, finer more compacted clays or gravels, altering flow patterns by creating channels, deepening parts of estuaries with consequent changes in sediment type;
2. Sea-level rise and coastal defence inducing changes to the period of exposure over the tidal cycle, with consequent changes in sediment consolidation and water content and in grain-size with changing wave-current energy. Flooding of what were previously terrestrial (or reclaimed) soils or submersion of intertidal areas;
3. Recharge of intertidal areas to retain dredged material within the estuarine system in order to reduce erosion rates or create new habitat. The possibility of smothering of benthic habitats, changing sediment texture both of which will affect the nature and rate of subsequent recolonisation;
4. Engineering works, such as ports and marinas, affecting sediment deposition or the nature of the deposited material, or leading to erosion due to changes in water movements; and,
5. Propeller scour caused by shipping movements - the clearance between the bottom of the hull and the bed of navigation channels can be as little as 1-2m even in major shipping areas such as Southampton Water, so the potential for impacts can be large.

Estuarine management requires an understanding of how benthic systems are likely to respond to these changes in order to assess the potential environmental effects of human activities. This is particularly relevant to those estuaries that have experienced a greater degree of industrialisation.

Recognition of the linkages and feedbacks between the physical environment and inhabitant biota is important to any assessment of morphological change. These linkages and feedbacks are being assessed in this project.

EXPECTED OUTPUTS

The EstProc project (will) provide the following outputs for use by researchers, scientists and engineers:

- Scientific Reports and Papers that have been produced by the partners;
- A workshop will be held as an open presentation to the scientific and engineering community concentrating on the scientific and technical achievements and discussing the best ways for the audience to access them;
- Final report summarising in clear English the principal results and conclusions, and how the users of the research can pick up and implement the results;
- Specific reports and papers produced both individually and on a collaborative basis detailing technical aspects of the work undertaken;
- Improved methodologies or algorithms for representing processes and their interaction in estuaries;
- A metadata report detailing the data used in the project and how the data can be utilised in future projects; and,
- An update on future research requirements in the field of estuarine process research that will underpin the long-term goal of developing the Estuary Impact Assessment System.

The publication of the final deliverables is scheduled for November 2004.

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