Joint Defra / Environment Agency Flood and Coastal Erosion Risk Management R&D Programme

Characterisation and prediction of large-scale, long-term change of coastal geomorphological behaviours: Final science report

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Environment Agency

defra
Department for Environment Food and Rural Affairs

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Steve Killeen

Steve Killeen

Head of Science

Executive summary

With the advent of climate change, it is vital to understand and predict coastal geomorphological change in order to assess flooding and erosion risks and to plan, appraise and develop sustainable coastal management solutions.

Until now, our capability to predict coastal morphological change on a broad scale has been limited and has not always allowed us to fully consider the impacts of coastal management options and climate change in strategic planning and decision-making.

New research in this report has sought to develop a framework and conceptual model to predict long-term and large-scale geomorphological evolution, linking our understanding to the treatment of coastal and estuarine environments. Substantial progress has been made in developing conceptual models and in quantitative analysis of coastal geomorphological change.

To provide generic tools applicable in any UK location, it is necessary to understand the geomorphological behaviour of the coastal system as a whole and links between its component parts. A functioning coastal system is made up of features which combine and interact over a range of timescales. Coastal features are themselves made up of one or more geomorphological elements or units. These form the basic building blocks of the coastal system and as such are the starting point for this study. The coastal system will also be constrained at a large scale by geological controls, such as headlands, and supply of sediments forming the main geomorphological features.

A framework for assessing coastal geomorphological change is supported by the conceptual models of geomorphological features and elements which form the basis for assessing the impacts of coastal management options, including the cessation of management. Answers can be delivered in a consistent fashion for any location. The conceptual model was implemented numerically to ‘proof of concept’ level using existing systems-based models applied to a coupled coast and estuary system; this demonstrated the benefits of the approach and showed how the results could be used to inform practical coastal management decisions. Expert geomorphological analysis and systems analysis were also used to evaluate existing engineering tools and methods for quantifying coastal change.

A graphical method of mapping coastal geomorphological systems and interactions was developed to aid discussions with outside groups of how a coastal system works. The mapping approach is scale independent and is a useful starting point for analysis of geomorphological systems and for strategic planning. It helps to construct baseline knowledge and formal understanding, highlights uncertainty and removes the ‘black box’ nature of existing coastal prediction methods. The approach was applied to three coastal locations and easy-to-follow guidance on its use was produced. Independent assessment of the approach was carried out at another location which confirmed the approach’s usefulness in shoreline management plans (SMP) in identifying broad scale links, developing skills and training for coastal managers and offering a means of communication between different partners.

In the long-term, the outputs from this project will enable better planning of coastal works and better understanding of the consequences of not intervening. It will help coastal practitioners, local authorities, Environment Agency, Department for Environment, Food and Rural Affairs (Defra) and others involved in strategic planning to assess risks and plan for change. This report also makes a number of recommendations for the application and development of existing methods for quantifying coastal change.

This final science report of project SC060074 is based on work carried out with the Environment Agency by HR Wallingford, Royal Haskoning, University College London, University of Southampton, Kenneth Pye & Associates, Newcastle University and British Geological Survey. The report should be read in conjunction with Whitehouse *et al.* (2008), Walkden and Rossington (2009), and French and Burningham (2009). A project website is also available at www.coastalgeomorphology.net

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The project is grateful for advice received from Steering Group members (Tim Kermode, Suresh Surendran, Stefan Laeger, Owen Tarrant) and those who contributed to the consultation process: Graham Lymbery (Sefton District Council) – who also kindly participated in a test of the system mapping approach, Rod Jones (Countryside Council for Wales), Kerry Keirle (Welsh Assembly Government), Lee Swift, Geoff Astle, Karen Thomas, Gary Watson (Environment Agency), Emyr Williams (Pembrokeshire County Council), Stewart Rowe (Scarborough Borough Council).

We would also like to thank the Steering Group and Jim Hall from University of Newcastle for reviewing this report.

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1. Preamble

This document is the final science report for the project *Characterisation and prediction of large-scale long-term change of coastal geomorphological behaviours* (Environment Agency R&D project SC060074). The report draws together contributions from the research team which comprised: HR Wallingford, Royal Haskoning, University College London, University of Southampton, Kenneth Pye Associates, University of Newcastle and British Geological Survey.

The report should be read in conjunction with supporting documents (Whitehouse *et al.*, 2008; Walkden and Rossington, 2009; French and Burningham, 2009) and a project website is also available at www.coastalgeomorphology.net.

The next section contains an introduction explaining why this research is important for the Environment Agency's role in flood and coastal erosion risk management. The aims of the project are described followed by the research results. The majority of this report covers the outcomes of new research into long-term coastal geomorphological behaviour. As well as evaluating existing methods and using existing datasets, insights are generated through a new approach to coastal system mapping and the use of reduced complexity modelling to a coupled coast and estuary system.

1.1. Introduction

The Environment Agency plays a strategic role in coastal erosion and flood risk management. To manage coastal erosion and marine flood risk, particularly over long timescales and within large-scale systems, good understanding and prediction of coastal geomorphological behaviour is required. This project developed the basis of an approach for the Environment Agency to achieve this goal. The management of complex coastal features (such as illustrated in Figure 1.1) requires an appreciation of the past, present and future behaviour and evolution of individual elements within a mosaic of interlinked elements forming a particular coastal feature.

Figure 1.1 Pagham Harbour – illustration of a coastal geomorphological feature.

Coastal geomorphological behaviour relates to landform features and land forming processes that are shaped by atmospheric, terrestrial and marine processes. In order to measure the geomorphological evolution of a stretch of coastline, it is necessary to analyse the system state in terms of:

- the nature of the coastline and its composition;
- its origins (antecedent conditions);
- its controlling and forcing mechanisms;
- its behavioural characteristics.

Coastal landforms are dynamic systems that function over a range of temporal and spatial scales (see Box A).

Box A – Example timescale and spatial scale changes in functioning coastal geomorphological systems	
Timescales: • Seconds – turbulent fluctuations in hydraulic flow • Hours – storms, tides • Months – seasonal climates • Years to decades –lunar nodal cycle • Decades to centuries – re-orientation • Millennia – evolution over geological timescales	**Spatial scales:** • Millimetre – sand grain movement • Metres to hundreds of metres – coarse-grained sediment transport during a storm • Hundreds of metres to kilometres – fine-grained sediment transport during a storm • Hundreds of kilometres – large-scale geological re-orientation

Because of this dynamism, the understanding and prediction of coastal geomorphological behaviour is a continually evolving science.

A better ability to characterise and predict large-scale, long-term coastal geomorphological behaviour can help the Environment Agency in its core business activities, as shown in Figure 1.2.

The next section of the report describes the aims and objectives of the research.

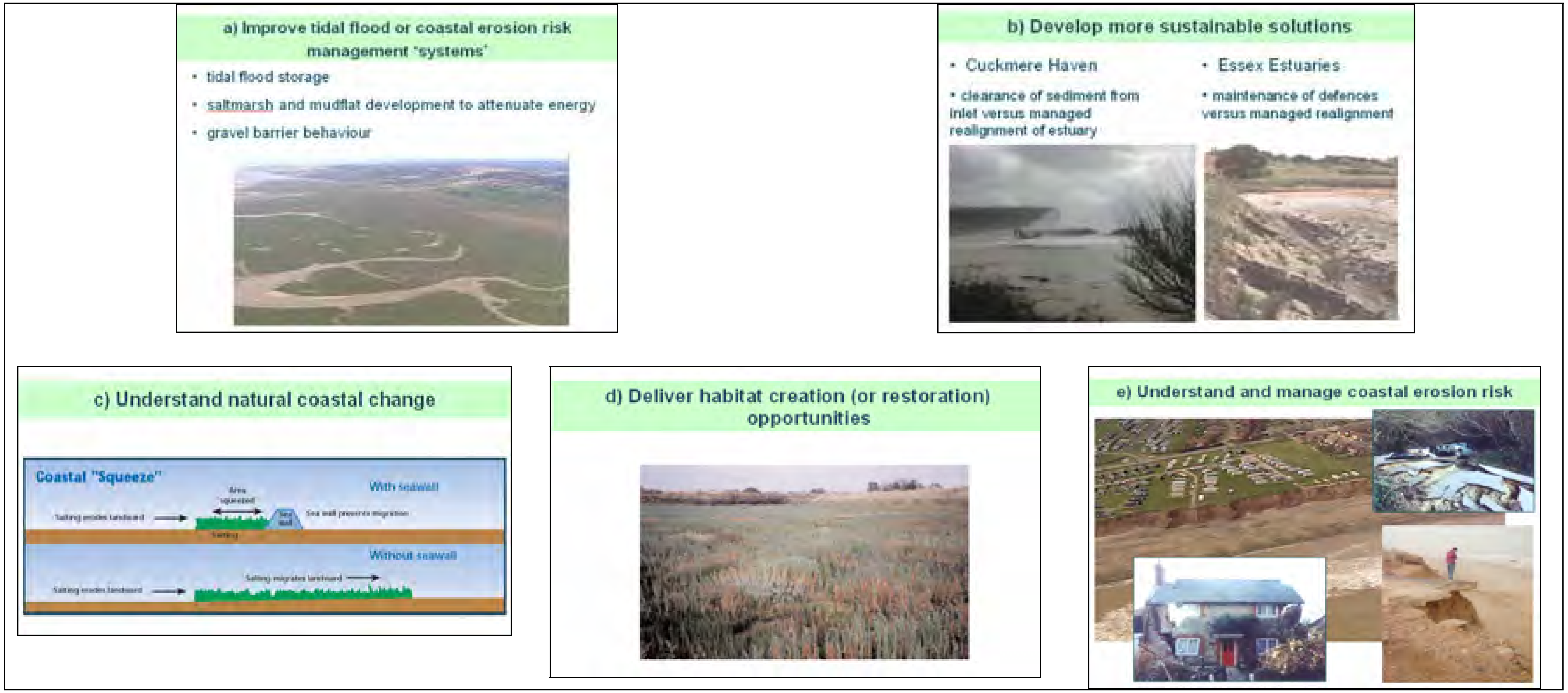


Figure 1.2 Role of understanding/predicting coastal geomorphological behaviour in Environment Agency core business activities.

1.2. Objectives and outline of report

This project is part of ongoing work to develop practical modelling and analytical tools to help coastal managers predict mid- to long-term geomorphological evolution of our coastlines and assess the impact of coastal management options with more certainty.

Three phases of research were originally envisaged by the Environment Agency, of which this project deals with Phase 1. The three phases are:

Phase 1	Conceptual model development
Phase 2	Model development for practical application
Phase 3	Trialling, refinement finalisation and dissemination

The aims of the present phase are to:

- Develop a framework for including an understanding of coastal geomorphological behaviour in coastal management decisions: see Chapter 3.
- Consider geological context as an underlying basis for past and future behaviour of the coastal system: see Chapter 4.
- Consider the range of coastal geomorphological features and elements and the effects of coastal management activities on coastal geomorphological behaviour. The latter is considered in the light of natural analogues for the behaviour of the geomorphological elements: see Chapter 5.
- Establish a method for mapping coastal systems which is scale-independent and apply it to a range of case studies: see Chapter 6.
- Develop existing modelling approaches for a linked coastal and estuary system to demonstrate the translation from conceptual system model to a proof of concept quantitative modelling approach: see Chapter 7.
- Review a range of methods for assessing different types of coastal geomorphological behaviours: see Chapter 8.
- Show how the methods inform understanding of coastal behaviour and future change via expert geomorphological assessment: see Chapter 9.
- Show how the research outputs are applicable to coastal management: see Chapter 10.
- Consider the lessons learnt during the development and case study application of different methods and approaches and consider how further developments might lead to uptake of the research: see Chapter 11.
- Provide conclusions and recommendations for future stages of research: see Chapter 12.

2. Aim, audience and FCRM context for the report

2.1. Objectives and target audience

This work underpins the development of predictive tools and techniques that will help coastal managers in decision-making by enabling them to better understand the potential impacts of intervention or the cessation of management.

Issues faced by coastal managers vary with location and for this reason, a series of preliminary consultation meetings was held with organisations with interests in predicting large-scale long-term change of coastal systems from different regions around England and Wales, including representatives from several local authorities, the Environment Agency, and regional bodies such as Countryside Council for Wales. The aim of these meetings was to identify the different roles of management and issues faced by these individuals, thereby focussing research on these needs.

The main audience for this project's outcomes was defined as:

- People managing Shoreline Management Plans (SMPs) or other Coastal Defence Management Strategies (within the Environment Agency or local authorities).
- People working on SMPs and other large-scale costal studies such as Regional Habitat Creation Plans or Coastal Habitat Management Plans (consultants).
- Consultees on SMPs and related works.

Outputs from this project were tailored to meet the needs of this target audience, in particular those in the first two categories. The conclusions and recommendations also inform the future research agenda and plans for risk-based coastal management. More details of the consultation are available in Whitehouse *et al.* (2008).

2.2. Project goals and benefits

It is vital to understand and predict coastal geomorphology in order to assess flooding and erosion risks and to plan, appraise and develop coastal management solutions. Several key aspects to understanding coastal geomorphology include:

- sediment transport around the coastline, beaches, and to and from estuaries;
- morphological behaviour whereby differential sediment transport is translated into changes in sea bed levels and form;
- impacts of interventions;
- effects on outcomes such as flood risk and coastal erosion risk.

The project builds on a number of previous studies, and responds directly to needs arising from national initiatives such as *Foresight Future Flooding* (Office of Science and Technology, 2004) and *Making Space for Water* (Defra, 2004).

Prior to and outside of this project, an extensive consultation and review led to the development of a 'Coastal Vision' for science within the joint Department for Environment, Food and Rural Affairs (Defra)/Environment Agency R&D programme. The vision endorsed the conclusions from the *Foresight Future Flooding* project that "*research is urgently required to improve the capability of coastal morphological models to support decision-making by providing accurate predictions of local morphological change and broad-scale morphological responses to coastal engineering and management*." To meet these needs, the 'Coastal Vision' called for programmes of research to develop broad-scale sediment transport, morphology and impact models to better predict changes to the coastline, and improve our ability to assess and manage the risk of flooding and coastal erosion. This project evaluated the tools and techniques required to predict medium and long-term changes, and to evaluate a range of potential coastal management interventions. It was the first phase in a programme of work to develop systems methods in support of risk-based coastal management.

Coastal geomorphology describes the sedimentary processes and landforms which determine the geometry of the coastline - including, for example, the location of cliffs, profiles of beaches and the sediment balance. Processes including erosion, accretion and transport of beach sediment, recession of cliffs and dunes, loss of key headland features, and emergence of geological controls can all have a major influence on the shape of the coastline, and on risks from flooding and erosion. Sediment movements both longshore and cross-shore determine morphology and most predictive models represent implicitly or explicitly sediment transport either as a linking quantity between geomorphological elements or in a predictive sense to determine the rate of change. The reliability of the predictors will vary depending on the processes required for a particular application and whether these are represented by the model at the right scale.

The morphology is also influenced or controlled by coastal structures such as breakwaters, groynes and sea defences and also by natural features such as headlands. These generally modify sediment movements whether intended or not - and can may cause changes remote from their location. In some cases the hard defences may be intermittent and the effect of maintaining or removing defences on whole stretches of coastline will need to be considered. In many cases there is a fine balance or equilibrium and this can be disturbed by changes to the external drivers; waves, tides and water flows. Climate change, in particular, may cause accelerated change and may disturb systems that are otherwise in equilibrium. There is a need to constantly improve the methods available to flood risk managers and engineers so that these factors can be taken into account.

Geomorphology has a direct effect on flooding and coastal erosion as the morphology and beach levels affect the height and direction of waves at the coast. This can affect the potential for flooding from overtopping, and can affect the forces acting on defences and hence their likelihood of failure or breach risk, such as through larger, more damaging waves and/or higher water levels at defences. Coastal flood defence structures may also be undermined and weakened by erosion of beach levels or soft rock substrates. Coastal erosion is an important and high-profile risk, partly controlled by sediment movements and geomorphology, and understanding future shoreline position depends on good models of these processes.

This project contributes directly to the agreed objectives of the Modelling and Risk (MAR) theme within the joint Defra/Environment Agency research programme. It provides a major contribution to the overall objective of improving risk assessment and management in Flood and Coastal Risk Management (FCRM). In turn, this improves our decision-making on and ability to reduce flood and coastal risk.

Benefits will be gained through better understanding of geomorphological elements and their links, a systems approach for coastal management, an evaluation of engineering methods and some system-based modelling of coast-estuary interactions.

With further development, these approaches will enable better planning and design of coastal works and better understanding of the consequences of not intervening. This will help the Environment Agency, Defra and other authorities to assess risks and plan for future change.

2.3. Modelling coastal evolution for coastal management

2.3.1. Source-Pathway-Receptor-Consequence (SPRC) modelling

The Environment Agency has, in recent years, developed a risk-based system-modelling approach to flood risk management (Sayers *et al.*, 2002, HR Wallingford, 2004, Evans *et al.*, 2004a, b, Hall *et al.*, 2006) which included the development of Risk Assessment for Strategic Planning (RASP), a Performance-Based Asset Management System (PAMS) and National Flood Risk Assessment (NaFRA). The overall aim is to manage flood risk as effectively as possible by inspecting, maintaining, repairing and if necessary replacing flood defences to achieve the required performance and to reduce risk. Central to these developments has been the adoption of a Source-Pathway-Receptor-Consequence (SPRC) model of risk, illustrated in Figure 2.1. The *Language of Risk* (Gouldby and Samuels, 2005) definitions are as follows:

- **Source:** the origin of a hazard, for example, heavy rainfall, strong winds, surge and so on.
- **Pathway:** route that a hazard takes to reach receptors. A pathway must exist for a hazard to be realised.
- **Receptor:** the entity that may be harmed, such as a person, property, habitat.
- **Consequence:** impact such as economic, social or environmental damage/improvement that may result from a flood.
- **Risk:** is a function of probability (of the hazard), exposure and vulnerability and its consequence.

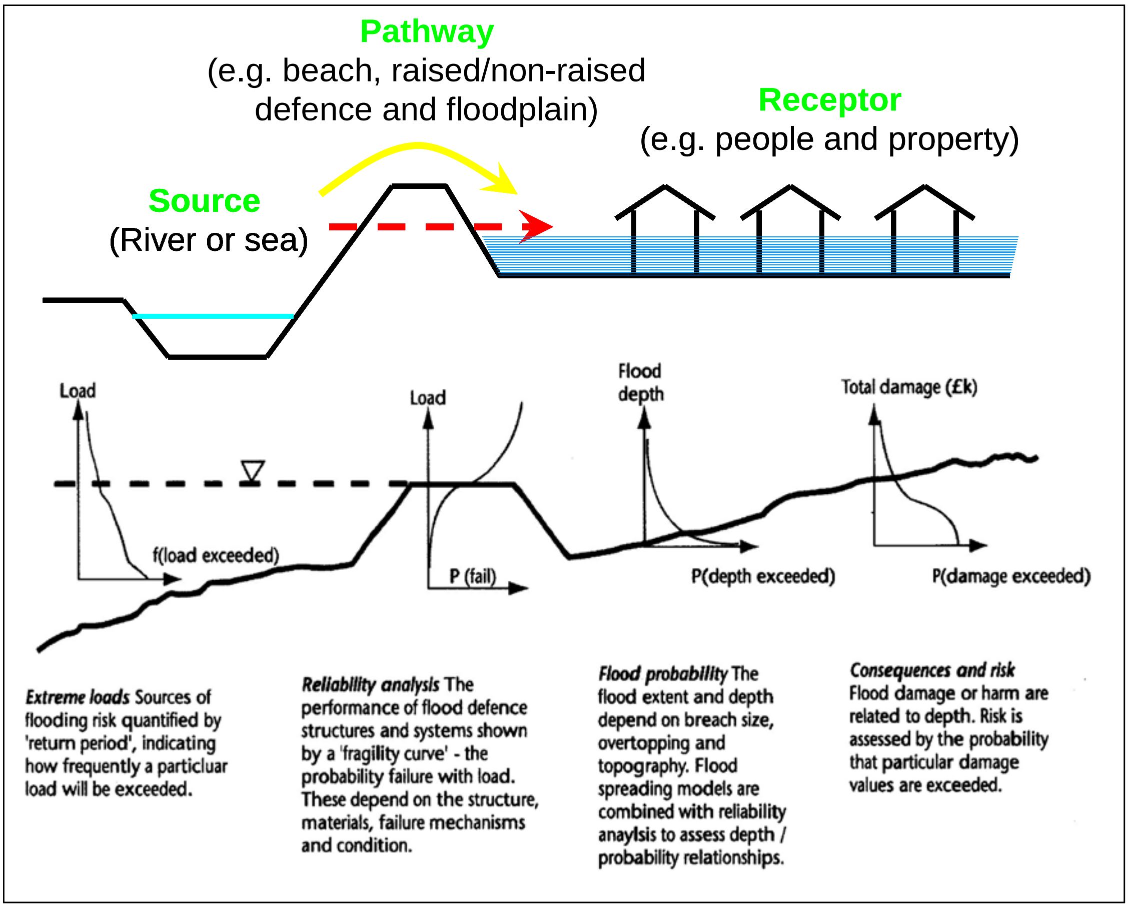


Figure 2.1 Source-Pathway-Receptor-Consequence model of flood risk (from Sayers *et al.*, 2002).

2.3.2. Including SPRC in a Decision Support System (DSS) framework

Much of the work in this field has centred on modelling the risk of fluvial flooding, although coastal flooding has also been included. SPRC models have been included in a methodological framework for a Decision Support System (DSS), which includes modules for the SPRC terms as well as four additional modules to represent risk, external drivers (for building scenarios), the management response (for building strategic alternatives) and decision support (McGahey *et al.*, 2009). The overall modularity and information flow is shown in Figure 2.2.

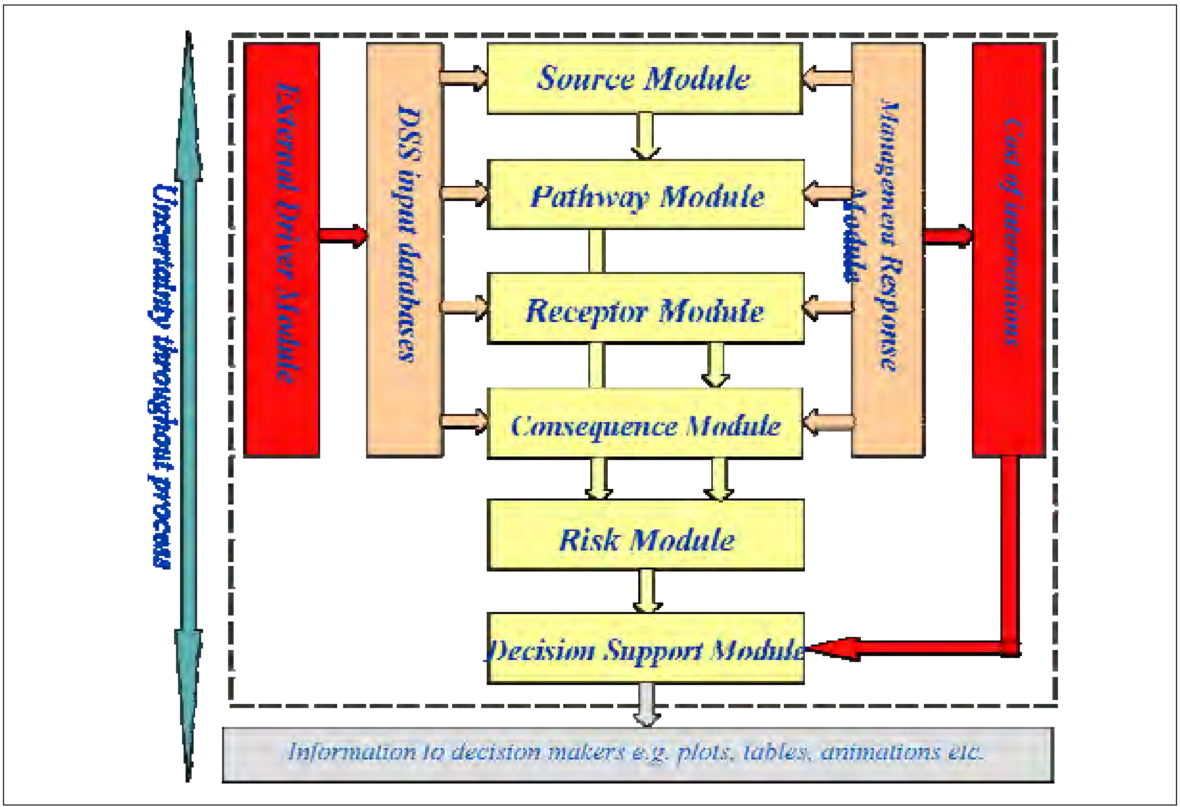


Figure 2.2 Methodological framework for a DSS (McGahey *et al.*, 2009).

The methodological framework includes the modelling of risk and uncertainty as an integral part of the framework. Comparisons can be made between alternative components of a coastal defence system or between entire systems. Comparing entire systems recognizes that each coastal defence, whether natural or man-made, is only a component of a system of defences and the risk from an event is a function of the probability of failure (of each component of the system) and the consequences of that failure. Moreover, the costs and benefits (monetary and non-monetary) of each element of a coastal defence strategy must be taken into account to establish the best strategy and focus investment (whether in maintenance, adaptation or replacement).

An example from the UK is the application of the RASP_DS (Decision Support) tool to the Thames Estuary (McGahey *et al.*, 2009). The information flow of the RASP_DS is given in Figure 2.3.

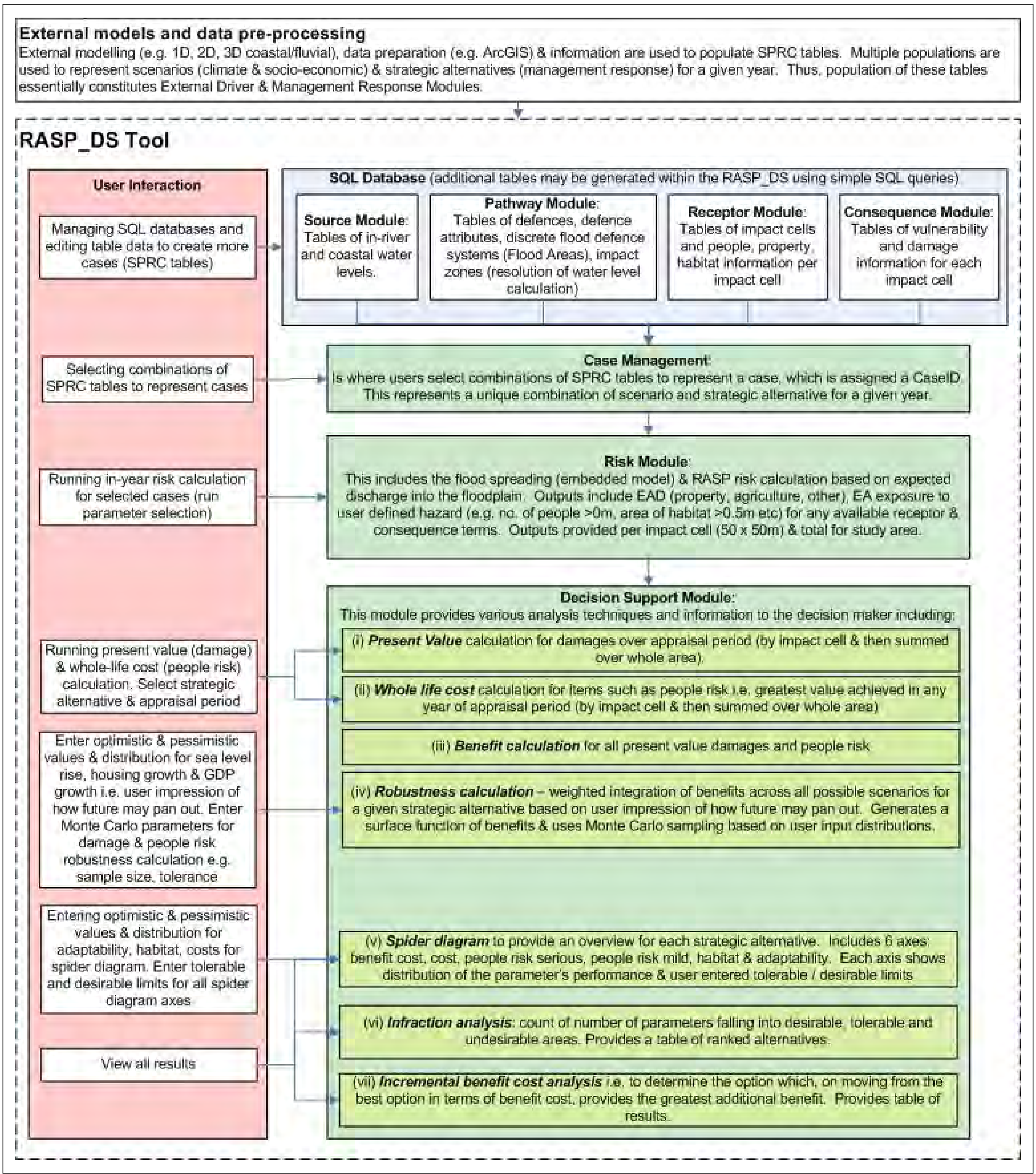


Figure 2.3 RASP_DS Information flow.

2.3.3. Role of bathymetry in risk modelling

Flooding may occur as a consequence of the overtopping of a defence (a term that includes beaches) or of its failure, with the latter leading to orders of magnitude more flooding. A structure may have several failure modes (different mechanisms for failing) and each will have its own fragility curve that gives the probability of failure as a function of its loading. Failure modes and fragility curves are included in the pathway module of a SPRC model (Figures 2.1 and 2.2).

Most of the modelling performed using the SPRC model of risk has been undertaken with a static bathymetry, apart from:

- the use of fragility curves for shingle barrier beaches to represent their probability of failure and hence of flooding during a storm;
- the inclusion of a simplistic toe scour term in the fragility curve for seawalls.

One notable exception to this has been the use of a modified Bruun Rule to calculate the change in coastal erosion rates from present day rates in a national assessment of future flooding (Evans *et al.*, 2004a, b, Thorne *et al.*, 2007). This found that coastal erosion accounted for three per cent of the total flood and coastal erosion risk for England and Wales, and that it deserved serious attention in the context of coastal zone management and the sustainability of coastal settlements.

In order to incorporate the modelling of large-scale long-term coastal behaviour into SPRC models of flood risk management, it is necessary to consider:

1. How bathymetry influences a coastal SPRC model.
2. What the form of the output from a model of large-scale long-term coastal behaviour will be.
3. How the management response affects the large-scale long-term coastal behaviour.

These issues will be considered in turn below.

2.3.4. Influence of bathymetry on SPRC model

The potential influences of bathymetry on an SPRC model of risk include:

- Offshore bathymetry is a controlling factor of the propagation of waves, tides and surges as they approach the coast. The SPRC model normally starts with combined wave and water level conditions at the toe of the defence. Changes in the bathymetry will lead to changes in the waves and water levels used to drive the SPRC model. Even changes in the beach slope will affect the way waves break and therefore affect the local wave conditions at a defence.
- Cross-sectional beach area and beach crest height will affect the ability of a shingle barrier beach to withstand breaching.
- The cross-sectional area of a dune will affect its ability to survive a storm without breaching.
- The cross-sectional area of a beach affects its ability to protect a shore platform and the base of a cliff from erosion and hence affects the probability of cliff failure.
- The level of a beach at the toe of a structure will affect the local water depth at the structure and hence the overtopping rate (which is important for some failure mechanisms) and the stability of a structure toe.

2.3.5. Output from a model of large-scale long-term coastal behaviour

The list above shows how the SPRC model can use a detailed bathymetry in the calculation of failure. A large-scale, long-term model of coastal behaviour may not give a detailed bathymetry (irrespective of its accuracy). It may provide information more in terms of a sediment budget or, like ASMITA (Chapter 7), give volumes of different elements. Additional work may be necessary to establish implications for the SPRC model of the reduced level of detail obtained when bulk parameters are calculated.

2.3.6. Effects of management intervention

The model of large-scale long-term coastal behaviour must take into account the effects of management interventions, which will partially control the movement of sediment within the coastal system.

There are two main methods for incorporating predictions of future bathymetry in the methodological framework (Figure 2.2), which are:

1. Pre-computing the bathymetries to be used by running the coastal evolution model as an external model (as shown in the top box of Figure 2.3) for each of the climate and strategic alternatives (which drive and partially control the sediment transport, respectively). The different bathymetries could be stored as a look-up table to be used as appropriate and without the need for further computation.

2. Deriving an emulator – a relatively simple and quick means of calculating the effect of the forcing on the bathymetry. Emulators can be run as part of the main programme as they are quick. They are often derived by parameterising the results from experiments or the simulations of more detailed models.

Given the complexity involved in large-scale, long-term predictions of coastal change, it seems unlikely that a suitable emulator will be created. Efforts should be concentrated on producing a coastal evolution model that can be run externally (in advance) and that will produce suitable results for incorporation into a DSS.

3. Framework for incorporation of coastal geomorphology into coastal management

3.1. Rationale for approach – individual approaches

Understanding coastal geomorphology is fundamental to the success of management decisions. At present, a wide range of tools and techniques are available to inform coastal managers of historical coastal developments and to predict future change. This project seeks to integrate existing methods for coastal and estuarial geomorphology, moving towards more joined-up thinking that can achieve the broad-scale modelling objectives set by the Environment Agency and Defra (Wheater, *et al.*, 2007).

In order to achieve this, a systems thinking approach was adopted here. A systems approach can function over a range of scales and incorporate the full range of modelling capacity. Its basis is that any part of an identified system can best be understood in the context of relationships with each other and with other systems, rather than in isolation. As an approach to problem solving, it places any issue within a wider context and helps to identify potential solutions, assessment techniques or further investigations and sits well within the framework discussed in Section 3.3.

3.2. Expert geomorphological assessment and methods

At present there is no single method or model that can answer all of the questions that coastal managers will pose. Indeed, it is highly unlikely that this will ever be achieved since coastal geomorphological behaviour occurs over a continuum of spatial and time scales and involves an extensive, perhaps infinite, combination of forces and responses, with complex interactions between different components of the system. As such, a degree of expertise will always be required when assessing and predicting large-scale, long-term coastal change.

However, a suite of tools, models and methods can be used to investigate different aspects of coastal geomorphological behaviour in a rational and logical manner. Key to successful analysis and projection of change is the appropriate selection and use of these tools for the nature of the coastline under investigation, critical interpretation of the outputs, and synthesis of the resulting information into a conceptual understanding of coastal geomorphological behaviour. This approach is often called expert geomorphological assessment, or EGA, and is best undertaken within an overall framework for the geomorphological investigations.

3.3. Framework for geomorphological investigations

Previous studies have looked at the formalisation of an approach for evaluating the morphology of estuaries (EMPHASYS, 2000; HR Wallingford *et al.*, 2006) and coasts (Southgate and Brampton, 2001). The proposed approach is based on this earlier work which describes a framework for understanding, that is, baseline evidence, and for decision-making set against a sound conceptual model.

Any assessment will consist of a scoping exercise, analysis of the way the system works, prediction of impacts, and discussion with client and regulator about the conclusions of the study. This may lead to further clarification of the issues arising from the project, and additional work to refine conclusions and presentation of the study outcomes. The steps proposed by Southgate and Brampton (2001) specifically relating to coastal morphology modelling were as follows:

1. Decide on length of coast and period over which predictions are required.
2. Establish what information is available for use in the assessment.
3. Establish what types of results are required/can be provided.
4. Decide which processes are important in altering morphology at the site.
5. Decide on appropriate tools and any associated validation processes.
6. Establish which aspects of the coastal system, management scenarios or sensitivities to perturbations (e.g. sea level rise) the tools will need to test.
7. Decide on how to interpret, synthesise and present the results.

These steps are similar to those components of an impact assessment defined in HR Wallingford *et al.* (2006) and summarised in Figure 3.1. The structure of Figure 3.1 is not definitive but is typical of the broad nature of the approach to support management decision-making.

Scoping involves the objectives and methodology of the project being mapped out. This stage includes:

- Consideration of the potential effects of natural change or a management intervention or project on a coast or coast-estuary morphology.
- Evaluation of the availability of data and potential requirement for new data.
- Identification of the needs of interested and affected groups/partners.

In practice this component overlaps with the next component, conceptual model development. The correct use of EGA (Expert Geomorphological Assessment) is heavily dependent on an understanding of the system being studied, nowadays often referred to as a conceptual model. A correct understanding of the system will form the basis for the correct choice of predictive methods and will enhance confidence in the conclusions of the study. An incomplete or incorrectly focused conceptual model may lead to incorrect assumptions about the system, poor use of predictive approaches and incorrect assessment of morphological change arising from management interventions.

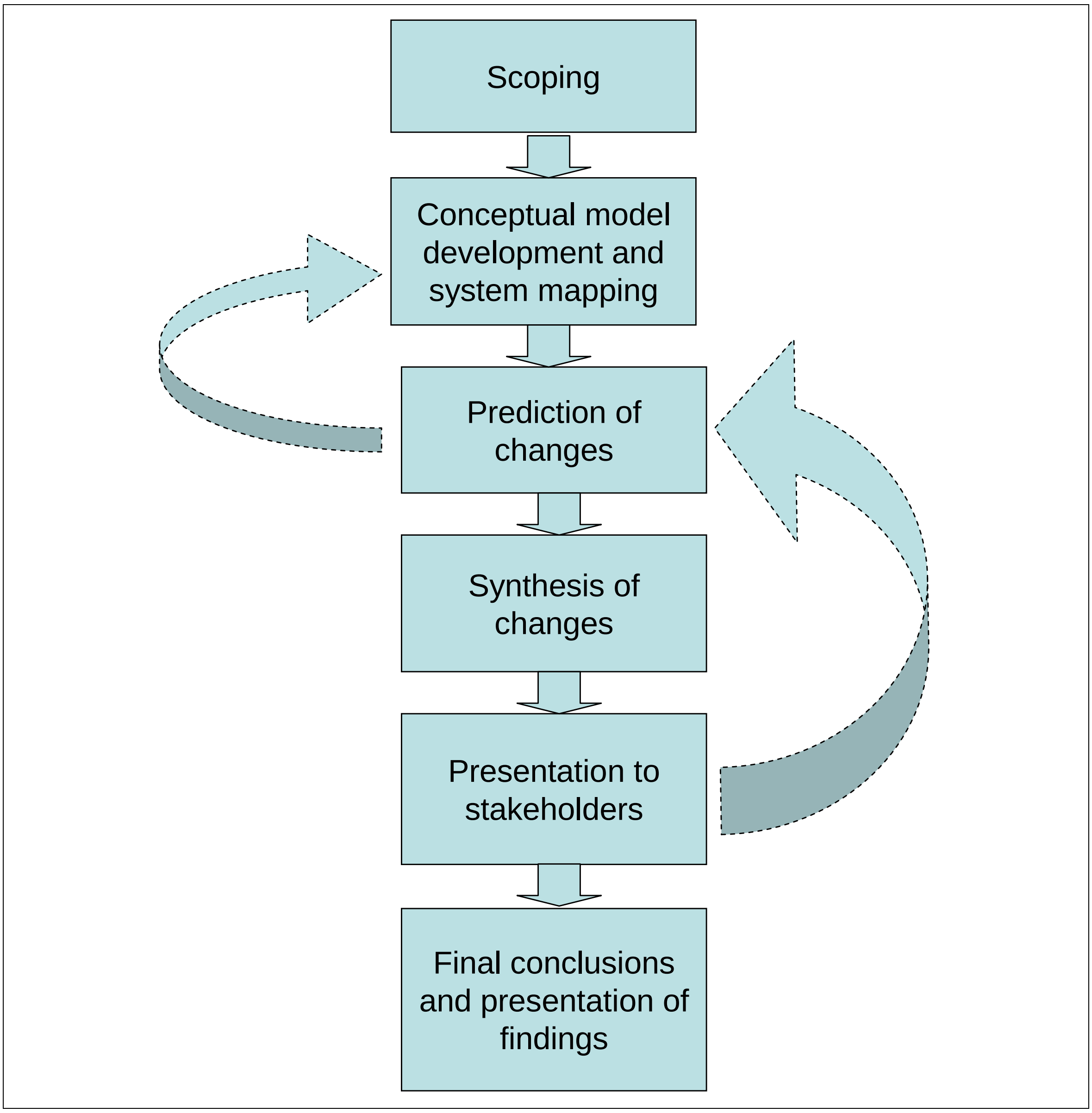


Figure 3.1 Study approach showing main stages and feedback loops that may be required.

The emphasis is on developing a framework for the second component in Figure 3.2, namely that of conceptual model development.

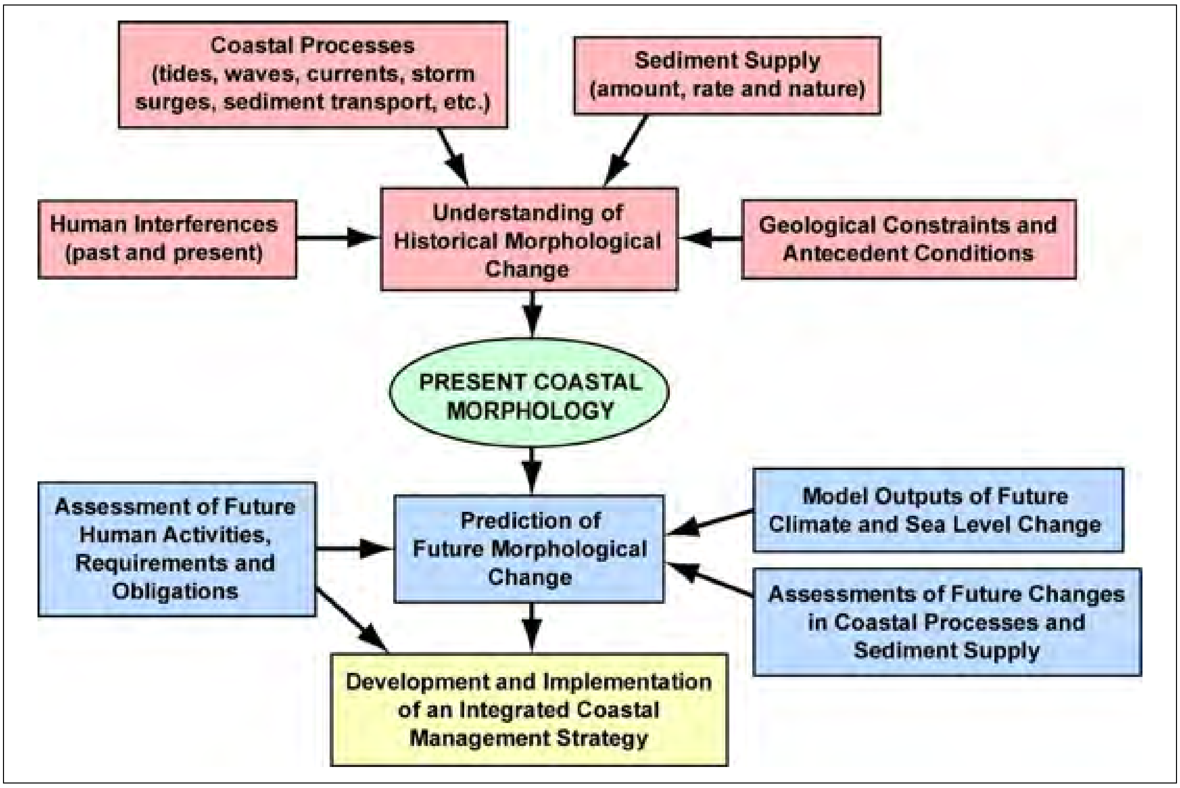


Figure 3.2 Aspects of expert geomorphological assessment relevant to the prediction of future coastal morphological change and development of an integrated coastal management strategy (after Pye and Blott, 2009a).

The next component in the overall framework is the implementation of predictive assessment (prediction of changes); the results from those approaches need to be interpreted and presented in a clear fashion to convey the right information to interested parties and other users of the study outputs. If a plethora of analytical approaches is implemented, some formal synthesis of the different results will be required (synthesis of changes). New insights may lead to an adjustment of the conceptual model and further predictive assessment being carried out.

Initial conclusions from the synthesis should be explored in a presentation and discussion with interested parties and users, where these discussions may lead to some clarification of the issues and the requirement for further predictive work. Finally, when all the outstanding issues have been addressed, the final conclusions of the assessment should be formally presented (presentation).

4. The coastal system

Explanation and prediction of coastal morphological character and change requires an understanding of the environmental context within which a particular section of coast lies, the interactions between different types of geomorphological elements and larger features on different timescales, and the importance of different forcing factors and constraints on such interactions. The environmental context includes the influence of background geological factors (tectonic movements, geological structure, lithology and relief framework), climatic factors, and oceanographic factors. These, in turn, affect coastal processes, patterns of sediment erosion transport and deposition, and ultimately the coastal morphology (Figure 4.1).

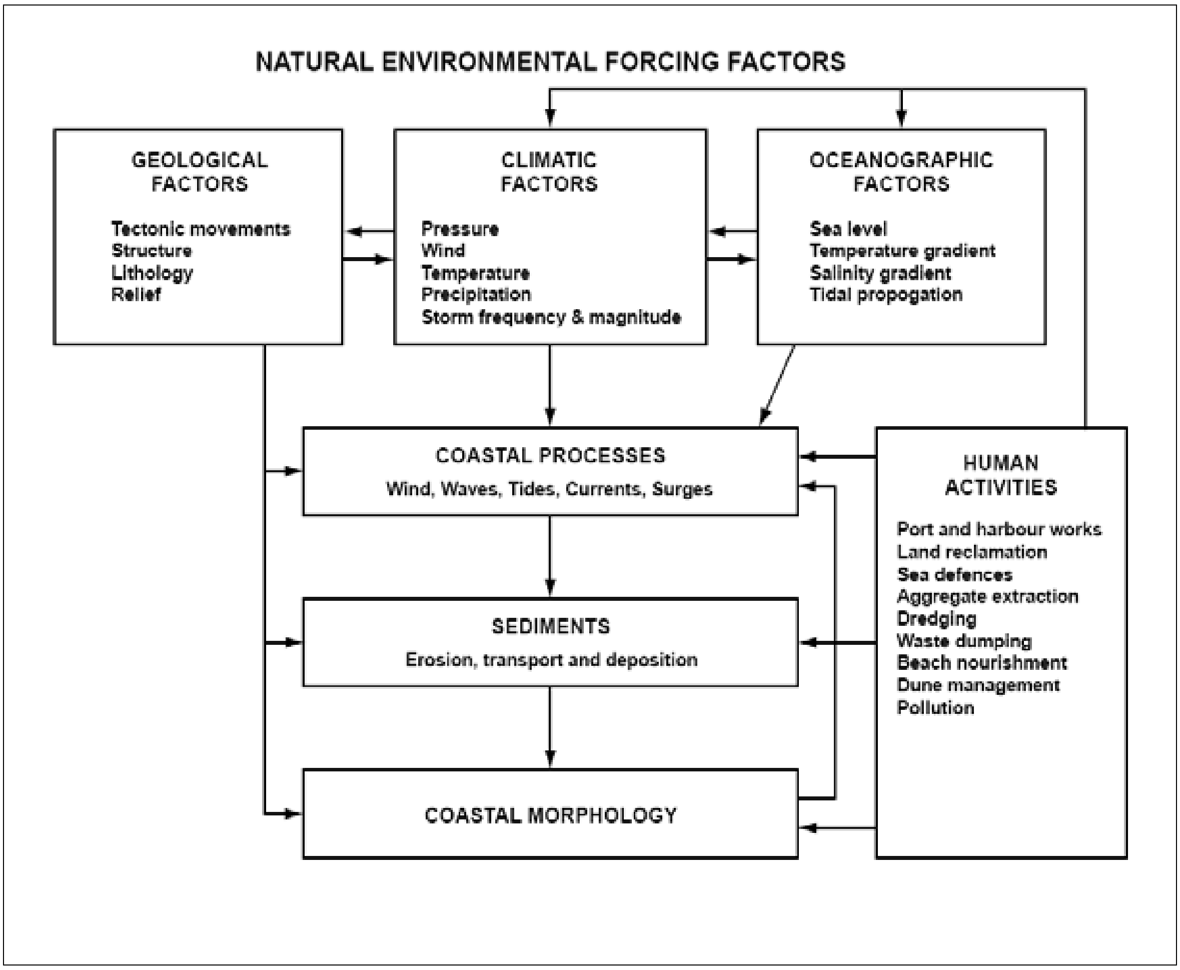


Figure 4.1 Principal components involved in coastal morphodynamics (after Pye and Blott, 2008a).

The coastal zone represents an interface between terrestrial, marine and atmospheric systems, where two-way flows of energy and matter take place between these systems across the coastal zone. At a simple level, land-ocean interaction can be considered in terms of flow of water and/or sediment from a river basin, through an estuary, to the coast and near-shore zone, from where it may be dispersed across a wider area of the inner and outer continental shelf to the shelf edge and deep ocean. In many circumstances, there may also be important return flows of water and sediment from the continental shelf to the coastal zone and into estuaries (see Figure 4.2).

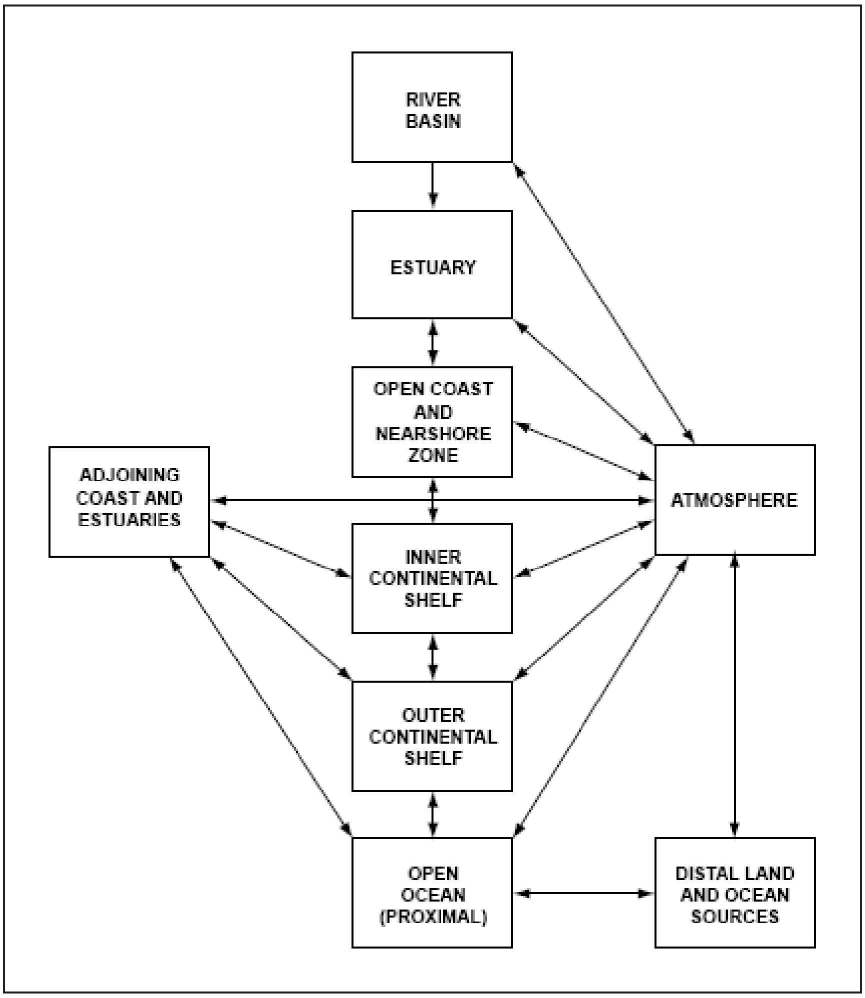


Figure 4.2 A conceptual model of land-ocean interaction.

4.1. Hierarchical approach

Sediment exchanges and morphological changes take place on a wide range of time and space scales ranging from small-scale, short-term to large-scale, long-term. Concepts and definitions of scale vary greatly, in part reflecting the problems and objectives addressed by scientists in different scientific disciplines (see Carter, 1988; Stive *et al.*, 1991; Kraus *et al*., 1991; Pethick and Leggett, 1993; Carter and Woodroffe, 1994; Cowell and Thom, 1994; Komar, 1999). For example, from a coastal engineering perspective Kraus *et al*. (1991) defined micro-, meso-, macro- and mega-spatial scales in terms of length scales of the order of mm-cm, m-km, km-10 km and above 10 km (sub-regional/regional), respectively.

Valentin (1952) proposed a useful conceptual model of large-scale, long-term coastal development which emphasises the balance between land emergence/submergence due to relative sea level change on one hand and sediment erosion/accumulation on the other (Figure 4.3). Many instances of shoreline tendency are entirely explicable or predictable in terms of these two factors alone.

Figure 4.3 Relative contributions of emergence and submergence (due to changing sea levels) and construction and destruction of land (by erosion and accretion) on coastal advance and retreat. Modified from Valentin (1952).

Correspondingly, they defined micro-, meso-, macro- and mega-time scales in terms of seconds-minutes, hours-days, months-years, and decades-centuries, respectively (Figure 4.4a). Also from an engineering perspective, Stive *et al*. (1991) recognized small-scale coastal evolution (SSCE) with a length scale of 100 m and timescale ranging from individual storms to seasonal changes, medium-scale coastal change (MSCE) with a length scale of one km and timescale of the order of years, and large-scale coastal evolution (LSCE) with a length scale of 10 km and timescale of decades. Pethick and Leggett (1993) subsequently combined and extended the MSCE and LSCE scales to include extreme events with time scales of up to one in 250 years and also longshore and offshore distances large enough (of the order of several to tens of km) to include the effects of high magnitude, low frequency (HMLF) events. They referred to this extended scale as Integrated Scale Coastal Evolution (ISCE).

A further conceptual scheme proposed by Cowell and Thom (1994), primarily from a geomorphological perspective, identified four combinations of time and length scale which they described as "instantaneous", "event", "engineering" and "geological" scales (Figure 4.4b). However, from a geomorphological and sedimentological perspective, Pye and Blott (2008a) considered it more appropriate to consider only the "macro-"and "mega-" spatial scale categories of Kraus *et al.* (1991), and the "geological" category of Cowell and Thom (1994) as large-scale (length scales ranging from 10 km to hundreds of km), and Kraus *et al*.'s "mega-" timescale category and parts of Cowell and Thom's "engineering" and "geological" scale fields as long-term (time periods ranging from several decades to millennia; Figure 4.4c).

More recently, Cowell *et al.* (2003, p815) proposed the term "coastal tract" as "*a spatially contiguous set of morphological units representative of a sediment sharing coastal cell*". The term is derived from the geological concept of a *depositional systems tract* which was originally developed to aid interpretation of three dimensional facies architecture of sedimentary sequences in the search for oil and gas (see Thorne and Swift, 1991). A schematic representation of the components in an example coastal tract is shown in Figure 4.5. In some situations the boundaries of the coastal tract may be clearly defined by geological features (such as major headlands which separate embayments or littoral sediment cells), but in other situations, for example on long straight coasts or those with a wide continental shelf, the boundaries of the tract may be unclear, and arbitrary boundaries may need to be imposed. In fact, it may be possible to define a nested hierarchy of coastal tracts at varying spatial scales. For example, at a large scale the entire North Sea coast of the UK could be treated as a coastal tract, within which smaller sub-tracts could also be legitimately be defined (such as the coast of Eastern England between Tweed Heads and North Foreland or, at an even smaller scale, the Wash-Fenland embayment; Figure 4.6).

In any consideration of coastal morphology and evolutionary change, it is important at the outset to define the boundaries of the system under consideration and to identify the environmental controlling factors, constraints on system behaviour and components within the system. The concept of the *coastal cell* was first defined in terms of littoral sediment source-transport-sink pathways (Bowen and Inman, 1966; Inman and Frautschy, 1966), and modified in terms of the concept of a closed *coastal sediment compartment* by Davies (1974). In practice, few coastal cells or compartments have firm boundaries and there is normally some degree of sediment exchange with areas further offshore or alongshore, especially in terms of finer grained sediment. Nonetheless, the concept of distinguishable sections of coast which share processes in common, including inter-related sediment budgets and morphological development, remains a highly useful one and has been used in coastal management (Motyka and Brampton, 1993).

The methodology developed during the *Futurecoast* project involved the identification of a number of Coastal Behaviour Systems (CBSs), within which processes, sediments and morphology interact (Cooper and Jay, 2002). Identification of the CBSs involved assessment of the following aspects:

- shoreline and offshore geology (lithology, stratigraphy, structure and tectonics);
- offshore features and their interactions with the shoreline;
- hydrodynamic and sediment processes;
- Holocene evolution;
- historical trends;
- estuarine influences (such as tidal flushing, presence of deltas).

Within each CBS a number of smaller sections of coast, termed Shoreline Behaviour Units (SBUs), were identified, the plan form evolution of each SBU being dependent on inter-linkages between the factors listed above. Examples of SBUs include embayments, drift- and swash-aligned shorelines, source-corridor-sink units, barrier islands and tidal inlets, estuaries and tidal deltas. These SBUs in turn represent linked assemblages of fundamental coastal geomorphological units (GUs), which included cliffs, shore platforms, beaches, barriers, dunes, marshes and tidal flats. For each GU, formation was obtained relating to formation and evolution process, typical behaviour, links with other GUs, sensitivity and future behaviour tendency. A similar approach is adopted in this study.

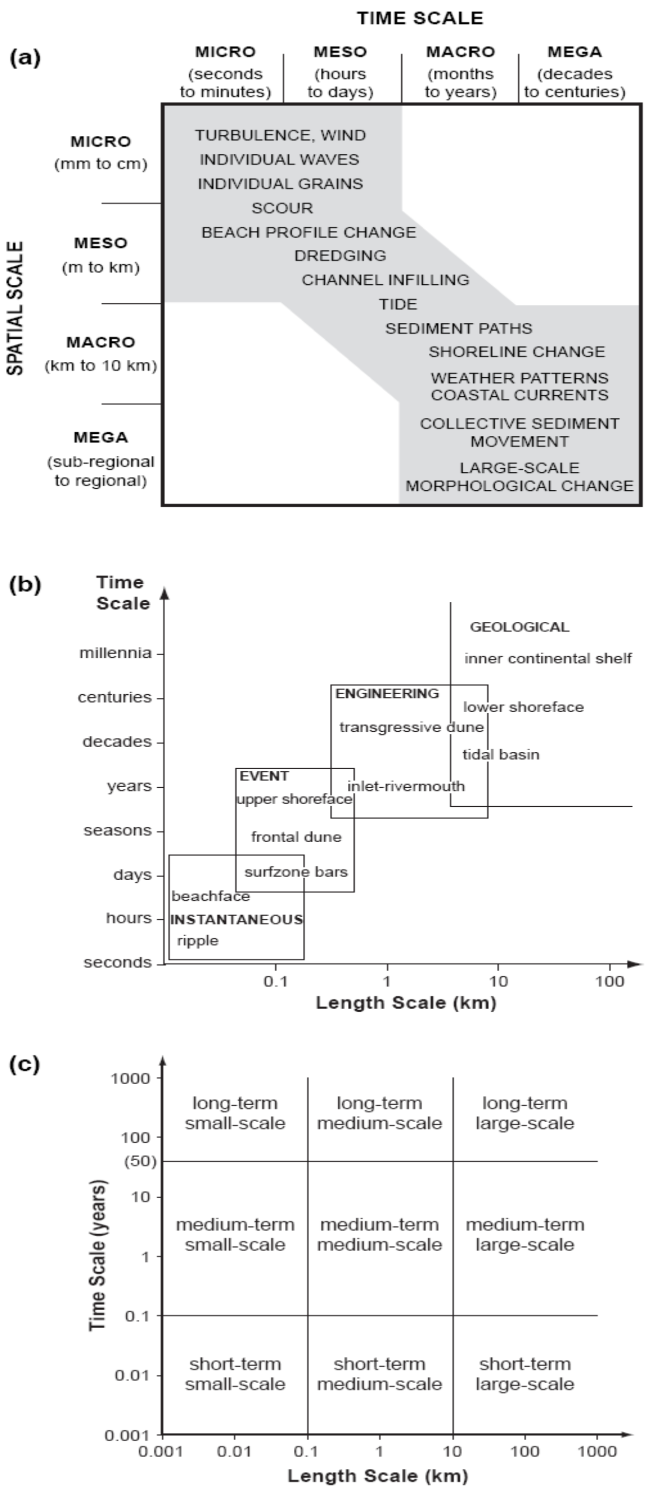


Figure 4.4 Alternative definitions of spatial and temporal scales involved in coastal evolution (a) Kraus *et al*. (1991); (b) Cowell and Thom (1994); (c) Pye and Blott (2008a).

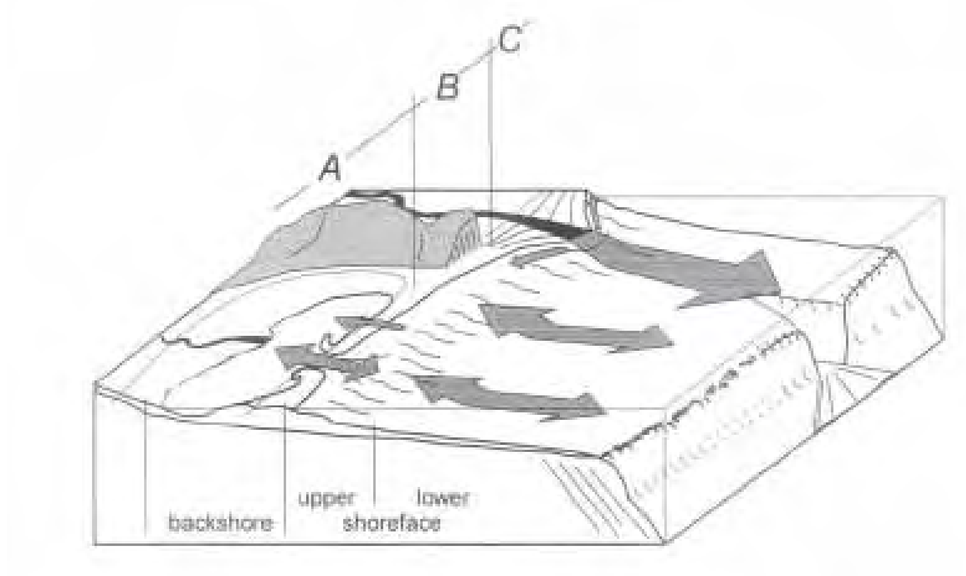


Figure 4.5 Physical morphology encompassed by the 'coastal tract'.

The upper shoreface may variously include (A) dune, washovers, flood-tide deltas, lagoonal basins and tidal flats; (B) mainland beaches; and (C) fluvial deltas. After Cowell et al. (2003a).

4.2. Controls

The importance of geological factors as fundamental controls on the nature and evolution of coastal morphology has been recognized since the earliest days of coastal geomorphological investigation. At the broadest scale, that of continents and sub-continents, coastal morphological development is determined by plate tectonic processes (Inman and Nordstrom, 1971). The United Kingdom and adjoining continental shelf sit on the north-western margin of the Eurasian Plate, which separated from the North American plate as a result of the opening of the North Atlantic Ocean. Parts of the UK and adjoining shelf area have experienced significant tectonic movements in the last 50 million years, notably associated with subsidence and tilting around the margins of the southern North Sea basin. During the past two to three million years, much of northern and central Britain became covered by ice on several occasions, causing isostatic depression of the Earth's crust and subsequent recovery (uplift) following deglaciation. During the height of the last (Devensian) ice age, ice extended from Scandinavia, across the northern North Sea, Scotland and northern England, and became contiguous with separate ice sheets centred in North Wales and Ireland. Around this time, sea level was of the order of 120-140 m lower than present and much of the continental shelf was exposed to sub-aerial processes. Following deglaciation, the sea rose rapidly and submerged much of the exposed land area (see papers in Shennan *et al*., 1992). Approximately 10,000 years ago, the southern North Sea, eastern English Channel and eastern Irish Sea were still dry land, but by around 4,500 years ago the UK coastline had acquired its present configuration (Figure 4.7).

Although erosion undoubtedly played a role, most of the coastal change during this 5,000-year period occurred as a result of submergence. The rate of sea level rise during the early Holocene is likely to have been too rapid for soft sediment shorelines to have responded in the equilibrium manner predicted by the Bruun Rule of shore erosion (Bruun, 1962, 1988). The broad configuration of the British coast was established by 4,500 years ago and its position and general outline were determined largely by the pre-existing relief and especially by the distribution of relatively high areas composed of 'hard' rock which resisted erosion. Such hard rock outcrops formed anchor points which have strongly influenced the subsequent pattern of sediment transport and coastal morphological change during the mid to late Holocene. After 4,500 B.P (Before Present), coastal change around the UK coast principally involved erosion of soft cliffs, often composed of glacial and fluvio-glacial deposits, marine reworking of submerged Pleistocene sediments, and infilling of bays and estuaries. Initially such processes were rapid, but in the later Holocene slowed markedly in many areas as the potential supply of marine and coastal sediment became exhausted (and in some places cut off by engineering works from the eighteenth century onwards).

Serious attempts to develop numerical models of long-term (in an engineering sense) morphological development began in the 1970s and continued during the 1980s and early 1990s (see de Vriend, 1987, 1992a; de Vriend *et al*., 1993). A major difficulty in this is that the methods for short and medium-term modelling cannot readily be applied to longer term prediction owing to the non-linear character of most coastal processes and morphological responses (Wright and Thom, 1977; Stive *et al*., 1991; Terwindt and Battjes, 1991; Phillips, 1992). During the past 15 years there have been sustained attempts to develop and apply numerical modelling methods more applicable to such non-linear behaviour (see Dearing *et al*., 2006). A range of models have also been developed which draw heavily on procedures developed to help interpret sedimentary sequences in the geological record related to oil and gas exploration, and the historical development of coastal sedimentary sequences during the Quaternary (see Cowell *et al*., 1995, 2003a, 2003b; Storms *et al.*, 2002).

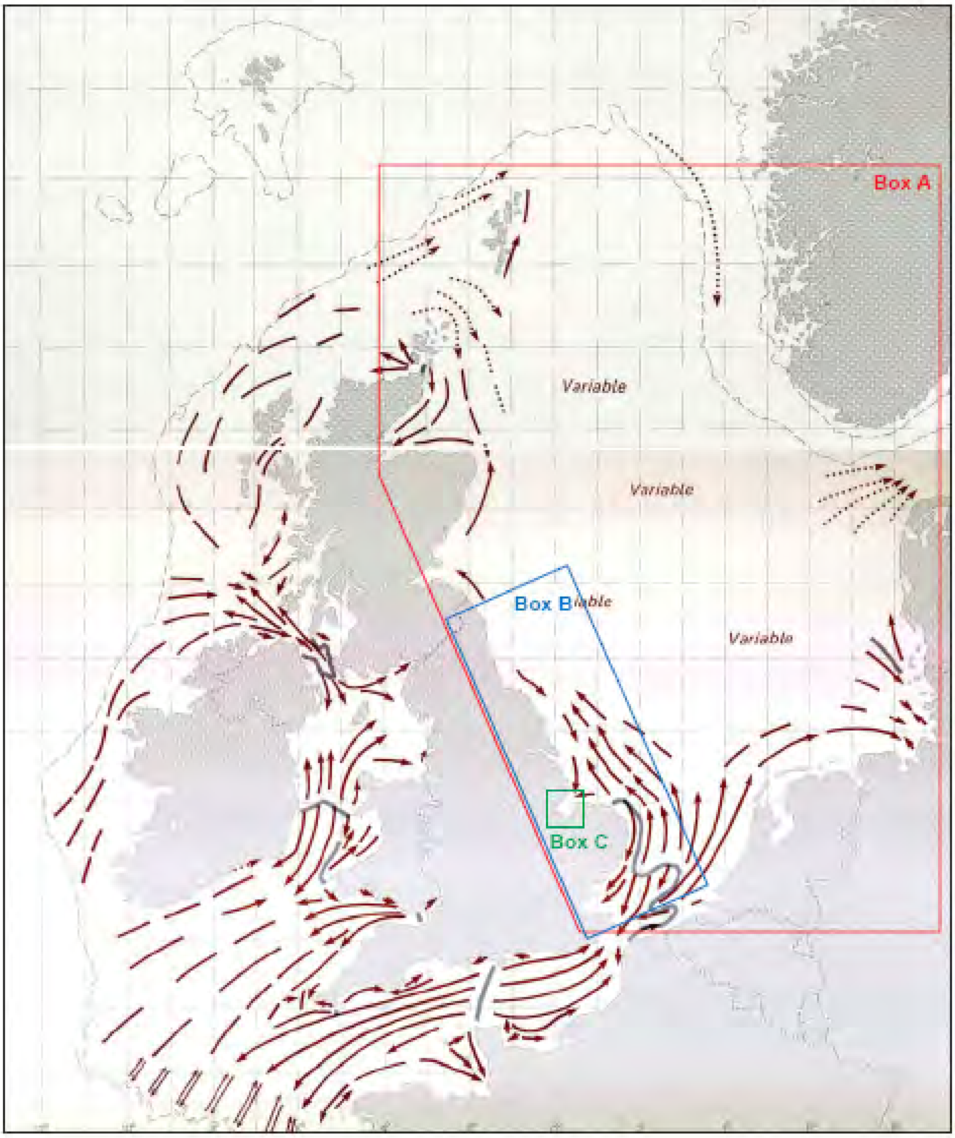


Figure 4.6 Long-term sand transport directions.

Boxes represent example coastal tracts at different scales; (Box A) North Sea; (Box B) East Coast of England; (C) Wash-Fenland Embayment. Modified from Lee and Ramster (1981).

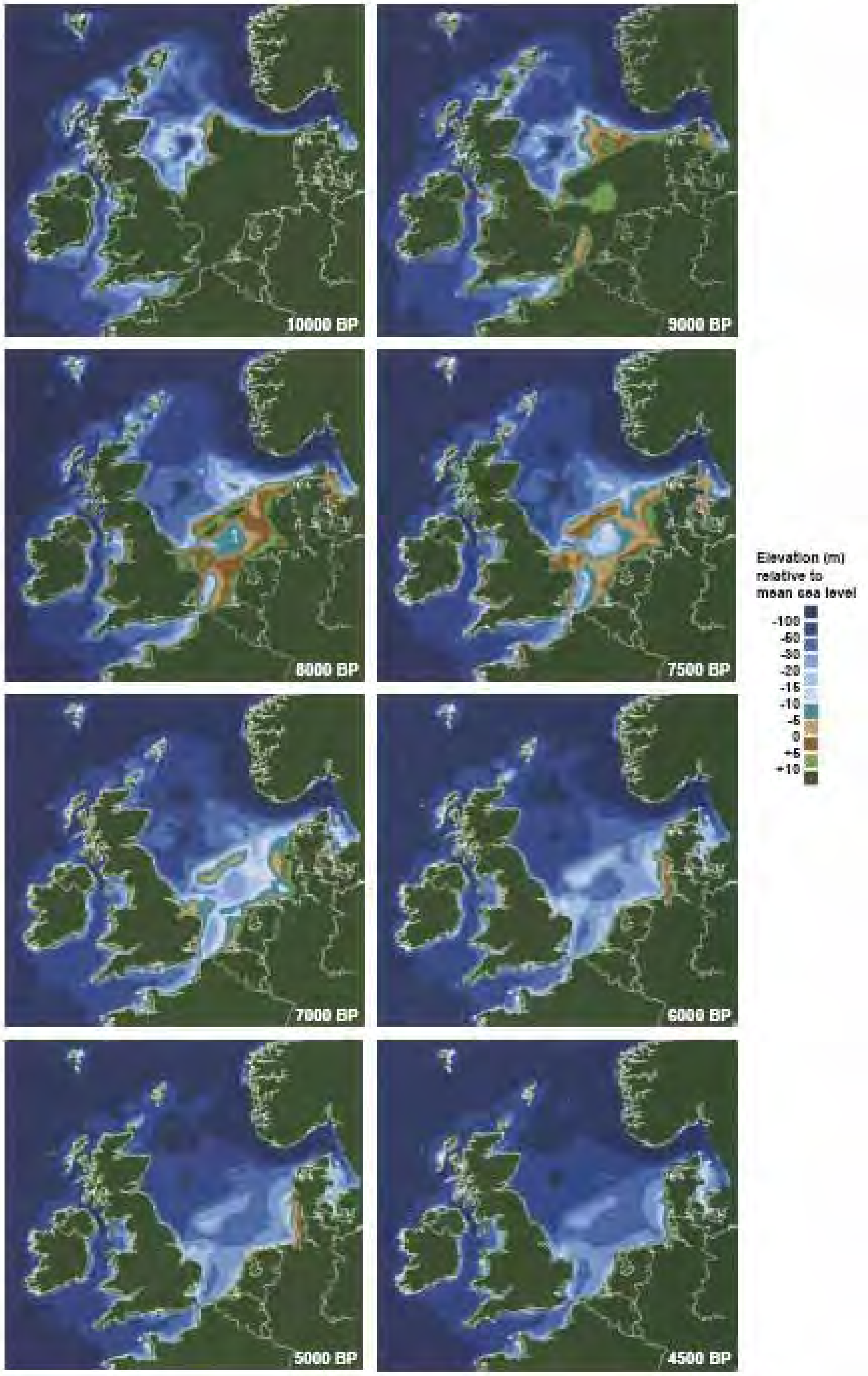


Figure 4.7 Palaeogeographic reconstructions of northwest Europe (after Shennan *et al.,* 2000).

5. Description of geomorphological features and elements and interventions

5.1. Geomorphological features and elements

For a comprehensive description of geomorphological features and elements and their links, the reader is referred to the inception report for this project (Whitehouse *et al.*, 2008). The conceptual model thus formed by the use of an element level description of the coastal system is expanded further in Chapter 6 of our report. In Whitehouse *et al.* (2008) the geomorphological elements were defined, as these form the smallest scale building blocks of the coastal system being represented in the approach adopted here. The elements described were:

- Sea cliffs
- Coastal dunes
- Coastal lagoons
- Beaches
- Shore platforms
- Tidal flats
- Saltmarshes
- Sandbanks and channels

An element within sandbanks and channels required separate identification:

- Inlet-associated banks

More information is given in Whitehouse *et al.* (2008) in which each element is described in a standardised format summarising the long-term and wide-scale morphological changes that can take place and the current state of knowledge regarding analysis and management approaches.

To provide generic tools applicable at any UK location, it is necessary to understand the geomorphological behaviour of the coastal system as a whole and the links between its component parts. A functioning coastal system is made up of features, which combine and interact over a range of timescales. Coastal features are themselves made up of one or more geomorphological units or elements. These form the basic building blocks of the coastal system and as such are the starting point for this study. An example of a coastal system showing features and elements is presented in Figure 5.1.

Figure 5.1 Example of a coastal system with features (green) and elements (white) (from Whitehouse *et al.*, 2008).

5.2. Generic coastal features

Ten features were identified as representing the medium-scale geomorphological texture of our coasts; these are described below. For convenience and to provide context, the feature level description from Whitehouse *et al.* (2008) is reproduced in the following sections. Each feature and its associated set of elements can be taken to form a generic description.

5.2.1. Seabed

The area of seabed of interest in this study is situated on the continental shelf, which separates shallow coastal waters from the deep ocean. The historical evolution of the seabed is controlled by sea level fluctuations, particularly in response to ice coverage, whilst the composition of the seabed is governed by the local geology and available sediment supply from river discharge and coastal erosion. Coastal seabed sediments range from fine mud and clays to shingle and glacial boulders. Sediments are reworked by tidal currents and (in shallow water) wave action to form bedforms such as ripples and sandwaves and large-scale features such as banks and channels.

5.2.1.1. *Associated geomorphological elements*

- Sandbanks and channels
- Shore platforms
- Beaches

5.2.2. Open coast

The coast is essentially defined as being that part of a land mass which borders the ocean or its saltwater tributaries. Specifically, an open or pelagic coast refers to a coast that fronts the open ocean as opposed to sheltered coasts found within gulfs or bays. The open coast is a dynamic system whose evolution is controlled by its inherent composition, by long-term drivers such as sea level fluctuations and isostatic variability; and by the prevailing hydrodynamic regime.

An emergent coastline is a coastline which has experienced a fall in sea level because of a global sea level change or local uplift. Emergent coastlines are identifiable by the coastal landforms, which are above the high tide mark, such as raised beaches. Alternatively, a submergent coastline is a coastline which has experienced a rise in sea level, due to a global sea level change, local subsidence or isostatic rebound. Submergent coastlines are identifiable by their submerged or "drowned" landforms, such as rias (drowned valleys) and fjords.

A concordant coastline is a coastline where bands of different rock types run parallel to the shore. These rock types are usually of alternating resistance, so the coastline forms distinctive landforms. A discordant coastline is a type of coastline formed when rock types of alternating resistance run perpendicular to the shore. Discordant coastlines feature distinctive landforms because the rocks are eroded by ocean waves.

5.2.2.1. *Associated geomorphological elements*

- Cliffs
- Beaches
- Lagoons
- Dunes
- Shore platforms
- Tidal flats
- Sandbanks and channels

5.2.3. Headlands and bays

A bay is an area of water bordered by land on three sides and usually situated between headlands. A headland is a piece of land that juts into the sea from the coast. Headlands are formed when the sea attacks a section of coast consisting of alternating bands of hard and soft rock. The bands of soft rock such as sand and clay erode more quickly than those of more resistant hard rock such as chalk, granite and limestone. Waves erode the areas of softer rock more rapidly than the hard rock to form bays.

Wave refraction occurs around headlands, which concentrates energy on them. This results in the formation (and subsequent erosion) of landforms, such as caves, natural arches and stacks. Within a bay, refracted wave energy is dispersed which, along with the sheltering effect of the headlands, protects bays from storms. Beaches and other accretionary structures often form in bays as a result of the shelter provided by the headlands. A bay may vary in size from a few metres to hundreds of kilometres.

5.2.3.1. Associated geomorphological elements

Headland

- Cliffs
- Sandbanks and channels
- Shore platforms

Bay

- Beaches
- Saltmarshes
- Tidal flats
- Dunes
- Shore platforms

5.2.4. Spit

Sediments eroded from cliffs or transported into the sea by rivers may be worked into a variety of accretional landforms. One such feature is a spit, which comprises a beach and associated backshore and dunes that are tied to the coast at the proximal (landward) end. Spits are formed when a longshore current reaches a cove or headland, where the change in orientation is greater than 30^{o}. The resultant energy dissipation causes sediment to be deposited forming a bar, which eventually becomes a spit. Spits are most common on irregular coasts, where they grow across the mouths of bays or rivers. The majority of these features grow in the direction of predominant longshore sediment transport but other examples are known to align themselves almost at right angles to the prevailing wave direction. The distal end of the spit may terminate in a recurve, which is caused by wave refraction around the end of the structure or by the interaction between converging wave trains.

If the supply of sediment is interrupted, the sand at the proximal end of the spit may be moved towards the head, eventually creating an island. If the supply isn't interrupted, and the spit isn't breached by the sea (or, if across an estuary, the river) the spit may evolve into a bar with both ends joined to land, and a lagoon behind. If an island lies offshore near where the coast changes direction, and the spit continues to grow until it connects the island to the mainland, it is then called a tombolo. Saltmarshes frequently develop in the lee of the spit, where wave action is reduced.

5.2.4.1. Associated geomorphological elements

- Beaches
- Lagoons

- Sandbanks and channels
- Saltmarshes
- Dunes

5.2.5. Cuspate foreland

Beach material is moved along the coast by longshore drift until the coastline changes in orientation. At this point, material may be deposited, resulting in the formation of a spit. Cuspate forelands are formed when the prevailing wind and a powerful secondary wind in the opposite direction move sediment down the coastline from both directions to a place where the coastline changes. Over time, the two resultant spits merge into a triangular protrusion and a foreland develops. The majority of cuspate forelands are formed over a coastline that juts out into the sea at enough of an angle to allow the drifting beach material to 'spill over' as a result of longshore drift in both directions.

The deposited sediment is colonised by pioneer vegetation, which stabilises the foreland into a permanent coastal feature, encouraging further sediment deposition. Over time, the prevailing wind and hydrodynamic regime may cause the foreland to migrate along the coastline.

5.2.5.1. Associated geomorphological elements

- Saltmarshes
- Dunes
- Tidal flats

5.2.6. Inlet

An inlet is a narrow body between islands or leading inland from a larger body of water, often leading to an enclosed body of water, such as a sound, bay, lagoon or marsh. The term inlet usually refers to the actual connection between a bay and the sea. Inlets are commonly associated with barrier islands that have been breached during storm conditions. In many cases, the breach originates from the landward side of the barrier as water levels in the lagoon or bay rise due to excess runoff from the land. Onshore winds may create a surge on both sides of the barrier, which results in a downward slope of the sea surface towards the barrier. The resultant standing waves overtop the barrier at any low-lying points and may ultimately carve a channel through the structure. Tidal inlets of this kind are generally temporary features, as sediment transported alongshore rapidly repairs the breach. However, in many cases, the inlets may increase in size and depth to become principal avenues for the interchanges of water between the sea and the bay or lagoon.

5.2.6.1. Associated geomorphological elements

- Beaches
- Lagoons
- Sandbanks and channels
- Tidal flats

5.2.7. Tombolo

A tombolo is a deposition landform such as a spit or a bar, which forms a narrow piece of land between an island or offshore rock and a mainland shore, or between two islands or offshore rocks. They usually form because the island causes wave refraction, depositing sand and shingle moved by longshore drift in each direction around the island where the waves meet. Eustatic sea level rise may also contribute to accretion as material is pushed up with rising sea levels.

5.2.7.1. Associated geomorphological elements

- Beaches
- Dunes

5.2.8. Barrier island

A barrier island may be defined as an emergent, unconsolidated, generally linear body of sand or gravel that is separated from the mainland by a lagoon or marsh. Barrier islands are repositories for enormous volumes of sediment and as such are generally formed where there is an abundant supply of sediment and where the local bathymetric gradients are relatively shallow. The geological development of barrier islands varies with location. Many islands originated from elongated sand ridges that were submerged by rising sea levels around 5,000 years ago, whilst others may have developed from the longshore extensions of spits that were subsequently breached during storms and detached from the mainland by lagoons.

The seaward side of a barrier island is usually characterised by a bermed beach that is backed by dunes. The beach is often subject to intense wave action. Moving seawards, the dunes are succeeded by a grassy area known as a 'back island flat' which gives way to saltmarshes, sand flats and ultimately the lagoon.

Once formed, the barrier island complex may migrate landwards through overwash processes, thereby keeping pace with rising sea levels.

5.2.8.1. Associated geomorphological elements

- Beach
- Dune
- Saltmarsh
- Tidal flat
- Lagoon

5.2.9. Estuary

An estuary is a semi-enclosed coastal body of water with one or more rivers or streams flowing into it, and with a free connection to the open sea.

Estuaries are often characterized by sedimentation or silt carried in from terrestrial runoff and, frequently, from offshore. They are made up of brackish water. Estuaries are more likely to occur on submerged coasts, where the sea level has risen in relation to the land; this process floods valleys to form rias and fjords. These can become estuaries if there is a stream or river flowing into them. Estuaries often have many tributaries and develop complex patterns of banks and channels. Estuarine circulation is common in estuaries; this occurs when fresh or brackish water flows out near the surface, while denser saline water flows inward near the bottom. Anti-estuarine flow is its opposite, in which dense water flows out near the bottom and less dense water circulates inward at the surface. Estuaries are marine environments, whose pH, salinity, and water level are varying, depending on the river that feeds the estuary and the ocean from which it derives its salinity. The time it takes an estuary to completely cycle is called flushing time.

Estuaries may be classified according to the degree of mixing that occurs between saline and fresh water, but more useful in the present context is a classification based on their geomorphological properties, as listed in the Table 5.1 (ABP Marine Environment Research Ltd *et al*., 2008 – information also accessible through www.estuary-guide.net):

Table 5.1 Estuary classification

Type	Behavioural type	Rule
1	Fjord	Glacial origin, exposed rock platform set within steep-sided relief and with no significant mud or sand flats
2	Fjard	Glacial origin, low lying relief, with significant area of sand or mud flats
3	Ria	Drowned river valley in origin, with exposed rock platform and no linear banks
4	Spit-enclosed	Drowned river valley in origin, with one or more spits and not an embayment
5	Funnel-shaped	Drowned river valley in origin, with linear banks or no ebb/flood delta and not an embayment
6	Embayment	River or marine in origin (not glacial), with multiple tidal rivers meeting at or near mouth and a bay width/length ratio[1] of one or greater, and no exposed rock platform
7	Tidal inlet	Drowned coastal plain in origin, with barrier beaches or spits

[1] Where bay extends from sea opening to the confluence of the rivers

Such classifications provide a broad description of the type of estuary.

5.2.9.1. Associated geomorphological elements

- Saltmarsh
- Tidal flats
- Sandbanks and channels

5.2.10. River

A river is a natural waterway that transports fresh water through a landscape from higher to lower elevations. The water within a river is generally collected from precipitation through surface runoff and groundwater recharge (as seen at baseflow conditions/during periods of lack of precipitation) and release of stored water in natural reservoirs, such as a glacier.

The water in a river is usually confined to a channel made up of a stream bed between banks. In larger rivers there is also a wider floodplain shaped by flood waters over-topping the channel. Floodplains may be very wide in relation to the size of the river channel. This distinction between river channel and floodplain can be blurred, especially in urban areas where the floodplain of a river channel can become greatly developed by housing and industry.

A river flowing in its channel is a source of energy which acts on the river channel to change its shape and form. Rivers that carry large amounts of sediment may develop conspicuous deltas at their mouths, if conditions permit. Rivers whose mouths are in saline tidal waters may form estuaries.

5.2.10.1. Associated geomorphological elements

- Tidal flats
- Sandbanks and channels

The next section of this report deals with how human intervention can be represented as analogues for natural coastal geomorphological elements.

5.3. Human intervention in coastal evolution

Around much of England and Wales, the natural evolution of the coastline has been significantly affected by human intervention. Some of these interventions, such as the reclamation of inter-tidal areas, date back over 1,000 years and have thus undoubtedly affected the long-term evolution of our shorelines. In any practical methodology for anticipating the evolution of the UK coastline, therefore, it is necessary to include a representation of such intervention measures, particularly those that are designed principally to reduce the risks of coastal flooding and erosion, such as coastal defences. Table 5.2 shows how management techniques relate to the Defra shoreline policies (Table 4.1 in Whitehouse *et al.*, 2008). While management techniques are effective at the local level, policy usually relates to a broader scale.

The dominant element to which management techniques is related appears to be the beach, and less frequently the cliff and tidal flat. If it is agreed that the general purpose of all management techniques is to prevent change in landward elements, the way in which the different techniques work needs to be recognised. For example, a beach can be managed by (i) recharge which uses natural processes to maintain its protective qualities, or (ii) groynes interrupting natural processes for the same aim. The ‘on-costs’ of the management also need to be considered – for example, sediment starvation downdrift of groynes, or recycling. To enable the representation of management interventions in coastal systems, an assessment was completed of how those interventions relate to natural system states, and how these can be represented as analogues of natural processes.

Table 5.2 Management techniques related to type of management and shoreline management policy.

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="3">Management technique</td></tr>
<tr><td>Hard defence</td><td>Soft defence</td><td>No interference</td></tr>
<tr><td rowspan="4">Shoreline Management Policy Defra (2006a)</td><td>Hold the existing line</td><td>Long terminal groynes
Short groynes
Seawalls and revetments
Breakwaters and reefs</td><td>Recharge
Recycling
Bypassing
Beach reprofiling</td><td></td></tr>
<tr><td>Advance the existing defence line</td><td>As above, plus
Reclamation embankments</td><td>Recharge</td><td></td></tr>
<tr><td>Managed realignment</td><td>Different engineered breach mechanisms and embankments</td><td>Use of fine grain dredged material (form of recharge)</td><td>No maintenance</td></tr>
<tr><td>No active interference</td><td></td><td></td><td>No maintenance</td></tr>
</table>

5.3.1. Classification

This section sets out an initial classification of the commonest intervention schemes, drawing analogies to natural coastal features or processes. Treating management or intervention measures in this way simplifies their representation in any predictive methodology or model of coastal evolution. For example, the recycling of beach sediments can be treated as an alteration to the representation of longshore sediment transport that would be needed in a model of that beach.

The main problem with including human intervention and management schemes in the prediction of coastal evolution, however, is not in specifying their physical effects but in the uncertainty about changes in such interventions or management in the future. For example, the sudden collapse of a seawall or construction of a new coastal harbour would radically alter the coastline in that area. In addition, such events may also result in new elements having to be included in the representation of processes affecting the evolution of that coastline, for example if a new tidal inlet formed and entered the sea in the gap created by the failure or removal of a seawall.

In some cases, sudden changes in coastal defence schemes, and the like, have an analogy in natural features and processes. For example, a sudden severe fluvial event might result in a sudden deposition of sediment on a beach similar to that created by a beach recharge scheme. However, significant and sudden natural changes of this sort are rare in the UK compared to their man-made equivalents.

In any scheme of representation of human interventions that draws on natural analogues, the intervention itself and effect of the intervention need to be distinguished in subsequent analysis.

5.3.2. Beach recharge

Beach recharge is the addition of sediment to beaches, typically to improve their capacity to dissipate wave energy and form a “soft” barrier between the sea and other defence structures such as seawalls. Such operations, at least in the UK, occur only occasionally, with intervening gaps of perhaps 10 years or more. Elsewhere, for example in the Netherlands, recharge is carried out more regularly.

In either case, the effects of such operations on beach and coastal evolution are broadly equivalent to the supply of sediments from rivers (compare the situation in the Middle East where occasional intense rain storms fill wadis that then deliver large quantities of sediment to the coast in a short time) or from the onshore movement of sediment from the offshore zone.

Neither analogy is entirely satisfactory. The natural episodic arrival on a beach of sediment from deep water, without the formation and gradual evolution of any intermediate nearshore banks, is rather a remote possibility and one that certainly would be difficult to demonstrate and quantify around the UK coastline.

Rivers tend to deliver the sediment over a very short frontage, forming a delta, whereas beach recharge operations typically include lateral spreading of the sediment to produce a roughly constant beach width. However, longshore drift quite quickly redistributes beach sediments delivered by episodic river discharges and would do so if the beach recharge material was placed as an “artificial delta”, so that in the context of long-term evolution, this difference may not be important. This is therefore concluded to be the best way of classifying beach recharge.

5.3.3. Recycling

Beach recycling is the process by which sediment is collected from one part of a beach and deposited further “updrift”, and this is typically carried out at intervals of six months to three years. During the period between the end of one recycling operation and the next, the beach widths at each end of, and between, the ends of the frontage over which recycling operations take place will vary substantially, perhaps by as much as 20 m or more. Over the long-term, the effect of recycling generally maintains beaches so their width changes only slowly, for example as some sediment escapes from the downdrift end of the frontage and cannot be recycled as a consequence. These recycling operations can therefore be regarded as equivalent to a localised alteration to the net longshore drift, equivalent to that produced by a localised shift in the mean wave direction closer to the beach normal.

5.3.4. Bypassing

Beach bypassing involves the mechanical collection of beach sediment from one area where it has accumulated and redistributing it to another where beach widths have reduced. However in this case, the movement of sediment is in the same direction as the net longshore drift. Bypassing is typically used to transfer sediment past a natural or artificial obstruction to the longshore drift such as the mouth of a tidal inlet or the breakwaters of a coastal harbour.

In the former case, bypassing is used to prevent movement of the mouth of the inlet, and associated evolution of spits and/or ebb shoal deltas that can interfere with safe navigation, discharge of rivers or erosion of the coastline downdrift of the inlet.

In the latter situation, bypassing is typically used to compensate for the adverse effects on a coastline of introducing an artificial headland the may cause sediment starvation and erosion of beaches downdrift and cause beach sediment arriving on its updrift side to be carried into deep water or accumulate in dredged areas such as a harbour or navigation channel.

Such operations may be of a temporary nature, in connection with short-term engineering works, or be continued indefinitely. Where the distances involved in transporting sediment are short, and the annual quantities of sediment involved are modest (perhaps under 100,000 cubic metres/year), the usual method of bypassing involves excavators and tipper trucks as normally used in recycling operations. The frequency of such bypassing operations is also similar to those used for beach recycling. For larger quantities of materials, bypassing may need to be carried out on a more frequent basis, and a number of methods involving pipelines and pumps have been built to make bypassing more cost-effective. Although bypassing has been carried out at numerous locations in the USA, and more recently Australia, there are few examples of bypassing in the UK, save at Shoreham where shingle is collected from west of the harbour arms and placed on the beach to the east.

It is difficult to find natural analogies to mechanical bypassing of beach sediments. However the main long-term effect of these is to reduce or remove the effects of an obstruction to longshore drift that would otherwise need to be included in the consideration of how a coastline evolves.

5.3.5. Beach reprofiling

In a number of places around the UK coastline, bulldozers are used to artificially alter the cross-sectional profile of beaches to increase their crest levels. For some barrier beaches, sediment is collected from landwards of the beach crest and placed onto its crest or seaward face, thus reducing the rate at which such beaches are over-washed and moved landwards. Such operations are often carried out after severe storm events, on an *ad hoc* basis, to prevent or reduce overtopping of the beach in the following weeks or months. Such operations may also be helpful in restoring access along the beach at all states of the tide.

Typically, the result of such operations is a narrow beach crest often at a higher level than would be formed naturally, at the expense of a steeper cross-sectional profile. The steeper lower beach face will allow larger breakers to occur further inshore, and such operations also alter the natural permeability of shingle beaches, for example by exposing some of the below-surface layers of beach sediment to wave action.

The efficacy of such operations on their own, even in the short-term, is open to debate (NRA, 1994) although they undoubtedly have positive “public relation” benefits. There has been little in the way of research into this form of beach management.

Where such operations are limited to the seaward face and crest of beaches, reprofiling (sometimes called “beach scraping”) might be thought of as having a similar effect to that caused to the beach by a period of exceptionally long-period high-energy swell, or perhaps by a tsunami. There is no natural marine process, however, that replicates the collection of sediments washed over a barrier beach crest and replacement of it on or seaward of the beach crest.

In the Environment Agency’s southern region, the most common method of beach reprofiling (sometimes called “beach bumping”) is moving material, usually shingle, from the lower part of the beach to steepen the front slope and increase crest width. This is the opposite of the natural process where long period waves tend to reduce the beach slope, but similar to the normal summer process when small waves tend to build up the crest. This is usually carried out on the combined shingle/sand beaches.

5.3.6. Long groynes or harbour arms

In this classification, a distinction is made between long groynes and allied structures such as harbour breakwaters and shorter groynes that are typically built in groups. The main reason for making such a division lies in the practicalities of modelling the long-term evolution of the coastline in their vicinity, where “long groynes” could be individually represented while shorter structures could not. Inevitably this distinction is not entirely clear-cut, but as an initial guide it is suggested that long groynes are those that extend over 100 metres out from the high water line, affect beach plan shapes over perhaps 500 metres or more and are built singly.

The likely effects of long groynes include:

- Altering wave heights and directions along the shoreline by direct sheltering; diffraction and reflection.
- Altering and obstructing wave-induced currents. Long groynes often extend seaward of the outer edge of the nearshore zone within which such currents are normally constrained.
- Obstructing longshore drift and potentially diverting both longshore currents and the sediment they transport offshore.
- Altering nearshore tidal currents over a substantial length of coastline on either side of the structure.

Such long groynes are analogous to rocky headlands.

5.3.7. Short groynes and groyne fields

Short groynes are common in the UK. They are typically 40-80 metres long and built in groups (fields) designed to locally reduce the longshore drift rate at least on the upper part of beaches, and /or prevent tidal or wave induced currents running along the face of seawalls, promenades and coastal cliffs.

Their effects on physical processes are similar to those of long groynes, see above, but because they do not extend seaward of the outer edge of the nearshore zone within which such currents are normally constrained, short groynes are not likely to divert both longshore currents and the sediment they transport very far offshore.

Their long-term effects on beach plan shape are typically localised, within the bays between the groynes and extending along the coastline updrift and downdrift of the groyne field to perhaps five to ten times the groyne length.

In terms of long-term coastal evolution, short groynes might be best represented by reducing the longshore drift locally (this needs to be quantified on a case-by-case basis as in many cases the reduction in drift rates may actually be small) or, in the case where they also alter tidal currents, for example at the mouths of tidal inlets, by increasing the frictional resistance of the seabed.

5.3.8. Seawalls and revetments

Seawalls and revetments have a variety of effects on the beaches in front of them, although the intensity of these depends on both the characteristics of the structure, such as its slope, roughness and permeability, and on the beach in front of it, that is, its width, gradient and sediments.

Seawalls and revetments restrict the landward movement of upper beach contours and prevent or greatly reduce the input of new beach sediment from the hinterland to beaches, for example when built between the beach and soft cliffs or dunes. They also reduce the transfer of sediments from beaches to the hinterland, although wind action and overtopping waves can often result in significant quantities of sediment being deposited on the immediate hinterland.

When waves reach them, seawalls affect the longshore transport of sediment, as some of the incoming wave energy is reflected seawards. The reduction in alongshore directed momentum that would have been released by the breaking of those waves will in turn reduce the longshore currents the waves produce. However, reflected waves will produce greater agitation of the beaches and seabed in front of the wall. The balance between the reduction in longshore current speeds and increase in suspended sediment concentration is difficult to predict, but typically seawalls reduce the longshore drift passing in front of them.

Seawalls also alter the processes that lead to cross-shore sediment transport, beach profile changes and perhaps the long-term rates of interchange of sediments between beaches and the nearshore seabed. There is little evidence to support the commonly-held view that seawalls and revetments result in the flattening of beach profiles or greater long-term offshore losses of beach sediments, although there is often a localised scour trough immediately adjacent to the toe of such structures. The role of structure slope needs to be recognised.

In many ways, the effects of seawalls and revetments are analogous to that of hard-rock cliffs.

5.3.9. Detached breakwaters and reefs

The construction of detached breakwaters and reefs as coastal defences is a recent and still unusual practice in the UK, although it has been used elsewhere, particularly along the northern Mediterranean coastline and in Japan. More of these structures have been built as part of a harbour, although most of these are connected to the shoreline by a shore-perpendicular arm that itself acts like a long groyne (see Section 5.3.6).

These structures are analogous to rocky islands or outcrops on the nearshore seabed, and the design and prediction of their effects is often based on observations of their natural equivalents.

Their effects include:

- Partial dissipation of wave energy creating lower heights to landward.
- The refraction/diffraction of waves passing close by the structures, with perhaps some areas of slightly increased wave energy along the shoreline either side of the sheltered zone.
- A potentially complicated and time-variable pattern of currents produced by breaking waves and tides, with the potential to divert beach sediments well seaward of the surf zone.
- A strong tendency for the accumulation of beach sediment in their lee, potentially at the expense of erosion either side of the sheltered zone.

5.3.10. Reclamation embankments

In many UK estuaries, the tidal regime has been altered significantly by the construction of embankments that enclose a significant amount of the inter-tidal area. Such embankments can affect not only the estuary itself but the coastline either side of its entrance, for example by reducing the estuary's entrance channel dimensions and size of the ebb shoal delta. Such embankments continue to be built, such as the Cardiff Bay Barrage, or proposed, but simultaneously there are areas where older embankments may be removed (managed realignment) or allowed to deteriorate thus partly restoring the inter-tidal areas previously lost.

5.4. Using features and elements to develop system- mapping approach and comments on including interventions

The geomorphological features and elements described in Sections 5.1 and 5.2 were used to develop the system-mapping approach (Chapter 6) and, based on example mapping exercises, the set of elements was reviewed and expanded from that used by Whitehouse *et al.* (2008). The inclusion of human interventions described in Section 5.3 for open coast elements was represented in the system-mapping approach.   In the case of inlets and estuaries, tidal locking from the presence of tidal sluice gates might need to be included (such as Bembridge where sluice gates were installed in Victorian times). This was included in the approach in Chapter 6.

The range of interventions could be expanded in the future to include management techniques for fine-grained material recharge (such as the use of dredged material for soft sediment recharge and associated methods for retaining and enhancing sedimentation on mud flats) and different breaching methods for managed realignment and regulated tidal exchange where defences are maintained. Other interventions that might be covered include cliff stabilisation, and dune building or stabilisation. The physical analogue of this would need to be considered on a case-by-case basis.

6. Coastal system mapping

A major element of this project has involved the formalisation and demonstration of a method for broad-scale mapping of coastal geomorphological systems. Broad-scale system mapping is intended to characterise the interactions that govern coastal behaviour at various scales, and to provide a conceptual framework for the deployment of predictive models. The system mapping methodology presented here takes as its starting point the initial set of coastal features and elements defined in Whitehouse *et al.* (2008). Some amendments and additions to the initial classificatory scheme were required to capture the range of cross-shore and alongshore variation in landforms encountered around the coastline of England and Wales, and to incorporate the influence of engineered structures and other forms of management intervention.

This section sets out some guiding principles for the conceptualisation of large-scale coastal geomorphological behaviour within a systems framework, and from these, derives a procedure for consistent application of the system mapping methodology. The coastal system mapping methodology is demonstrated through three case studies (Figure 6.1). These have been chosen on the basis of their contrasting spatial scales, in order to sample a variety of coastal process settings.

The first case study covers a 73-km stretch of the Suffolk coastline between Lowestoft and Landguard Point (the entirety of coastal sub-cell 3c; Figure 6.1a). This stretch of coast is characterised by more or less continuous littoral drift system, punctuated by a number of small estuaries, and by interaction with offshore banks.

The second case study, Alnmouth Bay in Northumberland (Figure 6.1b), shows how the system mapping approach can be applied at a smaller scale (approximately 15 km) to a section of coast characterised by a less continuous littoral drift system and more marked geological controls.

Finally, Cardigan Bay in Wales (Figure 6.1c) is used to demonstrate the application of the approach at a larger scale to a 267-km stretch of coast that encompasses the entirety of coastal cell 9 (which includes two sub-cells). This coastline is predominantly rocky, with a series of outcropping headlands and bay beaches, several estuary mouths, dune and lagoon systems, and offshore reefs of glacial origin.

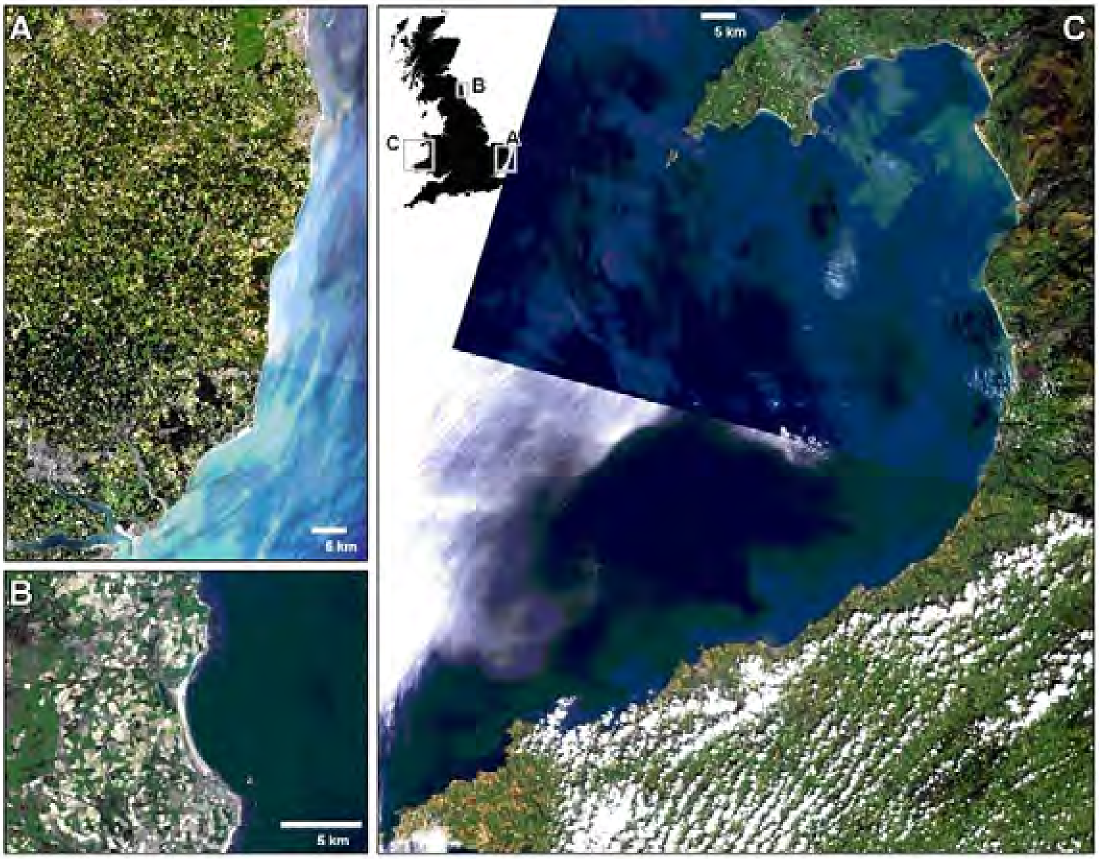


Figure 6.1 Location of three coastal system mapping case studies. a) Lowestoft to Landguard Point (Suffolk sub-cell 3c); b) Alnmouth Bay, Northumberland; c) Cardigan Bay, Wales (coastal cell 9). Scale bars are five km in each case.

6.1. Guidance on procedure for mapping

6.1.1. Approach and implementation

The broad-scale system mapping presented here is not intended to provide predictive modelling capability directly (in the way that was attempted in FD2117 'EstSim' (ABPmer *et al.* 2007), for example). Instead, system mapping provides a means of synthesising and formalising scientific understanding of how particular stretches of coast behave. It is a form of knowledge formalisation that allows disparate sources of information (or 'plain data') to be converted to usable knowledge and a more systematic understanding. The resulting maps provide an efficient means of encapsulating scientific understanding in a conceptual model of coastal system behaviour.

Coastal system mapping also provides a framework for the deployment of predictive models capable of simulating large-scale and long-term coastal morphodynamics. Predictive model development in this project comprises proof of concept work to couple an open coast model, SCAPE (Walkden and Hall, 2005), with an estuary model, ASMITA (Stive *et al*. 1998; van Goor *et al*. 2003; Kragtwijk *et al*. 2004) within the system mapping framework. Broad-scale system mapping is necessary to identify the important sediment sources, stores and sinks, and to define the connectivity of coastal and estuary sub-systems; this understanding provides the basis for deciding the most appropriate spatial scale at which to undertake predictive morphodynamic modelling and aids the specification of model boundaries.

Given the subjective nature of knowledge formalisation, it is unrealistic to think in terms of a single coastal system map that is ‘valid’ for a particular location and scale of enquiry. Different experts will invariably interpret data and scientific literature in varying ways, and system mapping can thus provide a vehicle for the development of scientific consensus on the behaviour of a given coastal system. Alternatively, comparison of maps (and conceptual models) produced in isolation by different experts can reveal areas of consensus or understanding, and areas of disagreement or poor understanding. In either case, mapping should be undertaken in a logically consistent and rigorous manner.

Our methodology envisages coastal system mapping as a two-stage process. The first stage involves conceptualisation of the coastal system in terms of a set of discrete components and representation of the interactions between these components in diagrammatic form. In principle, this could be done as a pencil and paper exercise. However, construction of system diagrams is most easily accomplished with the aid of specialist computer software and, to this end, we used CmapTools (available as freeware from: http://cmap.ihmc.us). CmapTools was developed to aid the production of ‘concept maps’, graphical tools for organizing and representing knowledge. We departed from some of the conventions commonly adopted for concept mapping (such as imposition of a vertical hierarchy within the diagrams) and used the CmapTools software mainly as a convenient interactive tool for constructing coastal system diagrams. CmapTools is particularly useful for mapping geomorphological systems, notably because of its ability to attach metadata to system components. This can be used to append additional information on individual system components; this might include geographical information (such as coastal chainage or geographical coordinates) as well as images, reports and papers pertaining to specific locations.

The second stage of the coastal system mapping process involves analysis of the network properties of the system diagram to derive quantitative summary statistics that provide measures of the relative abundance of features and elements and their interactions. Additional measures of system complexity provide a basis for comparing different maps (such as alternative conceptualisations of the same coastal location or comparisons of maps produced for different sections of coast). CmapTools has no in-built analytical capability and analysis of the system structure must be undertaken separately. Although CmapTools uses a closed proprietary file format, it is possible to export the system map to an open XML format from which all of the important topological information can be extracted. A set of Matlab scripts (www.themathworks.com) have been developed to read and process XCM format files produced by CmapTools.

6.1.2. Guiding principles

Building on discussions at a project workshop held in Southampton in April 2008, general principles were set out to provide a logically-consistent basis for large-scale geomorphological system mapping. The principles can be summarised as follows:

Features

At a large scale (scale of existing cells or sub-cells for the coast of England and Wales), organisation of the coastal system is defined with reference to a set of features. These are assigned according to the geomorphological functioning of present shoreline. Features are typically connected by mass transfer pathways, which define the sediment budget system. Divergences or breaks in the continuity of the drift system define the sub-cell or cell boundaries.

The feature set presented by Whitehouse *et al.* (2008) was augmented in the light of the project workshop and experience from the case studies. Table 6.1 summarises the new feature set. We added *updrift coast* and *downdrift coast* features, used to provide boundaries where only part of a larger littoral drift system was mapped. A new *island* feature was also introduced, to deal with instances where features that cannot be considered barrier islands in a geomorphological sense, lie close enough to the coast to exert an influence (for example, by sheltering the coast from wave action). An example of this is Coquet Island, south of Alnmouth Bay, which is too small to warrant a detailed depiction of its various elements, but which clearly influences processes on the coastal headlands featured in its lee. Following discussions within the project team and at a second workshop held at UCL in October 2008, it was decided to represent the *offshore* zone as a single feature encompassing semi-discrete seabed sediment 'zones' and discrete banks (mapped out at element level).

Although it is appropriate to depict feature-feature links within the system diagrams, the functional connectivity of the sediment system is mapped out in more detail (and is best analysed) at the element level. Identification of multiple *offshore* features may be appropriate in a few cases. For example, a deep shipping channel might interrupt the natural connectivity of the seabed sedimentary system sufficiently to warrant separate offshore features. Landward, the *offshore* feature is bounded by the nearshore zone. The seaward boundary is less well defined but can be taken as the transition from a seabed on which sediments are actively stirred by waves and tidal currents to one that that does not actively participate in sedimentary exchanges that influence the contemporary coastal system.

Elements

Smaller-scale coastal system organisation is by elements, grouped with respect to features. Experience from the case studies dictated expansion of the provisional set of elements to include several new types (Table 6.2 summarises these revisions). These included two new hinterland elements, *low ground* and *high ground*, and representation offshore sediments and banks. The presence of active offshore bottom sediments was represented by *seabed sand* and *seabed gravel* (it is not necessary to explicitly map areas of rocky seabed within the offshore zone). The case study of the Suffolk Coast (sub-cell 3c) revealed a requirement to identify *beach ridges*, and to incorporate a classification of offshore banks (including inlet-associated banks, headland-associated banks, offshore banks) along the lines advocated by Dyer and Huntley (1999). Where banks effectively create offshore channels, these are indicated by named areas of *seabed sand*. True channels are associated with inlets and estuary mouths. Sub-tidal geological constraints are common in many areas and, in the case of Cardigan Bay, *offshore reefs* merit identification as an element type.

Table 6.1 Revision of coastal feature set. New features are indicated in bold.

Whitehouse *et al.* (2008)	Revised	Remarks
Seabed	**Offshore**	Revised offshore feature used to group seabed types and banks (both of which are considered to interact at the element scale)
Open coast	Open coast	
Headland	Headland	
Bay	Bay	
Spit	Spit	
Cuspate foreland	Cuspate foreland	
Inlet	Inlet	
Tombolo	Tombolo	
Barrier island	Barrier island	
	Island	Used to define non-barrier islands not mapped in detail but which exert influence on the coast
Estuary	Estuary	
River	River	
	Updrift coast	Use to bound part of larger littoral drift system
	Downdrift coast	

Interventions

It is usually impossible to conceptualise a stretch of coast without reference to structures and other forms of intervention. For example, the backshore along many stretches of coast is dominated by *seawall* or *revetment*. Structures, and non-structural interventions such as *sediment recharge* or *sediment bypassing*, typically exert an influence at the element scale. We also have *outlets* to represent sluices with regulated discharges (such as the Hundred River in Suffolk sub-cell 3c); these are not equivalent to *estuaries* or *inlets* in a geomorphological sense but nonetheless exert an influence on the coastal system at an element scale. Accordingly, a basic set of interventions has been appended to the set of elements (see Table 6.2). This list could obviously be expanded as required to suit particular applications. Further discussion of interventions is provided in Section 5.2.

Cross-shore dimension

Viewed at a feature scale, coastal systems are essentially linear in character. However, cross-shore links are also important at the element scale. Many sections of coast are backed by low-lying hinterlands that contain relict coastal and estuarine landforms. These include areas of reclaimed land that was formerly intertidal, and which could potentially be reactivated as a component of the broader coastal system given sufficient sea-level rise, retreat or breakdown of coastal barriers, or as a result of management decisions. The incorporation of these links is accomplished using a cross-shore zonation that builds on the ideas contained in the Tyndall Coastal Simulator (Hanson *et al*., 2007; Hanson *et al.*, in press).

Table 6.2 Revised coastal element set. New elements are indicated in bold. Note the addition of various types of intervention (including non-structural management interventions) to the foot of the element table.

Whitehouse *et al.* (2008)	Revised	Remarks
Elements		
Sea cliff	Sea cliff	
Coastal dune	Coastal dune	
Coastal lagoon	Coastal lagoon	
Beach	Beach	
Shore platform	Shore platform	
Tidal flat	Tidal flat	
Saltmarsh	Saltmarsh	
Bank and channel	**Channel** **Inlet-associated bank** **Headland-associated bank** **Offshore bank**	New classification of banks (after Dyer and Huntley, 1999) and separate channel (associated with estuary or inlet features)
	Beach ridge	New element
	Offshore reef	New element
	Seabed sand	New element
	Seabed gravel	New element
	Low ground	Implies low-lying hinterland that has been marine-influenced during Holocene; potentially reactivated by sea-level rise or breakdown of coastal barriers.
	High ground	Implies land above present tidal influence and which has not been marine-influenced during Holocene; a potential sediment source.
Interventions		
	Seawall	Structure
	Revetment	Structure
	Detached breakwater	Structure
	Long groyne or jetty	Structure
	Reclamation embankment	Structure
	Groynes	Structure
	Outlet	Structure
	Sediment recharge	Management intervention
	Sediment bypassing	Management intervention
	Sediment recycling	Management intervention
	Beach reprofiling	Management intervention
	Tide locking	Management intervention

The linear character of the coast is reflected in the assignment of large-scale features that correspond to the alignment and character of the presently active shoreline. Cross-shore variation in landforms is then represented by mapping out elements that define the key hinterland-backshore-foreshore-nearshore-offshore transitions. Landward of the shoreline, hinterland elements define a potential zone of coastal influence that includes contemporary coastal processes as well as reflecting the spatial 'envelope' of marine and coastal influence during the Holocene and likely behaviour in the near future. Classification of hinterland as low ground is taken to imply that the envelope of

Holocene coastal influence extends inland, as represented by contemporary fresh and brackish wetlands, reclaimed land and so on. High ground implies the absence of relict Holocene coastal environments, but indicates potential sediment sources that might be used (or activated) according to coastal erosion or the removal of structures. Backshore, foreshore, nearshore and offshore elements (or appropriate structures) complete the cross-shore representation of coastal system links. Obviously at some locations, it may be appropriate to recognise a more complex cross-shore element assemblage (for example, with several backshore transitions).

Feature-element hierarchy

System diagrams typically impose some form of hierarchical structure that allows system components at one level of abstraction to be regarded as sub-systems that can be explored in more detail at a lower level of abstraction. One way of doing this is to produce separate maps for each desired level of abstraction and to indicate in some way how these levels of interaction can be linked (an illustrative example is given in Figure 6.2). Thinking in terms of coastal features and elements implies at least two scales of abstraction. One way of doing this is to map a section of coast at the feature level and to produce separate maps detailing the element-level structure associated with each feature (Figure 6.3a illustrates this diagrammatically). A drawback with this approach is that the broad-scale structure of the system is represented in a very simple fashion through the relatively small set of feature-level components. This emphasizes the vertical hierarchy at the expense of the more complex web of links spanning various spatial scales that is typical of coastal geomorphological systems.

Given a two-level feature-element hierarchy, it is more logical to represent these within a single diagram that articulates the complexity of the system structure primarily at the element scale, with features used to impose a simpler higher-level organisation. This type of arrangement (illustrated in Figure 6.3b) is more suitable for coastal system mapping since it allows the hierarchy implied by the feature-element classification to be represented within a single 'layer' of a system map (of the kind that can be produced by CmapTools). Each feature has at least one element (a possible exception here might be features used to bound a given sub-system, such as sub-cell boundaries), and elements are not shared between features. This approach allows the same mapping principles and conventions to be applied at various spatial scales, depending on the application. This scale-independence is demonstrated more fully in the case studies presented later.

A hierarchical nesting of maps abstracted at different resolutions is not precluded. Indeed, the CmapTools software allows a user to set up folders of linked 'concept maps' that could be used to achieve a multi-scale representation that is rather closer to that envisaged in Figure 6.2. This way of doing things might be useful if coastal system mapping were to be applied for the entire coast of England and Wales, in which case a top-level map might contain links to feature-element level maps for each of the major coastal cells.

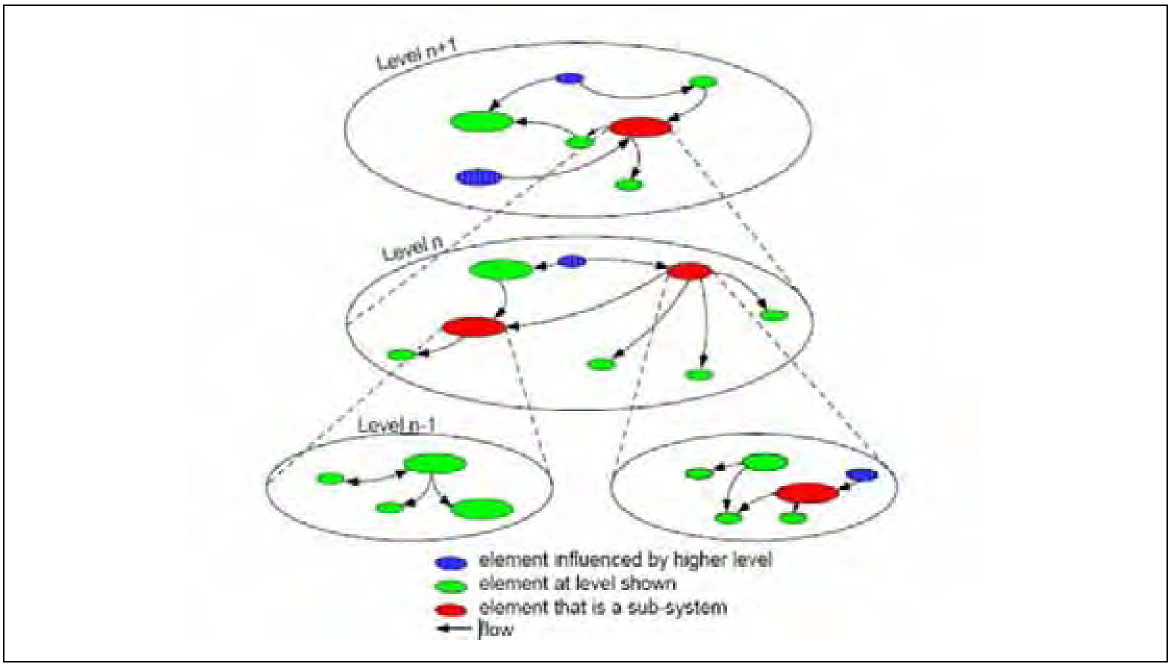


Figure 6.2 Idealised depiction of system linkages at different levels of abstraction (Townend, 2003).

Rationalisation of system structure

Systematic application of an element-level classification that incorporates both alongshore and cross-shore dimensions would result in a dense matrix of components from which it would be difficult to discern the most important links. The most obvious way of avoiding this is to rationalise the element mapping in the alongshore dimension whilst preserving important cross-shore element combinations (consistent with the classificatory scheme adopted for the Tyndall Coastal Simulator; Nicholls *et al*., 2005; Hanson *et al*., in press). The system maps in Figure 6.3 incorporate this kind of rationalisation, and the process is illustrated diagrammatically in Figure 6.4. The basic idea here is to represent the system graphically using as few elements as possible whilst retaining all of the important functional links. The extent to which this kind of rationalisation is necessary will clearly depend on the application and the scale and complexity of the system being mapped.

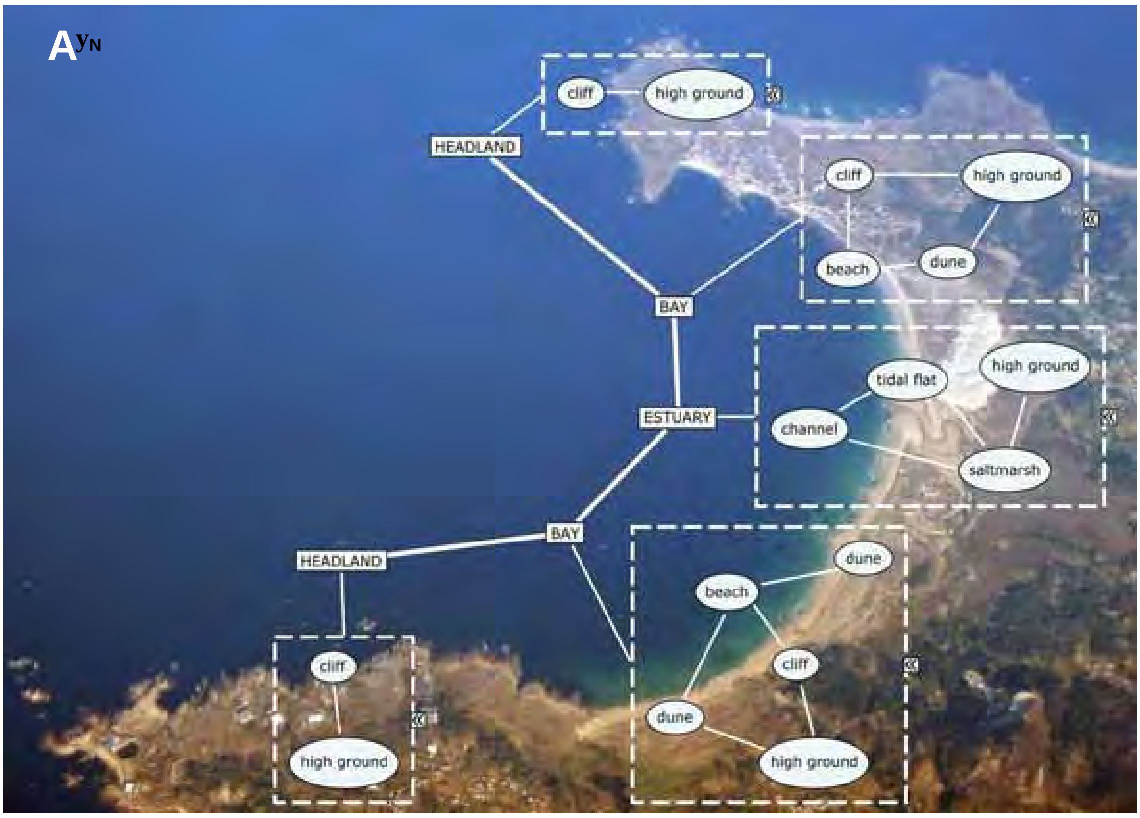


Figure 6.3 Alternative ways of showing feature- and element-level organisation of a coastal system: a) feature-level map with discrete element-level sub-systems; b) element-level connectivity with feature-level organisation imposed.

Link types

Links at element level are defined primarily according to how we believe the sediment transfer pathways operate. A useful convention is to denote these using solid lines, which can be arrowed to indicate a preferred direction of transport. Here, we are interested in long-term average behaviour and can ignore the fact that, in some locations and in a minority of years, opposing transports may occur. In some cases, bi-directional exchanges are more realistic (for example, because of two-way exchanges in the coastal processes). In other cases we may not be able to determine a clear preferred direction (for example, where transport is small or poorly known); such links are not assigned any direction. Where the sediment budget is well understood, it may be useful to denote the relative magnitude of the fluxes by weighting the line thickness. In this case, the system map becomes a tool for displaying sediment budget information in a qualitative or semi-quantitative way.

Many important links are not directly associated with mass transfer. An example is the two-way interaction between a seawall situated at the interface between a cliff (potential, but inactive sediment source) and a beach (a potential sink or store), or the effect of a headland in controlling the alignment of a bay beach. These links may be thought of in terms of ‘influence’ or ‘information exchange’ between system components. It is useful to denote influence-only links using a broken line to distinguish them from sediment transfers. Note that where there is a sediment transfer pathway, influence is implied; the sediment system is thus a subset of a larger set of influence pathways.

In some situations, separate sediment and influence links must be defined. For example, a coastal bank may receive sediment from a headland (a mass flux) whilst also reducing wave energy along its landward coast (an influence). Curved links can be used in these cases to avoid overlapping lines. The Suffolk case study illustrates this.

Mapping conventions

It is important for system maps to adopt a consistent symbolic representation. Figure 6.5 presents a suggested convention of symbols for features, elements and interventions, and the links between them. The scheme is designed to be generic and is not specific to any particular software. However, all the graphical components shown can be created in the CmapTools package used here.

Key aspects of the mapping convention include:

- symbolic distinction between features, elements and interventions;
- distinction between completely and partially mapped features, such as estuaries included in a broader coastal map but not represented in detail (for example, for reasons of clarity);
- distinction between sediment and influence links and the ability to represent the direction and relative strength of these.

Depending on the application, it may be necessary to arrange the system components in a geographical map, scaled against real-world coordinates, or in the form of a topological map which may be more visually communicative. Geographical maps can be constructed on top of a base map or image of a region of interest (see, for example, Figure 6.3). This is convenient for short stretches of coast (such as a single bay-headland system) for which high quality aerial imagery is available. Topological maps may be better for larger systems, where the map must convey a great deal of information and where the structure of the system is more important than the actual location of the components. Topological maps can still contain embedded meta-data on real-world spatial coordinates to allow spatial analysis (such as the distances along specific influence or sediment transfer pathways). Figure 6.6 illustrates the differences between geographical and topological mapping conventions.

Topological representations were used in the case studies presented in this report, partly because of the complexity of the larger studies, and partly because of the need to reproduce the resulting maps in a compact format. However, geographical maps may be more effective presentational tools for coastal practitioners. Preparation of maps on top of aerial imagery is a more intuitive process than more abstract mapping, and the resulting geographical maps are visually effective when produced in larger formats.

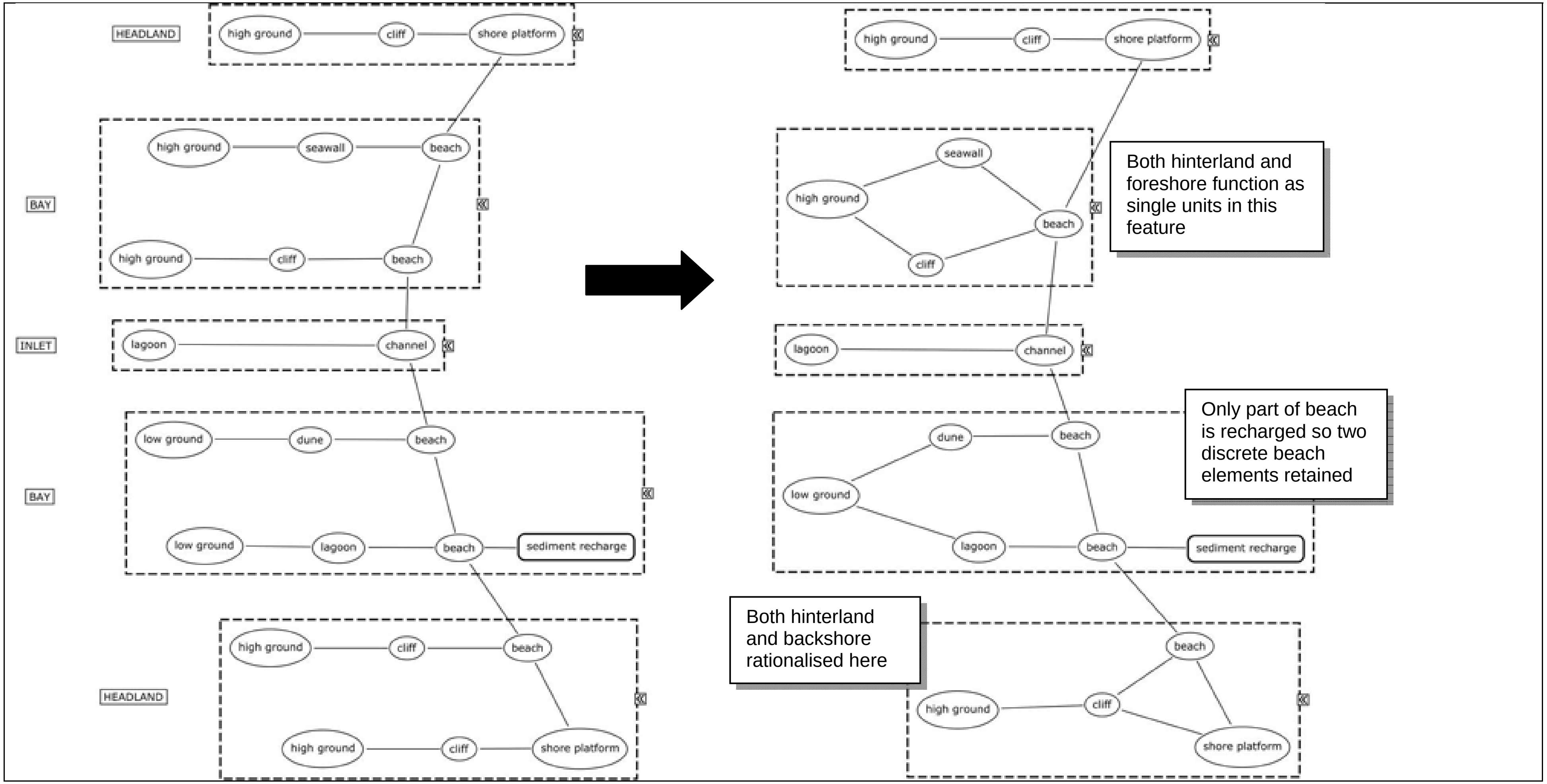


Figure 6.4 Rationalisation of system map at element-level for headland-bay system.

The aim is to represent the full range of alongshore variation in coastal characteristics using as few elements as possible. In this example, this is achieved by rationalising sequences of similar hinterland or foreshore geomorphology. Elements are not shared between features (feature sets do not overlap), and are not merged where specific influences are localised (note the depiction of a localised beach recharge in this example).

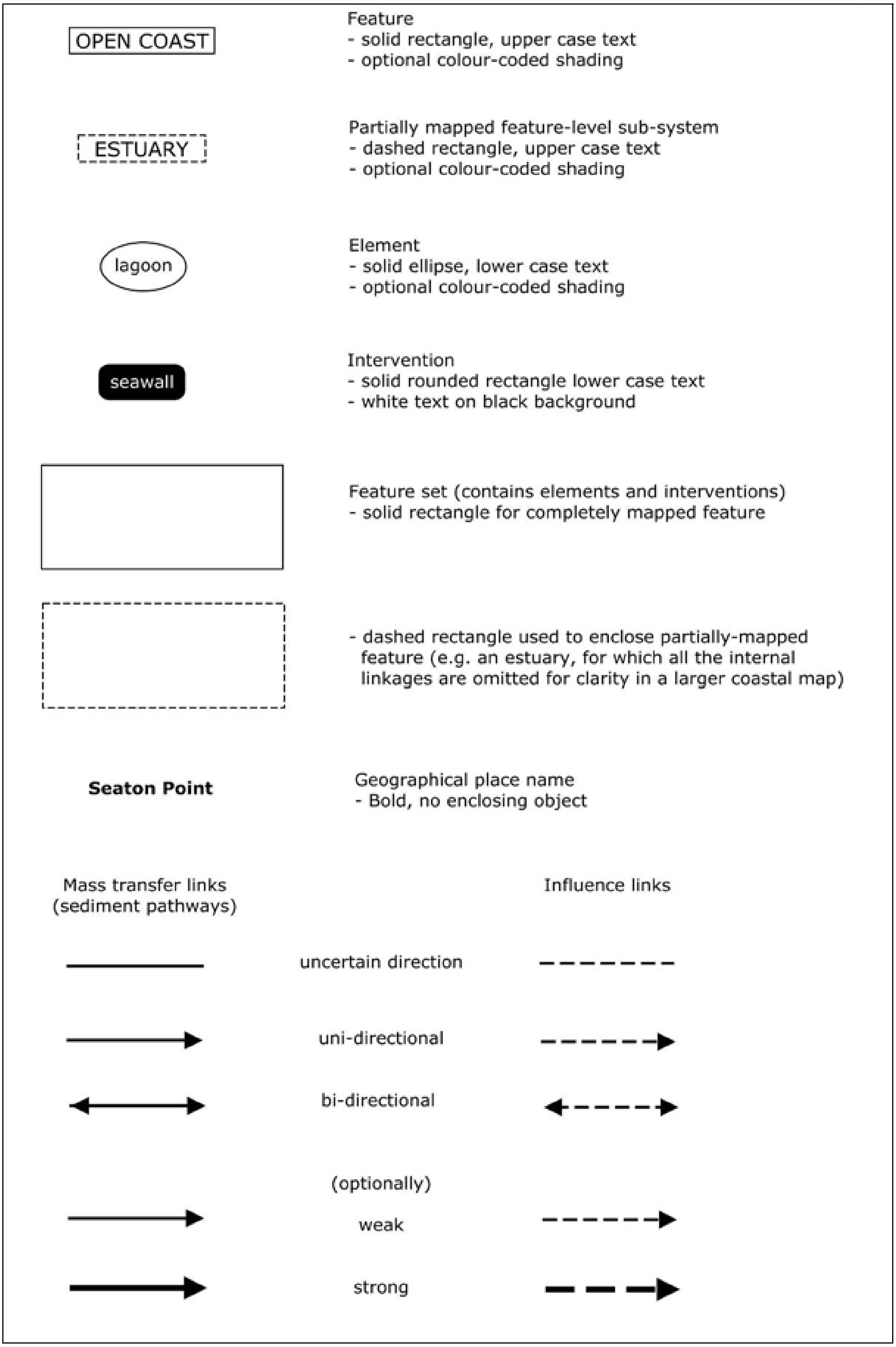


Figure 6.5 **Proposed convention for broad-scale coastal system mapping.**

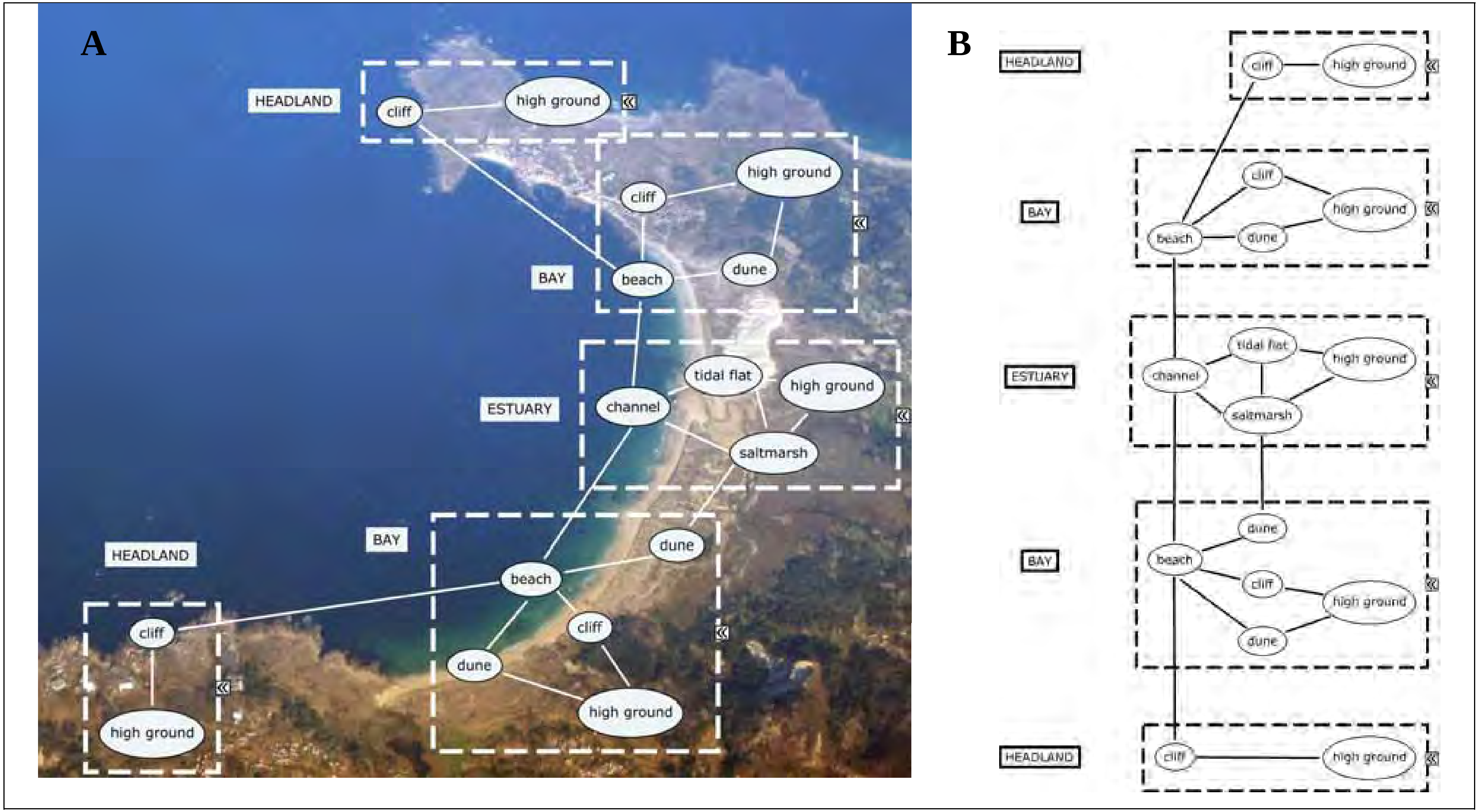


Figure 6.6 Illustration of the difference between a) geographical and b) topological mapping.

6.1.3. System mapping procedure

A step-by-step procedure for coastal system mapping is proposed here to ensure that maps are produced as logically and as consistently as possible. Although reference is made in places to CmapTools software, the procedure is essentially generic and could be adapted for other software or used as a basis for ‘pencil and paper’ mapping. The key stages are set out diagrammatically in Figure 6.7.

The following stages are proposed:

Stage 1: Specify region of interest and define problem

First, specify a region of interest. For England and Wales, a high-level system framework already exists in the form of coastal cells and sub-cells originally mapped by Motyka and Brampton (1993), and recently revised by Defra (2006a); this may provide an initial basis for bounding the region of interest. Second, define the nature of the problem. This might be a requirement to undertake broad-scale mapping as a framework for modelling; it might arise from a desire to carry out a ‘brainstorming’ exercise to synthesize expert opinion on the behaviour of a given stretch of coast; or it may stem from a need to provide context for more local management decision-making (such as the evaluation of alternative management options for an estuary mouth in the context of wider aspects of estuary-coast interaction).

Stage 2: Decide how the mapping process will be undertaken

Decide on whether mapping is to be carried out as a consensus-building exercise involving a large team of experts (possibility including non-experts and interested parties) or as a more direct synthesis of understanding by a single expert or small team working closely together. Consensus-based mapping can take the form of interactive brainstorming sessions in a workshop setting but might also be accomplished by comparison and merging of maps produced independently by a set of experts. These options are particularly suited to cases where the system is not well understood or where there are likely to be differences of opinion. Systems that are relatively well understood by the scientific community might be more amenable to more direct mapping by a small team working closely together, or even an individual expert.

Stage 3: Choose between geographic or topological mapping

Decide whether a geographic map or a topological map is appropriate: this will depend on the nature and scale of the application.

Stage 4: Assemble the required information and source materials

Assemble data sources, including large-scale base-mapping or aerial imagery (scanned aerial photographs, Google Maps and so on); research papers and reports; quantitative datasets (sediment budgets, tidal and wave climate information, modelled sediment transport rates and so on); and other sources of information (historical photographs, anecdotal evidence and so on). For geographic mapping, aerial or satellite imagery at a suitably high resolution can be loaded directly into CmapTools to provide a background on which the required system components can be arranged.

Stage 5: Define features

Identify principal coastal (and offshore) features along the contemporary shoreline. This can be done directly within CmapTools (with or without a digital base map loaded). For larger systems, however, it may be easier to set up a spreadsheet to hold both the feature- and element-level classification, along with any meta-data such as place names or map coordinates.

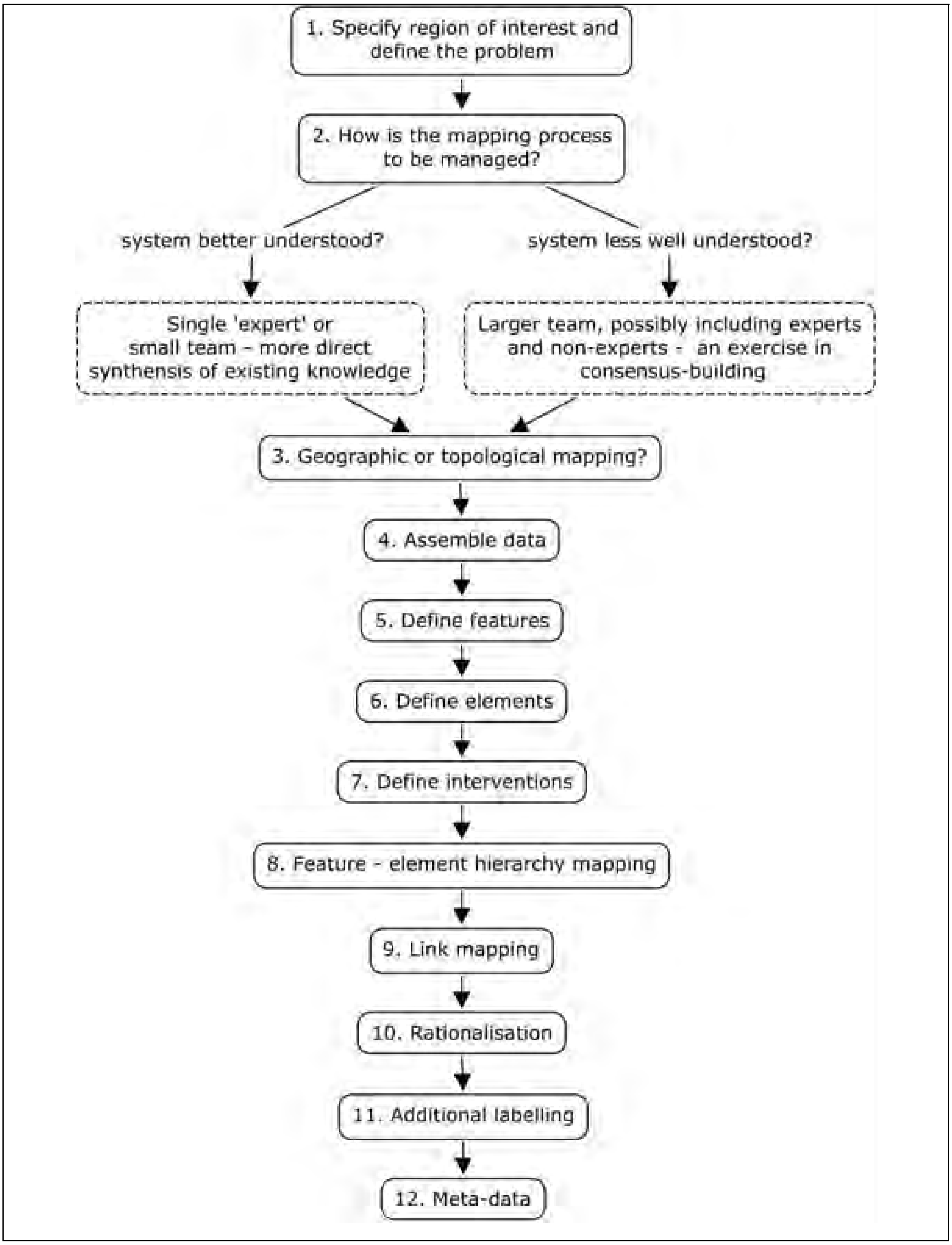


Figure 6.7 Flow chart illustrating generic system mapping procedure.

Stage 6: Define elements

Identify coastal (and offshore) elements associated with each feature, taking account of hinterland, backshore and foreshore characteristics.

Stage 7: Define interventions

Identify any structural or non-structural interventions. In some situations, a structure may replace an element in the natural cross-shore assemblage (for example, a seawall may replace a cliff). Alternatively, interventions may act to constrain the behaviour of elements (such as in the case of beach recharge, which constitutes an additional sediment source within the littoral system).

Stage 8: Feature-element hierarchy mapping

At this stage, feature and element symbols need to be created within CmapTools based upon the coastal classification assembled in spreadsheet form (these may already have been created graphically if a separate spreadsheet database has not been created). Mapping should conform to the conventions set out in Figure 6.5. Groups of elements and interventions are then used to create what CmapTools terms 'nested nodes'; these define their affiliation with higher-level features. Nested nodes (features) can be expanded to reveal full element-level detail or collapsed to display only the features.

Stage 9: Link mapping

Connectivity is mapped at the element-level according to the link types given in Figure 6.5. Line weightings can be used to denote the strength of sediment transfers or influences, if this level of understanding is available.

Stage10: Rationalisation

Rationalisation of the elements is usually necessary to highlight the system structure and avoid a dense matrix of elements within each feature. Rationalisation involves merging adjacent elements considered to behave as a single unit (Figure 6.4).

Stage 11: Labelling of features and elements

In CmapTools, geographic place names or other labels can be added to the feature or element symbols, and these can appear when pointed at by the screen cursor. Additional label text can also be added to the system maps to improve readability.

Stage 12: Addition of meta-data

CmapTools allows the inclusion of additional information within an undisplayed, but searchable field. Geographic coordinates and hyperlinks to images, research literature or datasets can be inserted here.

A worked example of this procedure, including a brief CmapTools tutorial (French and Burningham, 2009), is available via the project website (www.coastalgeomorphology.net). This provides additional information on how to accomplish the generic tasks within this particular software product.

6.1.4. System-level analysis

Coastal system mapping is intended to provide a high-level conceptual framework, within which various broad-scale modelling approaches (historical trend analysis, expert geomorphological assessment, reduced-complexity morphodynamic modelling and so on) can be pursued. However, system mapping can also serve as an analytical tool in its own right. Descriptive statistics and information on system structure provide an objective basis for comparing different maps (such as alternative conceptualisations by different experts, or present and future states), and summarising the relative abundance of feature and element types and their most common interactions (which might be used to determine which elements or features should be prioritised in the formulation of management strategies). Analysis of the influence and sediment transfer pathways can also be carried out to reveal the portion of the system that might be influenced by any change imposed upon a given element.

To this end, experimental Matlab scripts (available via www.geog.ucl.ac.uk/ceru/cmap) have been developed to read CmapTools concept map files exported in XML-XCM format and compute the following descriptive measures:

- Abundance tables for features, elements, interventions, and any linked sub-systems that are indicated but not mapped in detail.
- A matrix of interaction types, showing which kinds of interaction (cliff-beach; dune-beach; lagoon-beach ridge and so on) are most common.

Various measures of system complexity (such as mean and maximum connectivity for both the mass transfer and influence pathways, and by element type) and system path analyses would also be possible, and might be of interest for some applications. For example, for a given feature or element, what is the maximum length along the sediment transfer system and does this include any loops that feed back to updrift features (for example, via offshore channels and banks)? Or, how many closed loops does a system map contain (another measure of system complexity) or a particular element participate in? Alternatively, for a given element, what is the extent of the partial system that feeds sediment into this, or else influences it in some way?

Any statistical measures derive from the system maps as representation of the real world, rather than the actual system. They, therefore, reflect decisions made in the mapping process, particularly those relating to the resolution at which features and elements are identified and any differences in how the maps are rationalised.

6.2. Applications to three case studies

6.2.1. Coastal sub-cell 3c: Lowestoft to Landguard Point

The first case study includes the whole of coastal sub-cell 3c (Motyka and Brampton, 1993) between Lowestoft and Landguard Point, a coastal chainage of approximately 73 km (Figure 6.8). This is quite a long section of coast and is more complex in terms of the transitions between adjacent feature types than many other coastal sub-cells.

Figure 6.8 Lowestoft to Languard Point, Suffolk (sub-cell 3c).

From a management perspective, the major characteristics of the coastline between Lowestoft and Landguard Point include:

- A predominantly rural coastal frontage and hinterland with numerous small settlements and two large towns (Lowestoft and Felixstowe).
- Major industrial developments comprising nuclear power reactors at Sizewell and facilities of Port of Felixstowe (which are potentially influenced to some extent by the behaviour of Felixstowe coastal frontage and Landguard Point).
- Several stretches of eroding soft rock cliff, continued or accelerated erosion of which may lead to loss of property.

- Three small estuaries (Blyth, Alde/Ore, and Deben), all with substantial areas of reclaimed tidal floodplain increasingly vulnerable to flooding.
- Large areas of nationally and internationally important brackish and freshwater wetland habitat that are also vulnerable to flooding and to coastal change.

From a geomorphological perspective, this stretch of coast is notable for the strong connections that define a more-or-less continuous littoral drift system, the presence of numerous controlling headland and foreland features (including the various nesses), and the existence of process links between the nearshore and offshore bank systems. The complexity of these process links (which include sediment transfer pathways) means there are several places at which localised interventions (or changes in existing management policy) may have much broader implications for the functioning of the coastal system. Interaction between open coastal and estuarine processes is also potentially strong. For example, changes in tidal prism may affect inlet stability and the timescales of sediment bypassing via estuary ebb tidal deltas, whilst breaching of the coastal barrier at Slaughden would lead to a major reconfiguration of the Alde/Ore estuary (with implications for the stability of Orford Haven).

Application of Stages 1 through 7 of the system mapping procedure to coastal sub-cell 3c resulted in the coastal feature and element set shown in Table 6.3. There is a strong correspondence between the classification in Table 6.3 and that developed by the Tyndall Centre for Climate Change for use in the Coastal Simulator (Hanson *et al.*, 2007), which is shown in Table 6.4. The Tyndall project similarly identified a number of generic coastal elements (five) and cross-shore combination of elements (five). These descriptive terms can be used to identify the extent of the functional coastal system under a variety of coastal management policies. Elements located landward of a permanent artificial defence line are considered to no longer form part of the coastal system, leaving the remaining ‘active’ elements to be reclassified using the cross-shore profile types; an example of this is illustrated in Table 6.4 by comparing the coastal system under two management policies, ‘Hold the line’ and ‘No defences’.

Our scheme for the assignment of coastal features also incorporates both alongshore and cross-shore variation. The longshore dimension exerts a stronger influence on the organisation of the system at meso-scales (of the order of 10 to 100 years), while the cross-shore assemblage of features is indicative of potential shifts in coastal system organisation that might occur over longer timescales (evidenced by the envelope of Holocene variability). Thus, where the hinterland is classified as ‘low ground’, breaching of coastal barriers or sustained retreat may restore tidal exchange to presently reclaimed land, leading to the creation of new tidal flat, saltmarsh or lagoon.

The coastal system map is shown in Figure 6.9. Note that a distinction is made between influence links between system components and those that define the sediment transfer pathways.

Table 6.3 Initial classification of coastal features and elements within sub-cell 3c.

Chainage	km	Feature	Elements *Hinterland*		***Backshore***	***Foreshore***	***Nearshore***	***Offshore***	
Lowestoft	0.0	Inlet		*Lowestoft Harbour*		Channel	Headland-associated bank	*Newcombe Sand*	
Kirkley	1.7	Open coast	High ground		Seawall	Beach			
Pakefield		Open coast	High ground		Dune	Beach			
Kessingland Cliffs		Open coast	High ground		Dune	Beach			
Kessingland		Foreland	Low ground	*Benacre Ness*	Beach ridges	Beach			
Hundred River	8.5	Open coast	Low ground		Outlet		Headland-associated bank	*Barnard Sand*	*Covehithe Channel*
Benacre		Open coast	High ground		Cliff	Beach			
Benacre Broad	10.3	Open coast	Lagoon	*Benacre Broad*	Beach ridge	Beach			
Covehithe Cliffs		Open coast	High ground		Cliff	Beach			
Covehithe Broad	12.5	Open coast	Lagoon	*Covehithe Broad*	Beach ridge	Beach			
Easton Wood		Open coast	High ground		Cliff	Beach			
Easton Broad	11.6	Open coast	Lagoon	*Easton Broad*	Beach ridge	Beach			
Easton Cliffs		Open coast	High ground		Cliff	Beach			
Southwold	17.4	Open coast	High ground	*Gunhill Cliff*	Seawall	Beach			
The Denes		Open coast	Low ground		Dune	Beach			
Blyth estuary	18.8	Estuary		*Blyth Estuary*		Channel			
Walberswick		Open coast	Low ground		Dune	Beach			
Walberswick		Open coast	Low ground		Wetland	Beach	Headland-associated bank	*Dunwich Bank*	
Dunwich	23.9	Open coast	High ground		Cliff	Beach			
Minsmere		Open coast	Lagoon		Dune	Beach	Headland-associated bank	*Sizewell Bank*	
Sizewell		Open coast	High ground		Dune	Beach			
Thorpe Ness	34.3	Foreland	High ground		Beach ridges	Beach			
Thorpeness		Open coast	Lagoon	*The Meare*	Beach ridges	Beach			
Aldeburgh/Slaughden		Open coast	Channel		Seawall	Beach			
Sudbourne beach		Open coast	Low ground		Beach ridges	Beach	Headland-associated banks	*Aldeburgh Ridge & Aldeburgh Napes*	
Orford Ness	45.7	Foreland		Beach ridges		Beach			

Chainage	km	Feature	Elements *Hinterland*		***Backshore***	***Foreshore***	***Nearshore***	***Offshore***
Orford beach		Spit	Channel		Beach ridges	Beach		
Orford Haven	55.7	Estuary		*Alde/Ore*		Channel	Inlet-associated banks	*Orford Haven*
Shingle Street		Open coast	Low ground	*Oxley Marshes*	Beach ridges	Beach		
East Lane	59.3	Headland	Low ground		Seawall	Revetment		
Bawdsey Cliff		Open coast	High ground		Cliff	Beach		
Woodbridge Haven	63.3	Estuary		*Deben Estuary*		Channel	Inlet-associated banks	*Woodbridge Haven*
Felixstowe		Open coast	High ground		Seawall	Beach		
Cobbold's Point	66.4	Headland	High ground		Seawall	Beach		
Felixstowe		Open coast	High ground		Seawall	Beach		
Languard Spit	72.0	Spit	Channel		Beach ridges	Beach		
Harwich Haven	73.0	Estuary		*Stour Estuary*		Channel		

Table 6.4 Coastal classification for sub-cell 3c used in the Tyndall Coastal Simulator, showing cross-shore elements and longshore lengths of the active coastal system for two management scenarios.

	Geographical location	X-shore profile type (Active system)	Length on open coast (km)	Active Elements				
				Back-Barrier	Cliff	Barrier	Foreshore	Channel
Management option – no defences	Lowestoft	Barrier-backbarrier with channel	0.96	✓	×	✓	✓	✓
	Kessingland Cliffs	Non-barrier (cliffed)	4.49	×	✓	×	✓	×
	Benacre Ness	Fringing barrier	3.43	×	×	✓	✓	×
	Kessingland Level	Barrier-backbarrier	0.66	✓	×	✓	✓	×
	Benacre Cliffs	Non-barrier (cliffed)	0.66	×	✓	×	✓	×
	Covehithe Broad	Barrier-backbarrier	0.44	✓	×	✓	✓	×
	Covehithe Cliffs	Non-barrier (cliffed)	1.88	×	✓	×	✓	×
	Covehithe Broad	Barrier-backbarrier	0.43	✓	×	✓	✓	×
	Easton Cliffs	Non-barrier (cliffed)	0.74	×	✓	×	✓	×
	Easton Broad	Barrier-backbarrier	1.0	✓	×	✓	✓	×
	Easton Cliffs	Non-barrier (cliffed)	1.50	×	✓	×	✓	×
	Bus creek	Barrier-backbarrier	0.54	✓	×	✓	✓	×
	Southwold	Non-barrier (cliffed)	1.28	×	✓	×	✓	×
	The Denes/Blyth Estuary	Barrier-backbarrier with channel	1.42	✓	×	✓	✓	✓
	Walberswick	Barrier-backbarrier	4.46	✓	×	✓	✓	×
	Dunwich Cliffs	Non-barrier (cliffed)	3.09	×	✓	×	✓	×
	Minsmere	Barrier-backbarrier	3.06	✓	×	✓	✓	×
	Sizewell	Barrier-backbarrier	1.88	✓	×	✓	✓	×
	Thorpeness	Non-barrier (cliffed)	3.5	×	✓	×	✓	×
	The Haven	Barrier-backbarrier	2.37	✓	×	✓	✓	×
	Aldeburgh	Fringing barrier	1.16	×	×	✓	✓	×
	Slaughden	Barrier-backbarrier with channel	3.25	✓	×	✓	✓	✓
	Sudbourne Beach	Barrier-backbarrier with channel	6.96	✓	×	✓	✓	✓
	Orford Ness	Barrier-backbarrier with channel	7.02	✓	×	✓	✓	✓
	Orford Ness (Shingle Street)	Barrier-backbarrier with channel	4.4	✓	×	✓	✓	✓
	Bawdsey Cliff	Non-barrier (cliffed)	3.32	×	✓	×	✓	×
	River Deben estuary	Barrier-backbarrier with channel	2.15	✓	×	✓	✓	✓
	Old Felixstowe cliffs	Non-barrier (cliffed)	1.75	×	✓	×	✓	×
	Felixstowe	Ringing barrier	1.72	×	×	✓	✓	×
	Rivers Stour/ Orwell estuary	Barrier-backbarrier with channel	3.43	✓	×	✓	✓	✓
Management option – Hold the line	Lowestoft - Aldburgh/Slaughden (N.B Blyth Estuary)	Non-barrier (low)	42.5	×	×	×	✓	×
	Sudbourne beach	Barrier-backbarrier	7	✓	×	✓	✓	×
	Orford Ness	Barrier-backbarrier with channel	7	✓	×	✓	✓	✓
	Shingle Street- Felixstowe	Non-barrier (low)	16.75	×	×	×	✓	×

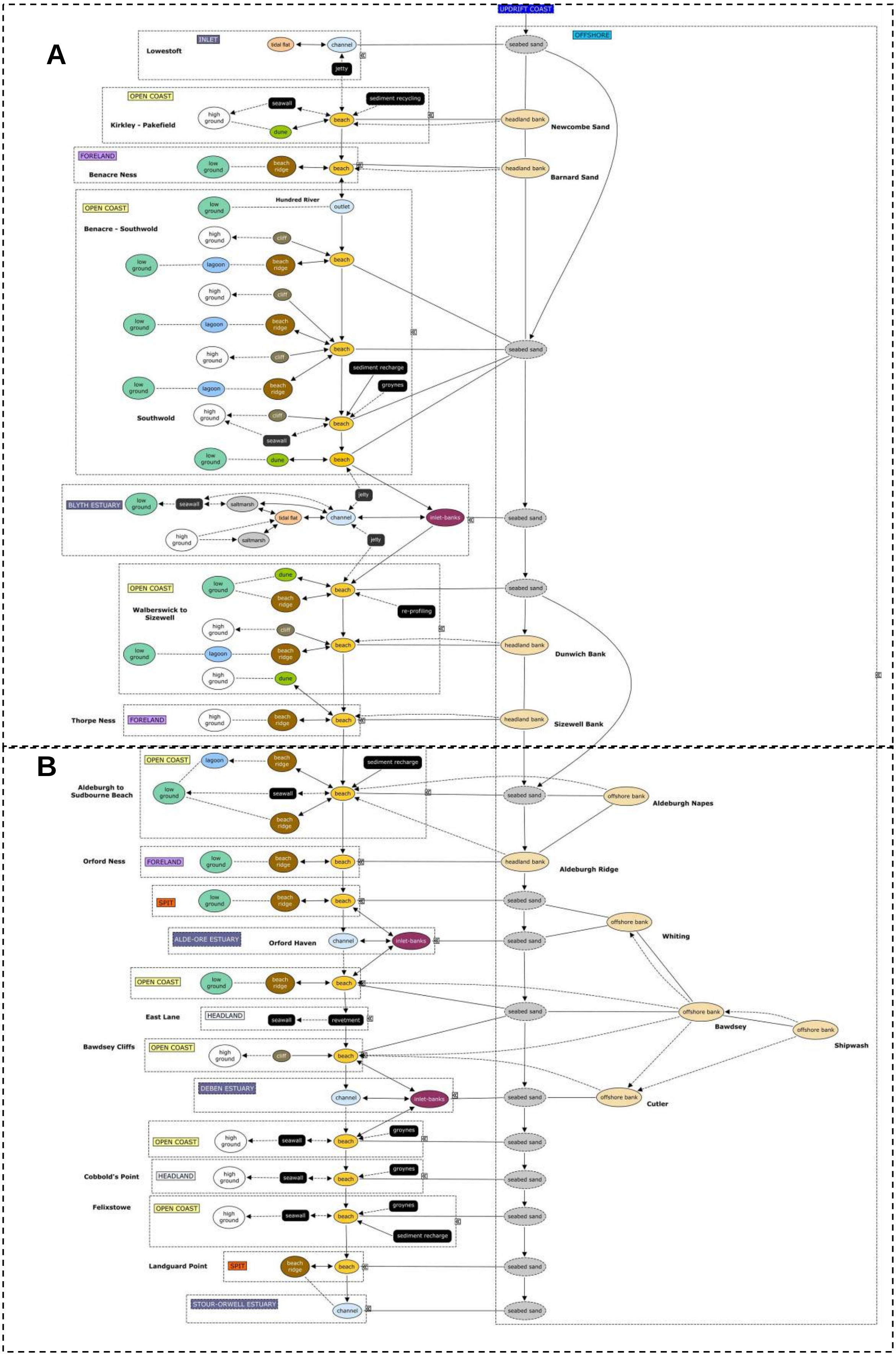


Figure 6.9 System map for coast between Lowestoft and Landguard Point. Insets A and B are expanded on the following pages.

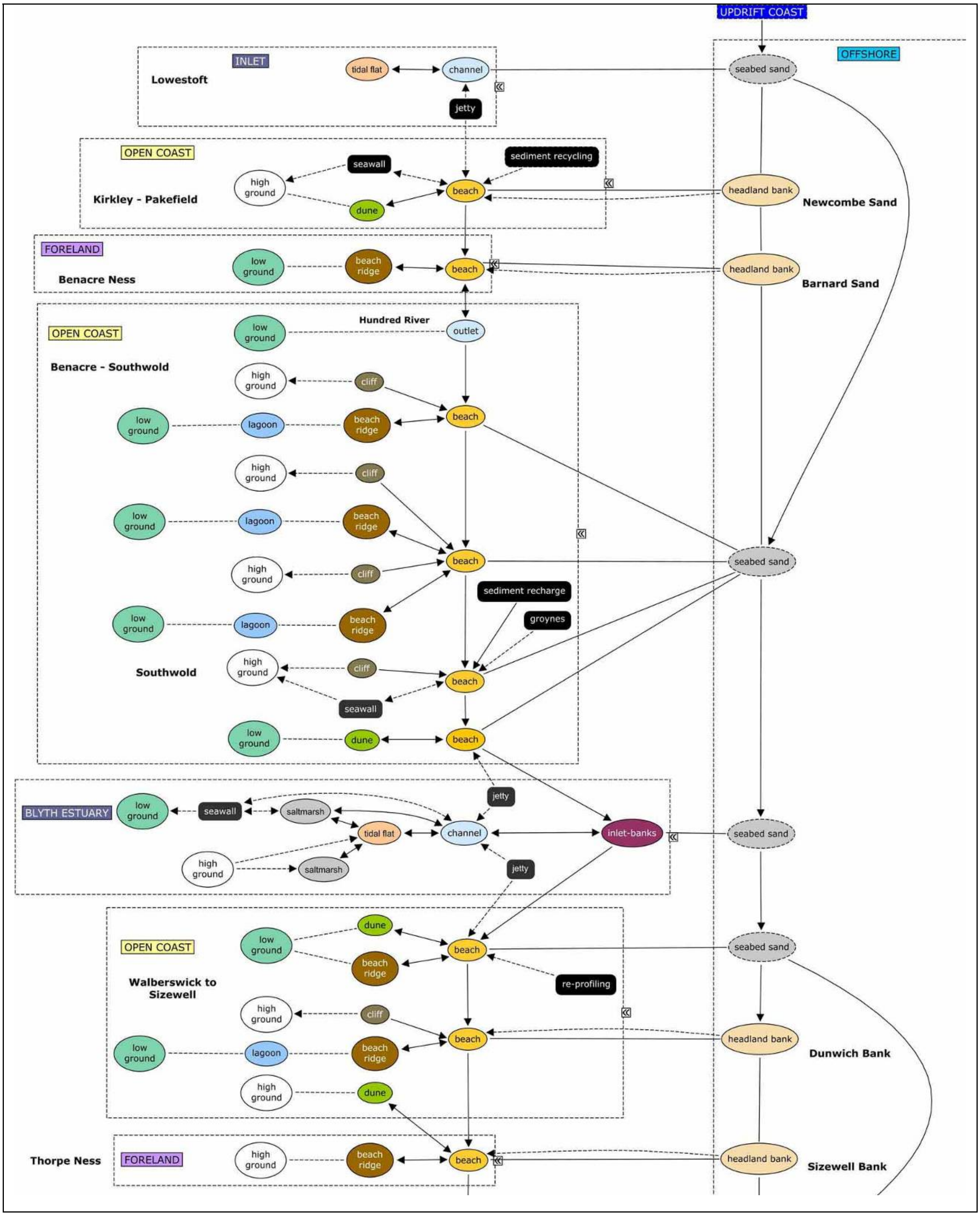


Figure 6.9 (continued): Inset A – Lowestoft to Thorpe Ness.

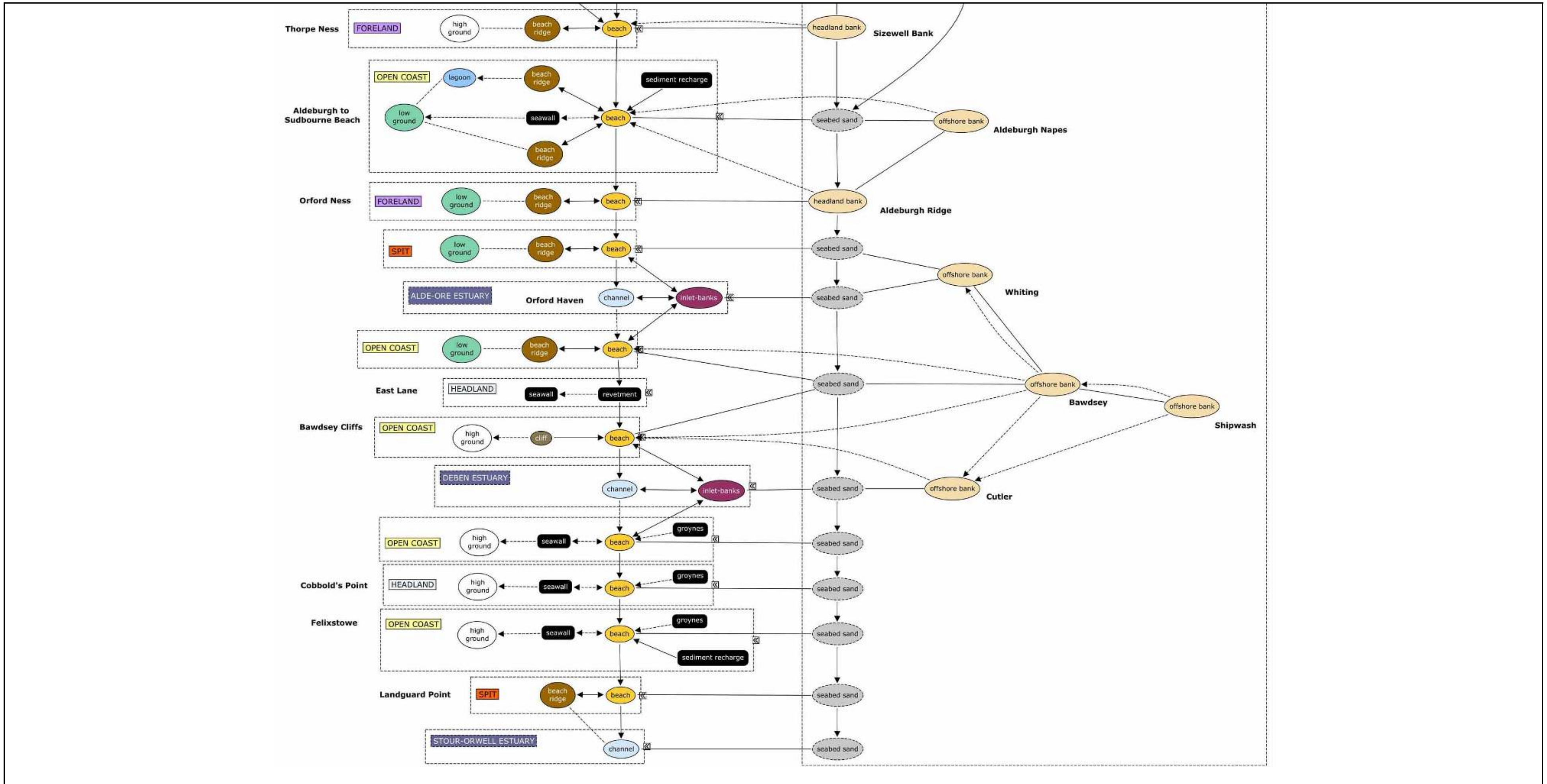


Figure 6.9 (continued): Inset B – Thorpe Ness to Landguard Point and the Stour-Orwell estuary.

The topological organisation of the system is much more evident from Figure 6.9 than from Table 6.4. At a glance, the map reveals the connectivity within the littoral drift system and its partial interruption by the estuary inlets. The existence of potential recirculation loops within the sediment transfer pathway network is also evident, and it is clear that the extent of any exchanges between the beaches and nearshore/offshore bank systems needs to be factored in to an analysis of coastal behaviour at this scale. These maps illustrate many of the issues and principles set out in the introductory sections of this report. The following are of particular note:

- The more detailed mapping of the Blyth Estuary (as an estuary feature) compared to the partial mapping of the Alde/Ore, Deben and Stour/Orwell estuaries (presented, for convenience here, as partially mapped estuary 'sub-systems'). This illustrates how individual features can be included in the entirety or partially depending on the application (which in this case is purely a proof-of-concept exercise).
- The use of separate sediment transfer and influence links to represent the interaction between the various banks and the coast.
- Restriction of the sediment system mapping to fluxes of beach-grade material. Clearly exchanges of marine mud are important in determining the morphological evolution of the estuaries and their associated elements. However, mud suspended in offshore waters cannot be conceptualised as a set of discrete stores and it is more appropriate to think of a more diffuse reservoir that receives inputs from elsewhere in the North Sea and from localised sources (such as cliff erosion) and sources inputs to the estuaries.

At a feature level, the system map is easier to present in a geographical format (Figure 6.10). The geographical map emphasises the punctuation of the littoral drift system by numerous headlands, forelands and estuaries, and the finer scale structure in the southerly portion (Orford Ness to Landguard Point) compared to the northerly portion (Lowestoft to Orford Ness).

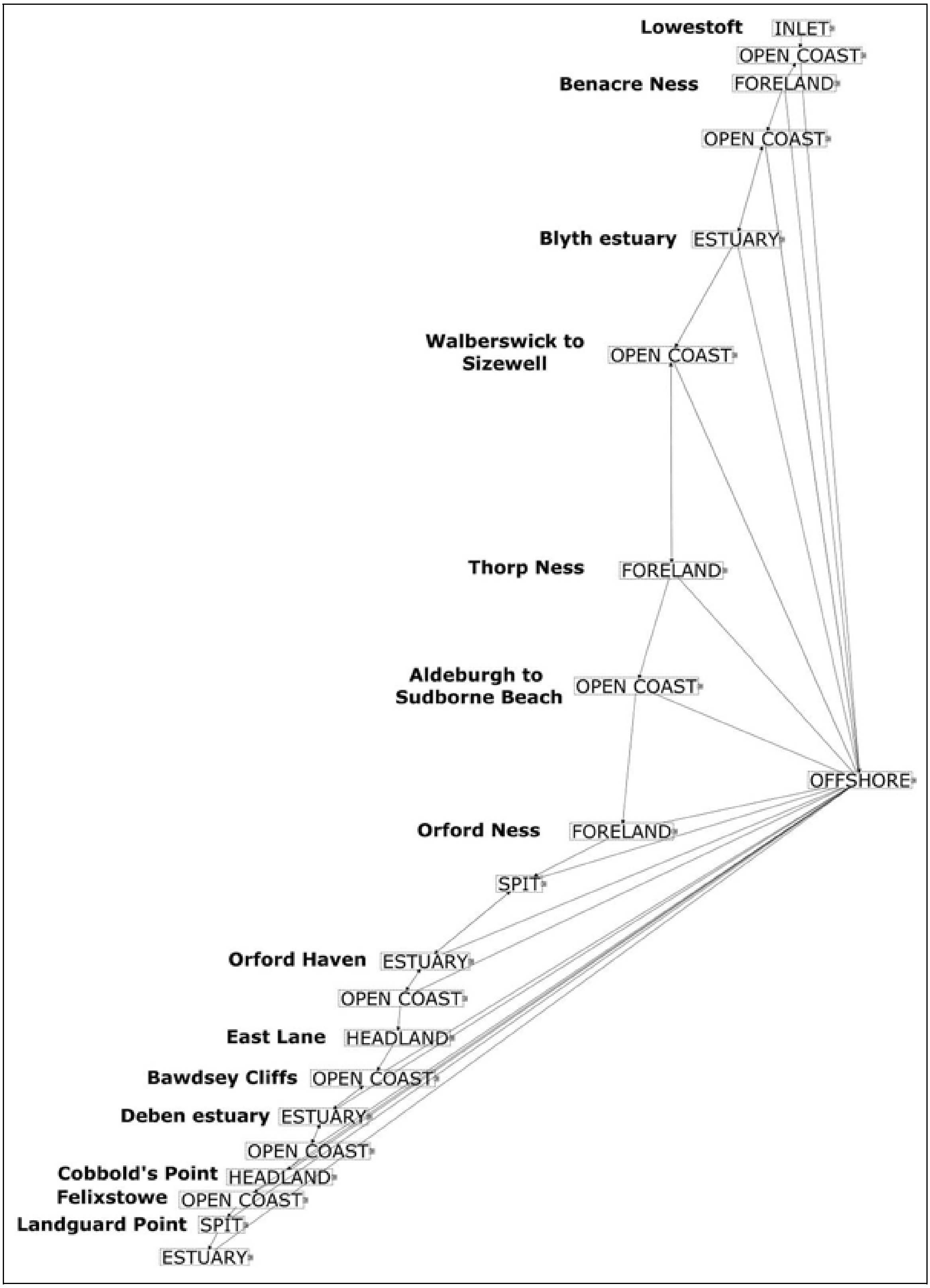


Figure 6.10 Suffolk coast between Lowestoft and Landguard Point mapped out geographically at the feature level.

In terms of element abundance, this coast is relatively rich in beach and beach ridge, and has a hinterland that alternates between low ground (with potential for reactivation of various forms of coastal wetland) and relatively high ground (which is a potential sediment source for the littoral drift system). This is reflected in the matrix of influence interactions between the various system components, which is summarised graphically for all of the influence links in Figure 6.11. The probability scores in this matrix simply represent the normalised proportion of interactions between system components that are of a particular type. Beach elements feature prominently in this matrix, with the alongshore continuity of the littoral drift system reflected in the high frequency of beach-beach interactions.

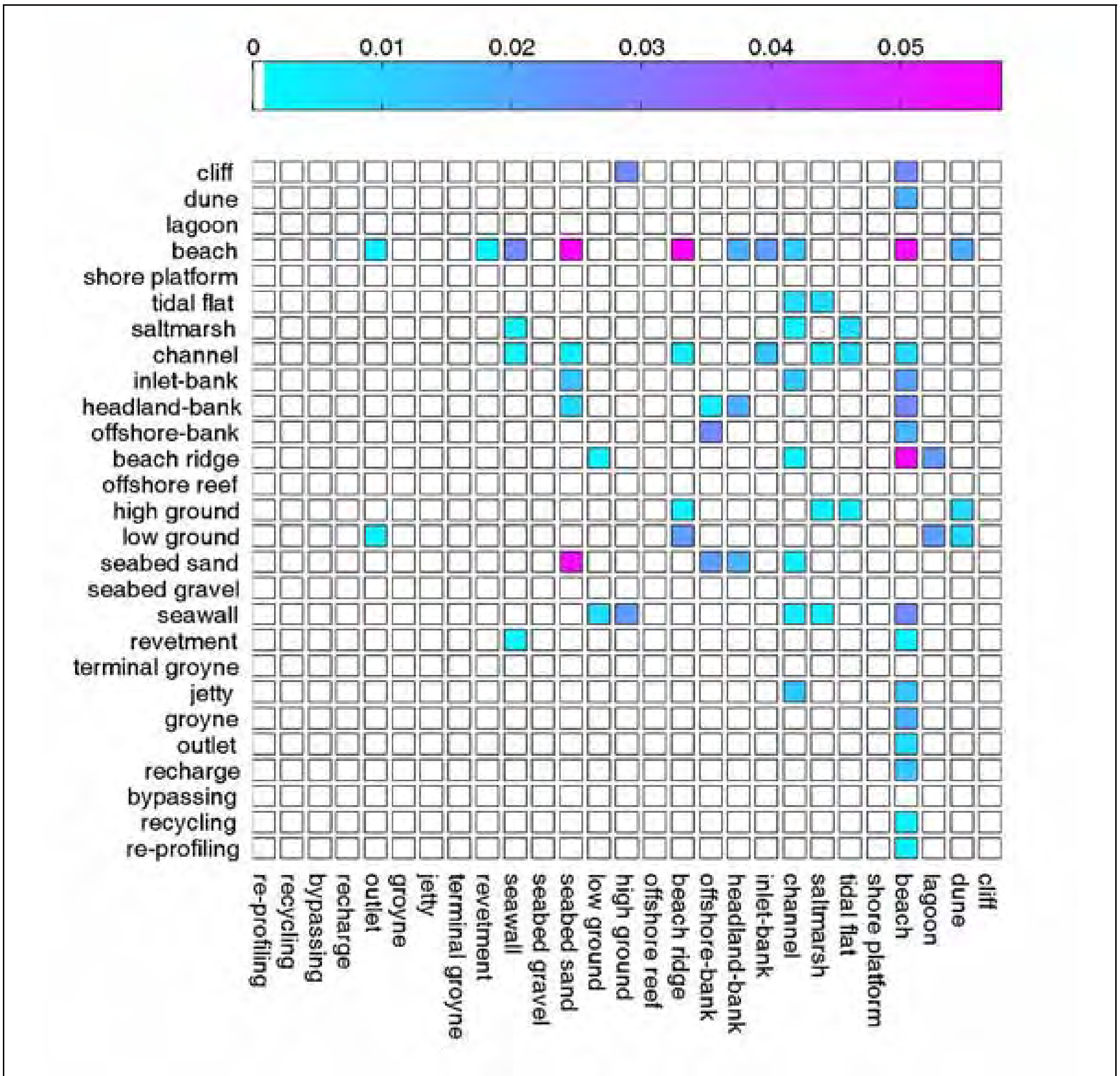


Figure 6.11 Interaction probability matrix for the system map in Figure 6.9.

Matrix includes whole set of elements and interventions, irrespective of occurrence. White cells indicate interactions that do not occur in this system map, colour-coded cells show varying probability of interactions that do occur. This analysis includes both directions of any bi-directional links as separate links.

Figure 6.12 is the interaction probability matrix for sediment transfers only and shows that beaches dominate the interaction matrix even more if just the sediment budget system is considered, although seabed exchanges are also important here.

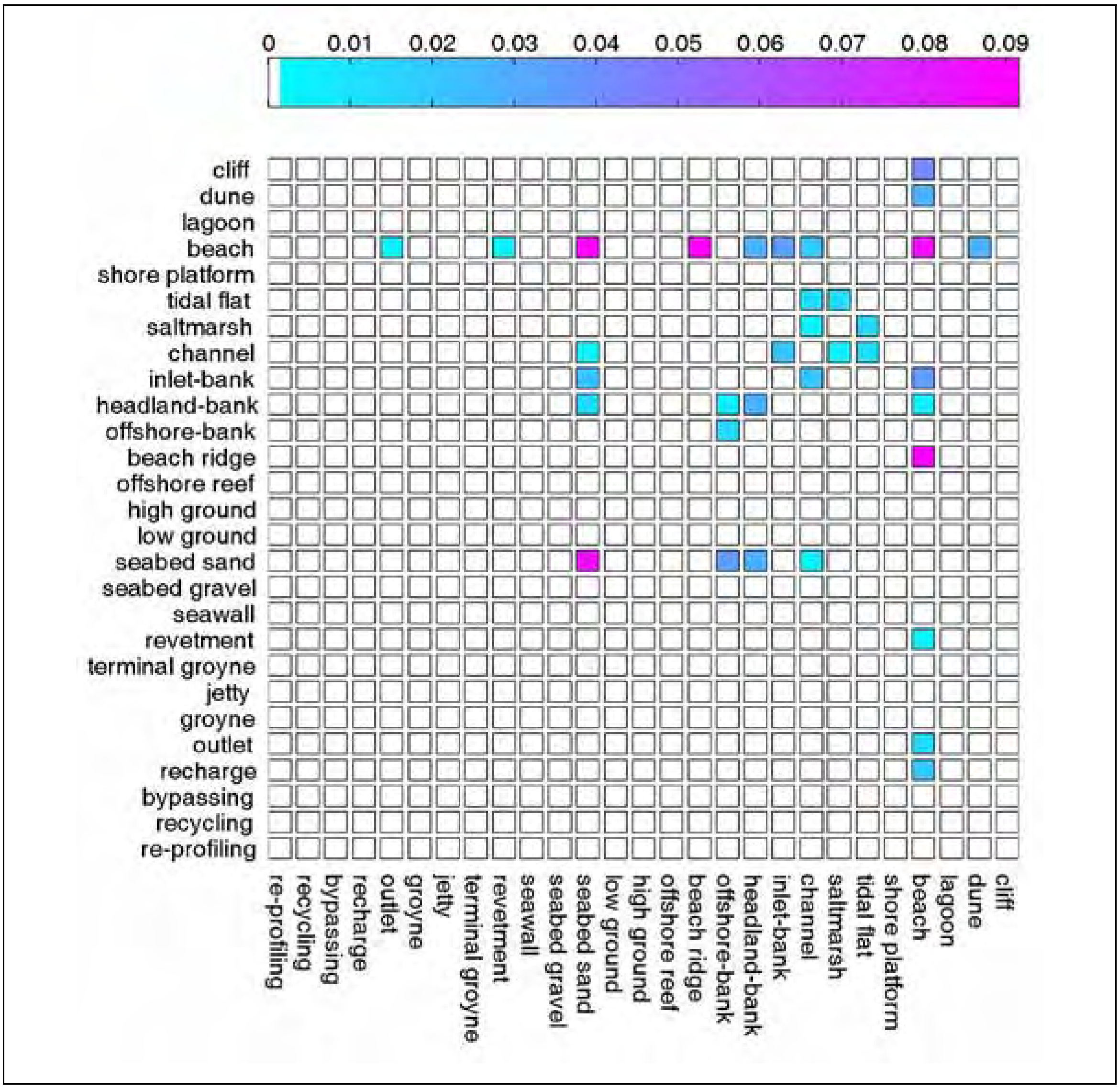


Figure 6.12 Interaction probability matrix for the system map in Figure 6.9, for *sediment transfers* only.

White cells indicate interactions that do not occur in this system map, colour-coded cells show the varying probability of the interactions that do occur. This analysis includes both directions of any bi-directional links.

Summary statistics for the system map (Table 6.5) show the prevalence of open coast, punctuated by headland, foreland and estuary control points. Less than 30 per cent of the links are known to be characterised by bi-directional exchanges of either sediment or other forms of influence; many of these are beach-seabed interactions. Sediment transfer occurs over a fairly high proportion (63 per cent) of the links.

Table 6.5 Summary statistics for system map shown in Figure 6.9, extracted directly from CmapTools-generated XML file.

System comprises 130 elements and element-level interventions:
6 cliff
4 dune
5 lagoon
18 beach
2 tidal flat
2 saltmarsh
5 channel
3 inlet-bank
5 headland-bank
5 offshore-bank
13 beach ridge
13 high ground
13 low ground
14 seabed sand
8 seawall
1 revetment
3 jetty
4 groyne
1 outlet
3 recharge
1 recycling
1 reprofiling

These elements are grouped into 21 features:
1 offshore
8 open coast
2 headland
2 spit
3 foreland
1 inlet
4 estuary

These elements are also linked to 1 unmapped feature-level subsystems:
1 updrift coast

Sediment transfer system pathways:
Number of components in sediment transfer system = 83
Number of sediment pathways = 111
Number of sediment pathways (incl. both directions of bi-directional paths) = 143
Fraction of bi-directional links = 28.8%

Influence network pathways:
Number of components in influence network = 131
Number of influence pathways = 185
Number of influence pathways (incl. both directions of bi-directional paths) = 226
Fraction of bi-directional links = 22.2%

Ratio of N(sediment_paths)/N(all_paths) = 0.63

6.2.2. Alnmouth Bay, Northumberland coast

The second case study is smaller in scale, comprising just 15 km of coastline between two headlands defining Alnmouth Bay on the Northumberland coast (Figure 6.13). This short stretch of coast comprises two main headlands (Seaton Point and Hauxley), separated by a sandy bay backed by low ground (Holocene infill). The headlands are composite features, and the associated geological control is largely the result of the limestone and grit shore platforms. Small beaches are generally limited to a superficial cover across the upper foreshore, which are then backed by modern dune or low cliff into older aeolian deposits. This is an important sediment transport route around Seaton Point, connecting beaches and dunes with the bay to the south. The beach-dune pockets on the Hauxley headland are less well connected due to seawall and revetment intervention.

Figure 6.13 Region of interest for Alnmouth Bay, Northumbrian coast.

Within the bay, the Aln and Coquet rivers form small estuaries behind dune barriers before entering the bay through small channels. The Aln is unconstrained and has a history of channel migration, whereas the Coquet is naturally constrained against the Hauxley headland, in addition to a number of estuary-mouth jetties. Within the bay, both channels and beach are connected to a sediment source across the seabed. At the headlands, exposed shoreplatform extends into the nearshore and the seabed link is structural rather than that of sediment-source/supply. Coquet Island imparts a structural control (wave-sheltering) on processes across the Hauxley headland.

Alnmouth Bay lies with Coastal cell 1, Sub-cell 1a, and its management issues have been reviewed by Babtie Group (2003) and more recently in the Shoreline Management Plan by Royal Haskoning (2009a). These chiefly relate to the beach and dune frontages within the bay units and processes in the vicinity of the small estuaries of the Aln and the Coquet River. Specific management issues include:

- Within the bay to the north of the Aln Estuary, there is concern over the vulnerability of sandy beach and dunes to erosion during storms (with implications for the golf course), and the link of this erosion to shifts in the alignment of the Aln channel. The main requirements here are to monitor and manage the various *ad hoc* defences put in place over the years and to manage public access to the dunes and beach.

- South of Aln Estuary, the dunes of Buston Links appear to be subject to more sustained erosional pressure, mitigated in places by concrete blocks placed along the shoreline in the 1940s as an anti-tank defence measure.

- South of the rocky shore platform at Birling Carrs (which acts as a minor headland), the dunes provide an important natural coastal defence, and management is needed to reinforce sections of dune weakened by erosion, and to manage public access.

- Warkworth Harbour (the outlet of the River Coquet) is protected by jetties to the north and south. The north jetty is largely in a fair condition, but its seaward tip had suffered structural damage and is in a poor state of repair (with health and safety implications for public access). The south jetty is in generally good condition following recent refurbishment, although a section of the southern quayside (further upstream of the jetty) failed during high river flows in September 2008. Harbour siltation is a problem, and necessitates occasional dredging from the main harbour channel and from the bar at the estuary mouth. Accumulating material is also regularly removed from the northern wave basin within the harbour and placed north of the harbour entrance within Alnmouth Bay.

- The dunes and soft rock cliffs of Amble Links appear relatively stable, although localised erosion becomes more apparent moving southwards along the Hauxley headland, where *ad hoc* protection measures exist in varying states of repair.

The feature and element assignment resulting from the system mapping is summarised in Table 6.6, and the coastal system map is shown in Figure 6.14. Compared to that for Suffolk sub-cell 3c (Table 6.9), the impression is that of a much more compartmentalised coast, with a less well-connected littoral drift system. The contrast between the essentially unconfined Aln and the engineered Coquet channels is also evident. As with the Suffolk example, it is necessary to subdivide the major features to take account of alongshore variability. The bays contain transitions in hinterland and backshore characteristics, and the major headlands contain small beaches perched on the shore platforms. Some consideration was given to alternative ways of treating the subtidal extension of the shore platforms, in a way that recognises their geological continuity (they are typically single features), whilst allowing the incorporation of these superficial beach deposits. One way of doing this would be to introduce a new sub-tidal rock platform element, but we were reluctant to enlarge the set of system components unnecessarily. Accordingly, we opted to classify both intertidal and sub-tidal rock platforms as shore platform, and to link adjacent shore platform elements where these effectively enclose perched sedimentary elements.

Table 6.6 Coastal features and elements within Alnmouth Bay.

Chainage		Feature	Elements								
	km		***Hinterland***	***Backshore***		***Foreshore***		***Nearshore***		***Offshore***	
Longhoughton	0.0	Headland	High ground	Cliff		Shore platform		Shore platform	*Longhoughton & Boulmer Steels*		
Boulmer	1.9	Headland	High ground	Dune		Beach	*Boulmer Haven*	Shore platform	*North/South Reins*		
Seaton Point	3.0	Headland	High ground	Dune		Shore platform		Shore platform	*Marmouth Scars*		
		Bay	High ground	Cliff		Beach					
Foxton Hall	4.6	Headland	High ground	Cliff		Shore platform	*Marden Rocks*				
Alnmouth		Bay	High ground	Dune	*Alnmouth Links*	Beach					
		Bay	Low ground	Dune		Beach					
Aln Estuary	6.3	Estuary				Channel					
Buston Links		Bay	Low ground	Dune		Beach					
		Bay	High ground	Dune		Beach					
Northfield	8.8	Headland	High ground	Dune		Shore platform	*Birling Carrs*				
Birling Links		Bay	High ground	Dune		Beach					
Castle Dikes		Bay	Low ground	Dune		Beach					
Coquet River	12.3	Estuary				Jetty Channel Jetty					
Amble		Headland	High ground	Seawall	*Pan Point*	Shore platform	*Pan Point*	Shore platform	*Pan Rocks*		
	12.8	Headland	High ground	Dune	*Amble Links*	Beach		Shore platform	*Wellaugh Point*		
		Headland	High ground	Seawall		Shore platform	*Wellaugh Point*	Shore platform			
		Headland	High ground	Dune	*Amble Links*	Beach		Shore platform			
		Headland	High ground	Seawall		Shore platform		Shore platform			
		Headland	High ground	Dune		Shore platform		Shore platform			
		Headland	High ground	Dune		Beach				Island	*Coquet Island*
		Headland	High ground	Dune		Beach		Shore platform			
Hauxley	15.0	Headland	High ground	Dune		Shore platform		Shore platform			

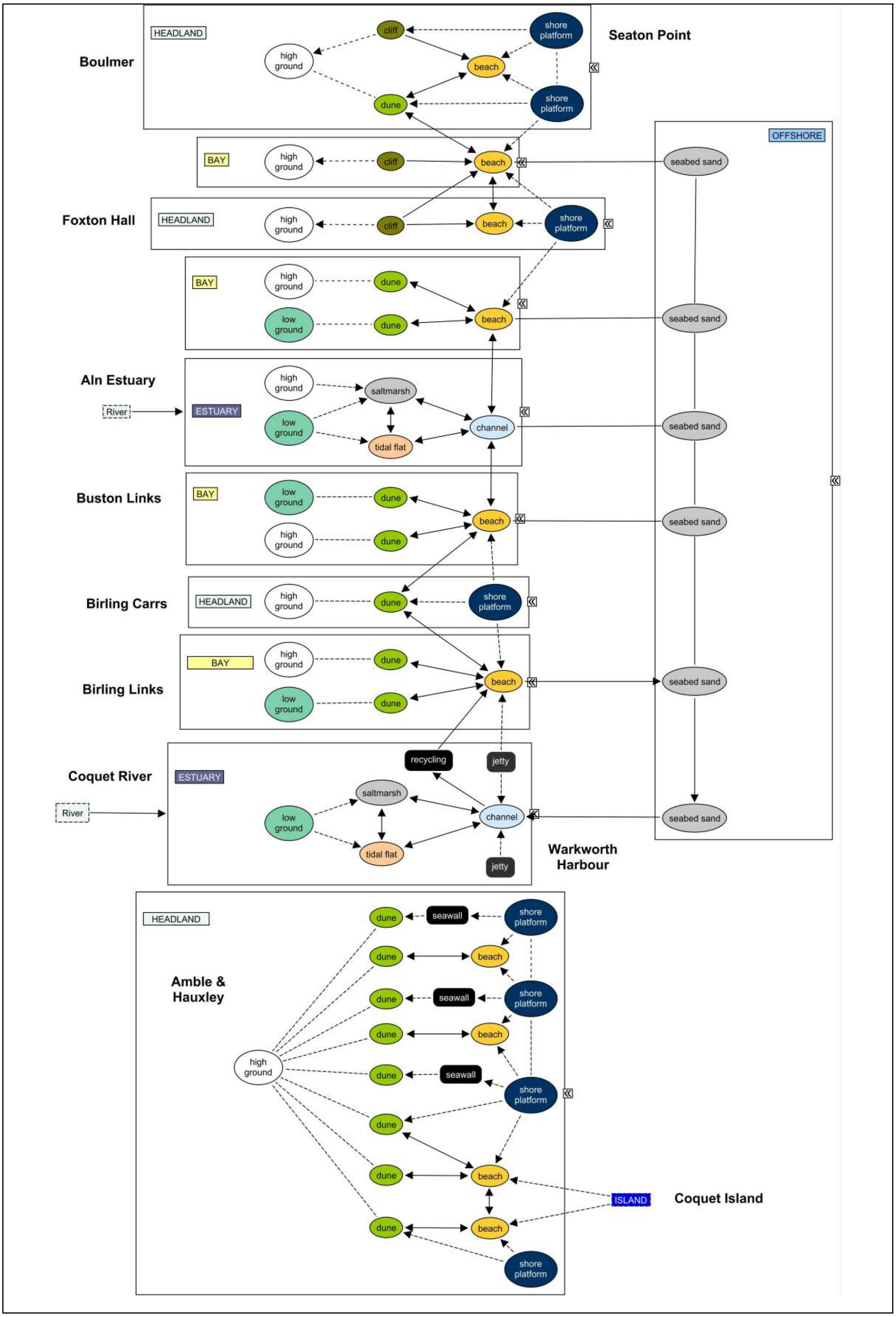


Figure 6.14 System map for Alnmouth Bay produced interactively using CmapTools.

Table 6.7 presents summary statistics extracted from the system map. Compared to the Suffolk example, this system map contains a smaller proportion of sediment transfer links, although the fraction of bi-directional exchanges is larger. This is consistent with oscillatory fluxes of material within the sub-bays and between beach and dune systems.

Table 6.7 Summary information for system map shown in Figure 6.14.

System comprises 69 elements and element-level interventions: 3 cliff 16 dune 10 beach 8 shore platform 2 tidal flat 2 saltmarsh 2 channel 9 high ground 5 low ground 6 seabed sand 3 seawall 2 jetty 1 recycling
These elements are grouped into 10 features: 1 offshore 4 headland 4 bay 2 estuary
These elements are also linked to 1 unmapped feature-level subsystem: 1 island
Sediment transfer system pathways: Sediment transfer system pathways: Number of components in sediment transfer system = 39 Number of sediment pathways = 42 Number of sediment pathways (incl. both directions of bi-directional paths) = 70 Fraction of bi-directional links = 67.0%
Influence network pathways: Number of components in influence network = 70 Number of influence pathways = 99 Number of influence pathways (incl. both directions of bi-directional paths) = 130 Fraction of bi-directional links = 31.3% Ratio of N(sediment links) / N(all links) = 0.54

Figure 6.15 and 6.16 show the element-level interaction matrix for the whole system (influence links) and the sediment system respectively. The influence system is less complex than that for Suffolk, and there is less interaction with the offshore zone. In terms of the sediment exchanges, beach-beach interactions are less prominent than beach-dune interactions.

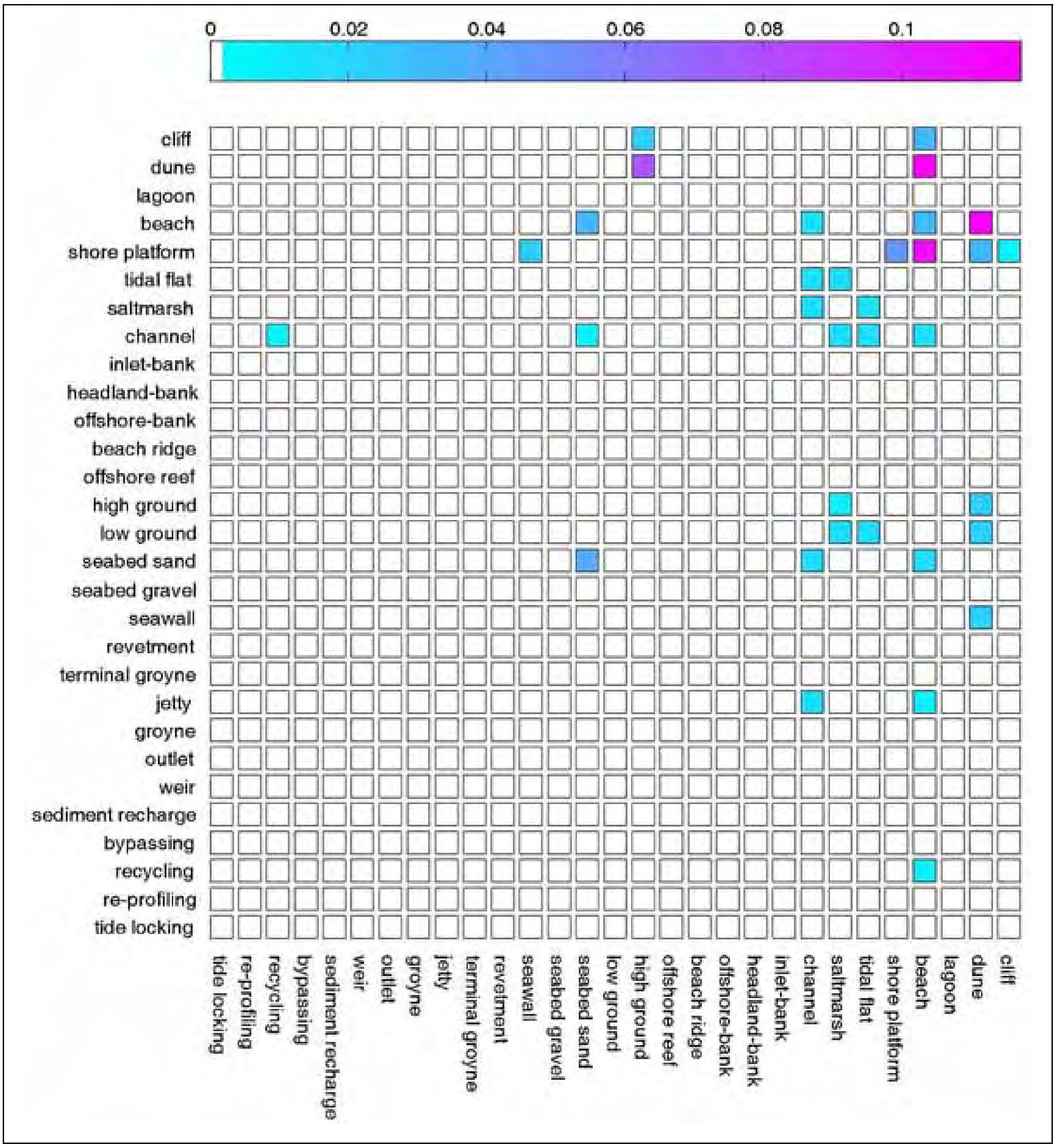


Figure 6.15 Interaction probability matrix for the system map in Figure 6.14.

Matrix includes the whole set of elements and interactions, irrespective of occurrence. White cells indicate interactions that do not occur in this system map, colour-coded cells show the varying probability of the interactions that do occur. This analysis includes both directions of any bi-directional links.

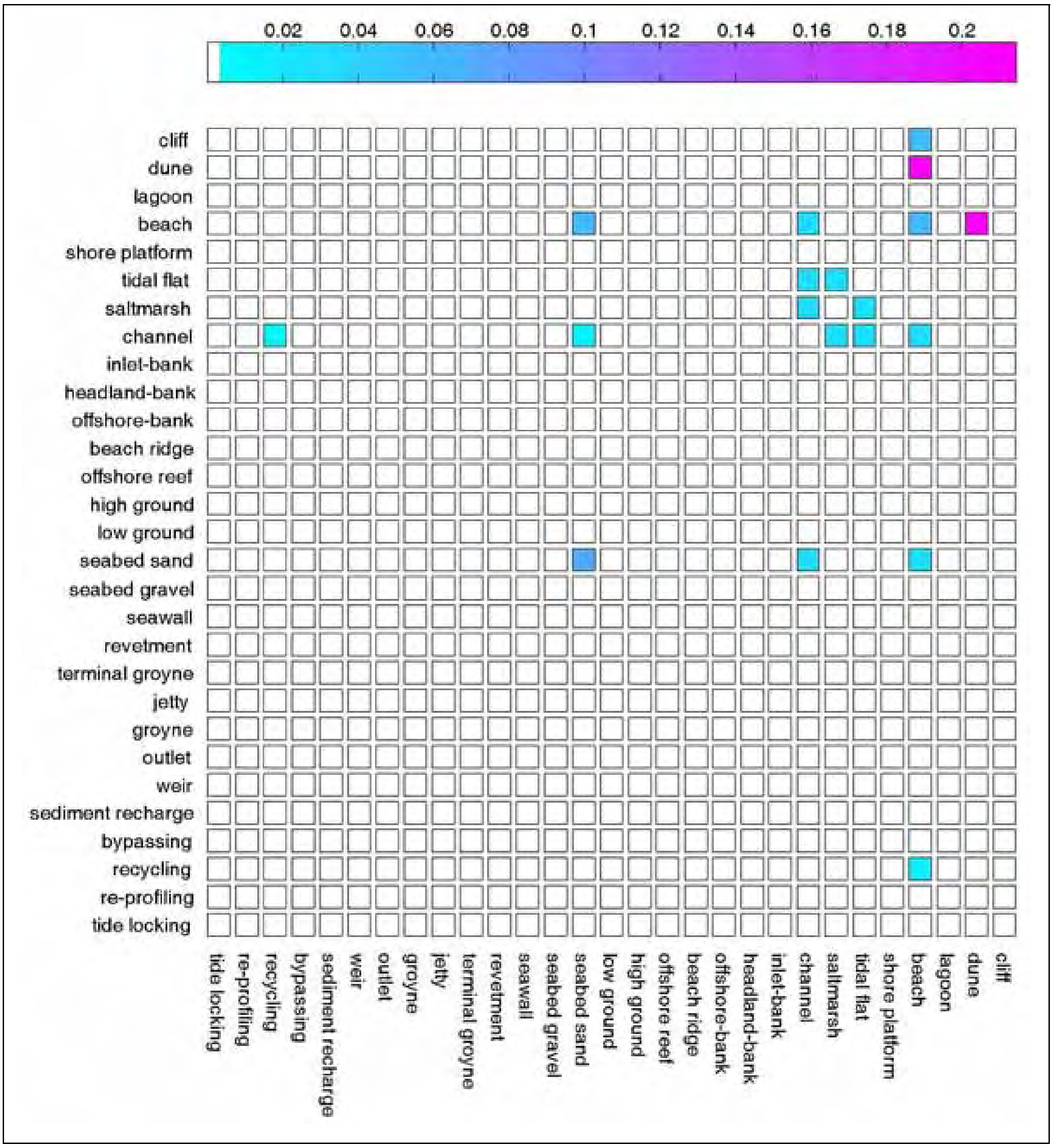


Figure 6.16 Interaction probability matrix for the system map in Figure 6.14, for sediment transfers only.

White cells indicate interactions that do not occur in this system map, colour-coded cells show the varying probability of the interactions that do occur. This analysis includes both directions of any bi-directional links.

6.2.3. Cardigan Bay

The final case study is much larger in scale, extending over nearly 270 km of coastline between the Llŷn and Pembrokeshire peninsulas on the west coast of Wales (Figure 6.17).

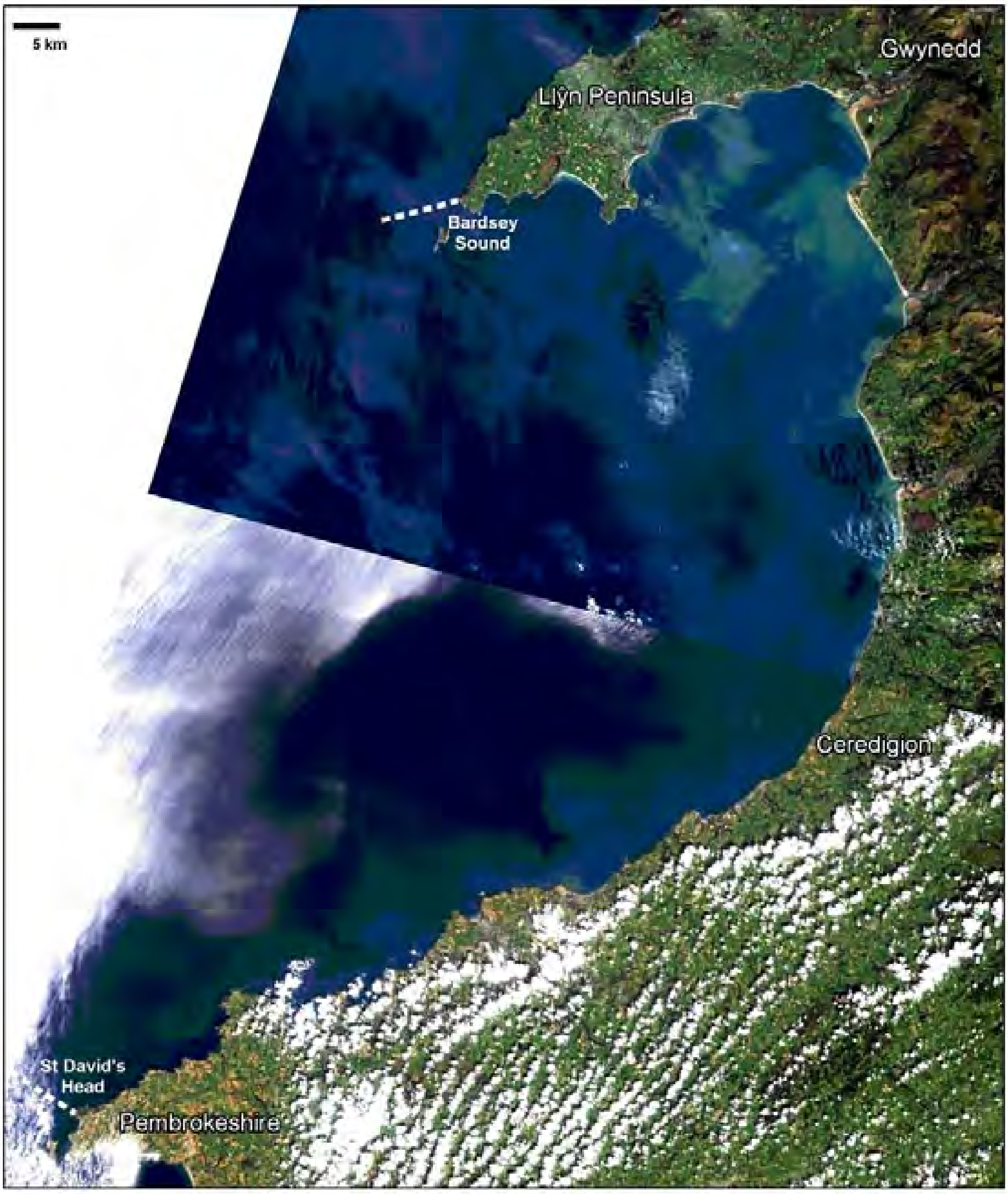


Figure 6.17 Cardigan Bay (cell 9).

Cardigan Bay is essentially a headland-bay system defined by the headlands of the Llyn Peninsula (to the north) and St David's Head, Pembrokeshire (to the south). The coastline covered in this cell spans three counties: Gwynedd, Ceredigion and Pembrokeshire.

Management issues include:

- Conservation of the natural environment: the region accommodates a great diversity of coastal habitats of local, national and international importance.
- Flood defence: the estuaries in Cardigan Bay incorporate extensive lowland environments, some of which have been historically embanked. Some of these sites rely on flood protection through seawall defence works.
- Coastal defence: shoreline recession through cliff erosion is prevalent throughout the region due to the sedimentary geology here (for example, at Hells Mouth bay). Locally, seawalls and revetments are used to maintain shoreline position in order to protect settlements and infrastructure from erosion – these have often had a clear local impact on coastal processes, primarily through reduced sediment-supply and offsets in shoreline recession. There is a regional priority to maintain beach levels as a means of reducing shoreline erosion.
- Navigation: although the maritime industry of Cardigan Bay has decreased in importance since the nineteenth century, there is still a local navigation requirement (mainly recreational) which has encouraged the construction and maintenance of jetties at smaller entrances (such as Afon Rheidol and Ystwyth).

Geomorphologically, Cardigan Bay comprises a complex array of coastal elements that contribute to more than 125 features (Table 6.8). The coastline is dominated by repeating suites of headland-bay systems, where foreshore sediment is compartmentalised between rocky headlands in the form of sand, gravel, cobble and boulder beaches. There are many situations of beach backed by eroding cliffs, and shore platforms are variably exposed depending on sediment cover. Several estuaries have formed in drowned valleys, with subsequent late Holocene dune barrier spit development. The estuaries are typically shallow and contain large expanses of tidal flat and saltmarsh. Elsewhere, smaller rivers meet the coastal system through incised river valleys fronted by beach and storm ridges.

Sediment throughout the cell is sourced primarily from cliff erosion, with additional contributions from the seabed and minor input from rivers. Alongshore sediment transport is intermittent as pathways are strongly controlled by the presence of rocky headlands. Within the larger bays, there is evidence of longshore sediment transport, particularly toward inlets: bypassing and estuary-coast connection takes place through inlet-associated banks (ebb and flood tidal deltas respectively).

The size and complexity of this system means that choices need to be made on the level of detail at which features and elements are resolved. Table 6.8 shows the results of an aerial photography-based geomorphological reconnaissance survey from which many very small-scale features are resolved. This level of detail may be appropriate for a small and clearly bounded system like Alnmouth Bay. However, it is not necessarily appropriate to map the entirety of a 270 km coastal cell in this way. For the purposes of this case study, it was decided to omit some minor details on the complex rocky headlands on the grounds that some of the small bay beaches pose few management problems. On the other hand, quite localised structural interventions can have highly visible implications for the functioning of what might otherwise be mapped as single bay beaches; details of this kind were retained on the basis of being highly relevant to management. Figure 6.18 shows a feature level map of the entirety of Cardigan Bay. The northern part, between Braich y Pwll and Afon Dyfi, is mapped out at the element level in Figure 6.1.

Table 6.8 Coastal features and elements within Cardigan Bay.

Chainage	Centroid			Feature	Elements								
	x_os	y_os	km		Hinterland		Backshore		Foreshore		Nearshore		Offshore
Braich y Pwll	213523	325847	0.0	Headland	High ground		Cliff		Shore platform				
Porth Felen	214401	324967	1.2	Headland	High ground		Cliff		Beach	*boulder/cobble*			
Trwyn Bychestyn	215010	324213	2.2	Headland	High ground		Cliff		Shore platform				
Parwyd	215400	324383	2.6	Headland	High ground		Cliff		Beach	*boulder/cobble*			
Pen Y Cil	215815	323985	3.2	Headland	High ground		Cliff		Shore platform				
Porth Meudwy	216314	325543	4.8	Bay		*incised valley*	River	*alluvium*	Beach	*sand*			
	216563	325966	5.3	Headland	High ground		Cliff		Shore platform				
Aberdaron Bay	216724	326254	5.7	Bay	High ground		Cliff		Beach	*sand*	Seabed		
	216775	326279	5.7	Bay		*incised valley*	River	*alluvium*			Seabed		
	216961	326322	5.9	Bay	High ground		Rock revetment		Beach	*sand*	Seabed		
	217105	326322	6.1	Bay		*incised valley*	River	*alluvium*			Seabed		
	217215	326322	6.2	Bay	Low ground		Seawall		Beach	*sand*	Seabed		
	217367	326296	6.3	Bay	High ground		Seawall		Beach	*sand*	Seabed		
	218011	326093	7.0	Bay	High ground		Cliff		Beach	*sand*	Seabed		
	218609	325602	7.8	Headland	High ground		Cliff		Shore platform				
Oguf Ddeuddrws	218566	325483	7.9	Headland	High ground		Cliff		Beach	*cobble*			
Trwyn y Penrhyn	218702	325246	8.2	Headland	High ground		Cliff		Shore platform				
Porth Cadlan	220039	326059	9.7	Headland	High ground		Cliff		Beach	*cobble*	Tombolo	*Maen Gwenonwy*	
Gallt y Mor	220404	326398	10.2	Headland	High ground		Cliff		Shore platform				
Porth Ysgo	220751	326423	10.6	Bay	High ground		Cliff		Beach	*sand*	Seabed		
	220937	326296	10.8	Bay	High ground		Cliff		Beach	*cobble*	Seabed		
	221309	326211	11.2	Bay	High ground		Cliff		Beach	*sand*	Seabed		
	221403	326068	11.4	Bay	High ground		Cliff		Beach	*cobble*	Seabed		
Trwyn Talfarach	221496	325720	11.7	Headland	High ground		Cliff		Shore platform				
Mynydd y Graig	223226	326821	13.8	Headland	High ground		Cliff		Beach	*cobble*			
Porth Neigwl	226992	327329	17.6	Bay	High ground		Cliff		Beach	*sand*	Seabed		

Chainage	Centroid x_os	y_os	km	Feature	Elements Hinterland		Backshore		Foreshore		Nearshore		Offshore	
Mynydd Cilan	229397	323016	22.5	Headland	High ground		Cliff		Shore platform					
Porth Ceiriad	230389	324489	24.3	Bay	High ground		Cliff		Beach	*gravel*				
	230508	324625	24.5	Bay	High ground		Cliff		Beach	*boulder/cobble*				
	230711	324709	24.7	Bay	High ground		Cliff		Beach	*sand/gravel*				
	231041	324786	25.0	Bay	High ground		Cliff		Shore platform					
	231431	324794	25.4	Bay	High ground		Cliff		Beach	*sand/gravel*				
Trwyn yr Wylfa	232099	324396	26.2	Headland	High ground		Cliff		Shore platform					
	232550	325500	27.4	Headland	High ground		Cliff		Shore platform				Islands	*St Tudwal's Island (E & W)*
Porth Bach	232431	326474	28.4	Headland	High ground		Cliff		Beach	*sand*				
Penrhyn Du	232380	326660	28.6	Headland	High ground		Jetty		Shore platform					
Borth Fawr	232290	326559	28.7	Bay	High ground	*Porth Tocyn*	Cliff		Beach	*sand*	Seabed			
	232087	326457	28.9	Bay	High ground	*Porth Tocyn*	Rock revetment		Beach	*sand*	Seabed			
	231915	326540	29.1	Bay	High ground	*Machroes*	Cliff		Beach	*sand*	Seabed			
	231718	326590	29.3	Bay	Low ground	*Machroes*	Seawall		Beach	*sand*	Seabed			
	231522	327162	29.9	Bay	Low ground		Dune	*Morfa Gors*	Beach	*sand; with groynes*	Seabed			
Abersoch	231763	328089	30.9	Headland	High ground		Jetty		Beach	*sand*	Seabed			
	231807	328254	31.0	Headland	High ground		Cliff		Beach	*sand*	Seabed			
	231610	328381	31.3	Headland	High ground		Jetty		Beach	*sand*	Seabed			
Afon soch	231344	328368	31.6	Estuary		*Afon soch*			Channel		Seabed			
Abersoch	231407	328464	31.7	Bay	Low ground		Dune		Beach	*sand*	Seabed			
	231509	328730	32.0	Bay	High ground		Cliff		Beach	*sand*	Seabed			
The Warren	232220	329861	33.3	Bay	High ground		Dune	*The Warren*	Beach	*sand*	Seabed			
Trwyn Llanbedrog	233750	330724	35.0	Headland	High ground		Cliff		Beach	*boulder/cobble*				
Llanbedrog	233452	331880	36.2	Bay	High ground		Cliff		Beach	*sand*	Seabed			
Carreg y Defaid	234208	332451	37.2	Headland	High ground		Cliff		Beach	*sand*			Island	*Carreg y Defaid*
Traeth Crugan	234208	332451	37.2	Bay	High ground		Cliff		Beach	*sand/gravel*	Reef			
	235320	333506	38.7	Bay	Low ground	*Afon penrhos*	Dune		Beach	*sand*	Reef			
	235860	333734	39.3	Bay	Low ground	*Afon penrhos*	Rock revetment	*Pwllheli Golf Club*	Sediment recharge	*sand*	Seabed			
Marian-y-mor	236825	334077	40.3	Bay	Low ground	*Afon penrhos*	Dune		Beach	*sand*	Seabed			

Chainage	Centroid			Feature	Elements								
	x_os	y_os	km		Hinterland		Backshore		Foreshore		Nearshore		Offshore
Marian-y-de	238641	334248	42.2	Headland	Low ground		Cliff		Shore platform				
Carreg yr Imbill	238895	334490	42.5	Headland	Low ground		Cliff		Beach	*sand/gravel*			
	238895	334763	42.8						Jetty				
Afon rhyd-hir	238775	334712	42.9	Estuary		*Afon rhyd-hir*			Channel		Seabed		
	238679	334737	43.0						Jetty				
Pwllheli	238559	335301	43.6	Bay	Low ground	*Afon erch*	Dune		Beach	*sand*	Seabed		
Abererch	239416	335793	44.6	Bay	Low ground	*Afon erch*	Dune	*chestnut fencing*	Beach	*sand*	Seabed		
Morfa Abererch	238559	335301	45.6	Bay	Low ground	*Afon erch*	Dune		Beach	*sand*	Seabed		
Penrhyn	242910	335444	49.9	Bay	High ground		Dune		Beach	*sand*	Seabed		
	243307	335285	50.3	Headland	High ground		Cliff		Shore platform				
	243466	335309	50.5	Headland	High ground		Cliff		Beach	*sand*			
	243640	335301	50.7	Headland	High ground	*Pen-ychain*	Cliff		Shore platform				
	243569	335468	50.9	Headland	High ground		Cliff		Beach	*sand*			
	243577	335515	50.9	Headland	High ground		Cliff		Shore platform				
	243601	335555	51.0	Headland	High ground		Cliff		Beach	*sand*			
	243640	335603	51.0	Headland	High ground		Cliff		Shore platform				
	243569	335880	51.3	Bay	High ground		Cliff		Beach	*sand*			
	243640	335603	51.6	Headland	High ground		Cliff		Shore platform				
Holiday Park	243708	336373	52.4	Bay	Low ground		Cliff		Beach	*gravel/cobble*	Reef	*cobble platform*	
	243764	336706	52.7	Bay	Low ground		Rock revetment		Beach	*sand*	Seabed		
	244113	336968	53.1	Bay	Low ground		Dune		Beach	*sand*	Seabed		
Afon wen	244248	337119	53.3	Bay	Low ground	*Afon wen*	River	*Afon wen*	Channel				
	244423	337119	53.5	Bay	Low ground		Dune		Beach	*sand*	Seabed		
Glanllynnau	245174	337238	54.3	Bay	Low ground		Rock revetment		Beach	*sand*	Reef	*cobble platform*	
	246991	337277	56.1	Bay	Low ground	*Afon dwyfor*	Cliff	*alluvium*	Beach	*sand*	Reef	*cobble platform*	
	247714	337190	56.8	Bay	Low ground	*Afon dwyfor*	Dune		Beach	*sand*	Reef		
Afon dwyfor	247872	337246	57.0	Bay		*Afon dwyfor*	River	*Afon dwyfor*	Channel				
	248261	337309	57.4	Bay	Low ground		Dune		Beach	*sand*	Reef	*cobble platform*	

Chainage	Centroid			Feature	Elements								
	x_os	y_os	km		Hinterland		Backshore		Foreshore		Nearshore		Offshore
	248968	337563	58.1	Bay	Low ground		Cliff		Beach	*gravel/cobble*	Reef	*cobble platform*	
Criccieth	249595	337650	58.8	Bay	Low ground		Seawall		Beach	*sand*	Reef	*cobble platform*	
	249873	337674	59.0	Bay	Low ground		Dune		Beach	*sand*			
	249992	337643	59.2	Headland	High ground	*Criccieth Castle*	Cliff		Shore platform				
	250085	337833	59.4	Bay	High ground		Rock revetment		Beach	*sand*	Reef	*cobble platform*	
	250165	337881	59.5	Bay	High ground		Rock revetment		Breakwater				
	250157	337960	59.5	Bay	High ground		Rock revetment		Beach	*gravel/cobble*			
	250603	338063	60.0	Bay	High ground		Seawall		Beach	*sand*			
	250762	338031	60.2	Bay	High ground		Dune		Beach	*sand*	Reef	*cobble platform*	
	251040	337992	60.4	Bay	Low ground	*lagoon*	Rock revetment		Beach	*sand*	Seabed		
Rhiw-for-fawr	251294	337877	60.7	Bay	High ground	*Rhiw-for-fawr*	Rock revetment		Beach	*sand*	Seabed		
	251795	337604	61.3	Bay	Low ground	*alluvium*	Dune		Beach	*sand*	Seabed		
Graig Ddu	252062	337389	61.6	Headland	High ground		Cliff		Beach	*sand*	Seabed		
Morfa Bychan	253281	336944	62.9	Bay	Low ground		Dune		Beach	*Black Rock Sands*	Seabed		
	254183	336480	64.0	Bay	Low ground		River		Beach		Seabed		
	254511	336450	64.3	Bay	Low ground		Dune		Beach	*North Bank*	Inlet-associated banks		
Afon Glaslyn	255587	336052	65.4	Estuary		*Afon Glaslyn*			Channel		Inlet-associated banks		
Morfa Harlech	255434	334994	66.5	Bay	Low ground		Dune	*Morfa Harlech*	Beach	*South Bank*	Inlet-associated banks		
	256603	332112	69.6	Bay	Low ground		Dune	*Morfa Harlech*	Beach	*sand*	Seabed		
Harlech	257280	330571	71.3	Bay	High ground		Dune	*Morfa Harlech*	Beach	*sand*	Seabed		
Llandanwg	256958	329013	72.9	Headland	High ground		Cliff	*till/glaciofluvial*	Beach	*boulder/cobble*			
Ymwlch	256780	328005	73.9	Bay	Low ground		Dune		Beach	*sand*	Seabed		
	256636	327624	74.3	Spit	Dune		Jetty		Beach	*boulder/cobble*			
Afon Artro	256620	327557	74.4	Estuary		*Afon Artro*			Channel		Seabed		
	256416	327497	74.6	Spit	Dune		Rock revetment		Beach	*mixed*			
Mochras	255248	326558	76.1	Headland	High ground		Cliff	*till*	Beach	*boulder/cobble*			

Chainage	Centroid			Feature	Elements								
	x_os	y_os	km		Hinterland		Backshore		Foreshore		Nearshore		Offshore
Morfa Dyffryn	255860	324189	78.5	Foreland	Low ground		Dune	*Morfa Dyffryn*	Beach	*sand*	Seabed		
Afon Ysgethin	257612	321770	81.5	Bay	Low ground		River	*Afon Ysgethin*	Beach	*sand*	Seabed		
Tal-y-bont	257688	321526	81.8	Bay	Low ground		Dune		Beach	*sand*	Seabed		
	257936	321170	82.2	Bay	Low ground		Rock revetment		Beach	*sand*	Seabed		
	258260	320694	82.8	Bay	Low ground		Dune		Beach	*sand*	Seabed		
	258571	320256	83.3	Bay	Low ground		Rock revetment		Beach	*sand*	Seabed		
	259089	319604	84.2	Bay	Low ground		Dune		Beach	*outcropping peat*	Seabed		
	259654	318454	85.4	Headland	High ground		Rock revetment		Beach	*sand*	Seabed		
Llanaber	259870	317844	86.1	Headland	High ground		Seawall		Rock armour				
Barmouth	260074	317496	86.5	Headland	High ground		Rock revetment		Beach	*sand*	Seabed		
	260505	316512	87.6	Bay	High ground		Seawall		Beach	*sand; with groynes*			
	260950	315629	88.6	Bay	High ground		Dune		Beach	*sand; with gravel outcrops*	Inlet-associated banks	*North Bank*	
	261458	315185	89.2	Bay			Jetty						
Afon Mawddach	261547	315128	89.3	Estuary		*Afon Mawddach*			Channel		Inlet-associated banks	*The Bar*	
	261432	314861	89.6	Spit			Dune		Beach				
Ro Wen	261318	314594	89.9	Bay	Low ground		Dune		Beach	*upper-gravel; lower-sand*	Inlet-associated banks	*South Bank*	
Fairbourne	261003	313940	90.6	Bay	Low ground		Revetment/ Seawall		Beach	*upper-gravel; lower-sand*			
	260080	311212	93.5	Headland	High ground		Cliff	*till/glaciofluvial*	Beach	*gravel/cobble*			
Llwyngwril	258353	309646	95.9	Headland	Low ground		Cliff	*alluvium*	Beach	*gravel/cobble*	Reef	*cobble platform*	
Llangelynnin	256803	306733	99.2	Headland	High ground		Cliff	*till/glaciofluvial*	Beach	*gravel/cobble*	Reef	*cobble platform*	
Tonfana	255957	303702	102.3	Headland	Low ground		Cliff	*alluvium*	Beach	*mixed*			
Afon Dysynni	256134	303304	102.7	Estuary		*Afon Dysynni*			Channel				
Morfa Gwyllt	256397	302881	103.2	Bay	Low ground		Dune		Beach	*sand*	Seabed		
	256829	302249	104.0	Bay	Low ground		Rock revetment		Beach	*sand*	Seabed		
	257032	301140	105.1	Outlet	Low ground		Rock revetment		Beach	*sand*	Sluice		

Chainage	Centroid			Feature	Elements								
	x_os	y_os	km		Hinterland		Backshore		Foreshore		Nearshore		Offshore
	256829	302249	106.3	Bay	Low ground		Rock revetment		Beach	*sand*	Seabed		
Tywyn	257870	300155	108.6	Bay	Low ground		Seawall		Beach	*sand; with groynes*	Seabed		
Penllyn	258154	299564	109.3	Bay	Low ground		Rock revetment		Beach	*sand*	Seabed		
	258262	299386	109.5	Outlet	Low ground		Rock revetment		Beach	*sand*	Sluice		
	258116	299647	109.8	Bay	Low ground		Rock revetment		Beach	*sand*	Seabed		
	258558	298687	110.8	Bay	Low ground		Dune		Beach	*sand*	Seabed		
	259762	295935	113.8	Bay	High ground		Dune		Beach	*sand*	Inlet-associated banks		
Afon Dyfi	260778	295356	115.0	Estuary		*Afon Dyfi*			Channel		Inlet-associated banks	*Aberdovey Bar*	
Tywni Bach	260503	294757	115.6	Bay	Low ground		Dune	*Tywni Bach*	Beach	*sand*	Inlet-associated banks		
Borth Sands	260357	293501	116.9	Bay	Low ground		Dune	*Tywni Mawr*	Beach	*upper-gravel; lower-sand*	Seabed		
Aberlerry	260476	292244	118.2	Bay	Low ground		Seawall		Beach	*sand; with groynes*	Seabed		
Borth	260701	290365	120.1	Bay	Low ground		Seawall		Beach	*upper-gravel; lower-sand; with groynes*	Seabed		
Upper Borth	260245	288698	121.8	Headland	High ground		Cliff		Beach	*gravel/cobble*	Shore platform		
	260011	288333	122.2	Headland	High ground		Cliff		Beach	*sand/gravel*			
	259449	287216	123.5	Headland	High ground		Cliff		Beach	*gravel/cobble*	Shore platform		
Sarn Gynfelyn	258916	285690	125.1	Headland	High ground	*incised valley*	River	*alluvium*	Beach	*gravel/cobble*	Reef?	*shore-normal gravel bar*	
	258579	284610	126.2	Headland	High ground		Cliff		Shore platform		Reef?		
Clarach Bay	258608	284026	126.8	Headland	High ground	*incised valley*	Rock revetment		Beach	*sand/gravel*			
	258644	283909	126.9	Headland	High ground	*incised valley*	River	*Afon Clarach*	Channel				
	258674	283727	127.1	Headland	High ground	*incised valley*	Wood revetment		Beach	*sand/gravel*			
Craigyfulfran	258294	282938	128.0	Headland	High ground		Cliff		Shore platform				
Aberystwyth	258281	282428	128.5	Bay	High ground		Revetment/ Seawall		Beach	*sand; with groynes*			
	258262	282237	128.7	Bay	High ground		Seawall		Beach	*sand*	Shore platform		
	258224	281952	129.0	Bay	High ground		Seawall		Beach	*sand*			

Chainage	Centroid			Feature	Elements							
	x_os	y_os	km		Hinterland		Backshore		Foreshore		Nearshore	Offshore
	258014	281704	129.3	Headland	High ground		Seawall		Shore platform			
	257849	281539	129.5	Bay	High ground		Seawall		Beach	*sand*	Shore platform	
	257963	281240	129.9	Bay	High ground		Seawall		Beach	*sand*		
	257938	280904	130.2						Jetty			
	257874	280878	130.3	Estuary		*Afon Rheidol & Ystwyth*			Channel			
	257823	280783	130.4						Jetty			
Tanybwlch	257919	280431	130.7	Bay	Low ground		Beach ridge?		Beach	*gravel/cobble*		
	257900	279828	131.3	Bay	Low ground		Beach ridge?		Beach	*sand/gravel*		
Ffos-las	256375	277241	134.3	Headland	High ground		Cliff		Beach	*gravel/cobble*	Reef?	
Pen Glog	254960	273240	138.6	Headland	High ground		Cliff		Shore platform			
	254420	271994	139.9	Headland	High ground		Cliff		Beach	*sand/gravel*		
Tregynan	253975	271256	140.8	Headland	High ground		Cliff		Shore platform			
Llanrhystud	252793	269851	142.6	Headland	Low ground		Cliff	*alluvium*	Beach	*mixed*	Reef?	
	252674	269740	142.8	Headland	High ground	*incised valley*	River	*Afon Wyre*	Channel			
	252585	269537	143.0	Bay	High ground	*alluvium*	Beach ridge?		Beach	*mixed*	Reef?	
	252172	268648	144.0	Bay	High ground	*alluvium*	Beach ridge?		Beach	*sand*		
	251201	268159	145.1	Open coast	High ground		Cliff	*till*	Beach	*mixed*	Reef?	
Llanon	250648	266813	146.6	Open coast	Low ground	*alluvium*	Cliff		Beach	*mixed*	Reef?	
	248864	264793	149.2	Open coast	High ground		Cliff	*till*	Beach	*gravel/cobble*	Reef?	
Aberarth	247886	264114	150.4	Open coast	High ground	*incised valley*	River	*Afon Arth*	Channel			
	247745	263974	150.6	Open coast	High ground		Cliff	*till*	Beach	*gravel/cobble; with groynes*		
	246830	263574	151.6	Open coast	High ground		Cliff	*till*	Beach	*gravel/cobble*	Reef?	
Aberaeron	245808	263295	152.7	Open coast	Low ground		Cliff	*alluvium*	Beach	*gravel/cobble; with groynes*		
	245516	263047	153.1						Jetty			
	245522	263009	153.1	Estuary		*Afon Arth*			Channel			
	245414	263022	153.2						Jetty			
	245268	262762	153.5	Open coast	High ground		Cliff	*till*	Beach	*gravel/cobble; with groynes*		
	244989	262571	153.9	Open coast	High ground		Cliff		Shore platform			
	244824	262495	154.0	Open coast	High ground		Cliff		Beach	*gravel/cobble*	Shore platform	
Clogfryn	244309	261993	154.8	Open coast	High ground		Cliff		Beach	*gravel/cobble*	Reef?	
	243890	261733	155.3	Open coast	High ground	*incised valley*	River	*alluvium*	Beach	*mixed*	Shore platform	

Chainage	Centroid			Feature	Elements							
	x_os	y_os	km		Hinterland		Backshore		Foreshore		Nearshore	Offshore
	243725	261574	155.5	Open coast	High ground		Cliff		Beach	*gravel/cobble*	Reef?	
	243522	261371	155.8	Open coast	High ground	*incised valley*	River	*alluvium*	Beach	*mixed*		
Gilfach-yr-Halen	243357	261358	155.9	Open coast	High ground		Cliff		Shore platform			
	243080	261100	156.3	Open coast	High ground		Cliff		Beach	*gravel/cobble*	Shore platform	
	242715	260812	156.8	Open coast	High ground		Cliff		Beach	*mixed*	Seabed	
	242419	260668	157.1	Open coast	High ground		Cliff		Shore platform			
	241808	260171	157.9	Open coast	High ground		Cliff		Beach	*mixed*	Seabed	
Little Quay Bay	240783	259764	159.0	Bay	High ground		Rock revetment		Beach	*mixed; with groynes*	Seabed	
	240685	259806	159.1	Bay	High ground		Cliff		Beach	*mixed*	Seabed	
	240613	259924	159.2	Headland	High ground		Cliff		Beach	*mixed; with groynes*	Reef?	
	240532	259895	159.3	Headland	Low ground	*incised valley*	River	*alluvium*	Channel		Reef?	
New Quay Bay	240488	259920	159.4						Jetty			
	239705	259462	160.3	Bay	High ground		Cliff		Beach	*upper-gravel; lower-sand*	Seabed	
	239047	259780	161.0	Bay	High ground		Rock revetment		Beach	*sand*	Seabed	
	239032	259898	161.1	Bay	High ground		Seawall		Breakwater			
	239010	260016	161.3	Bay	High ground		Seawall		Beach	*sand*	Seadbed	
	239084	260171	161.4	Bay	High ground		Seawall		Breakwater			
New Quay Head	238929	260208	161.6	Headland	High ground		Rock revetment		Beach	*mixed*	Seadbed	
	238825	260452	161.9	Headland	High ground		Cliff		Shore platform			
	238648	260444	162.0	Headland	High ground		Cliff		Beach	*mixed*	Seabed	
	238582	260496	162.1	Headland	High ground		Cliff		Shore platform			
	238493	260437	162.2	Headland	High ground		Cliff		Beach	*boulder/cobble*	Reef?	
	238412	260422	162.3	Headland	High ground		Cliff		Shore platform			
	238345	260378	162.4	Headland	High ground		Cliff		Beach	*gravel/cobble*	Reef?	
Bird's Rock	237739	260164	163.0	Headland	High ground		Cliff		Shore platform			
	237481	259839	163.4	Open coast	High ground		Cliff		Beach	*gravel/cobble*	Reef?	
Penrhyn	237385	259691	163.6	Open coast	High ground		Cliff		Shore platform			
Traeth y Coubal	237281	259417	163.9	Open coast	High ground		Cliff		Beach	*gravel/cobble*	Reef?	
	236594	258878	164.8	Open coast	High ground		Cliff		Shore platform			

Chainage	Centroid			Feature	Elements							
	x_os	y_os	km		Hinterland		Backshore		Foreshore		Nearshore	Offshore
	236240	258302	165.5	Open coast	High ground	*incised valley*	River	*alluvium*	Beach	*mixed*	Reef?	
	236040	258213	165.7	Open coast	High ground		Cliff		Shore platform			
	235900	257962	166.0	Open coast	High ground		Cliff		Beach	*mixed*	Reef?	
Craig Caerllan	235663	257903	166.2	Open coast	High ground		Cliff		Shore platform			
Cwmtydu	235575	257570	166.6	Bay	High ground	*incised valley*	Seawall	*alluvium*	Beach	*mixed*	Reef?	
	235515	257541	166.6	Bay	High ground	*incised valley*	River		Channel			
	234163	256314	168.5	Open coast	High ground		Cliff		Shore platform	*with occasional rock fall veneer*		
	232146	254992	170.9	Open coast	High ground		Cliff		Beach	*mixed*	Reef?	
	232028	255044	171.0	Headland	High ground		Cliff		Shore platform			
Traeth-yr-ynys	231548	255125	171.5	headland	High ground		Cliff		Beach	*sand*	Seabed	
Ynys-Lochtyn	231489	255731	172.1	Headland	High ground		Cliff		Shore platform			
	231161	255211	172.7	Headland	High ground		Cliff		Shore platform			
	231333	254993	173.0	Open coast	High ground		Cliff		Beach	*mixed*	Seabed	
	231323	254886	173.1	Open coast	High ground		Cliff		Shore platform			
	231328	254825	173.1	Open coast	High ground		Cliff		Beach	*mixed*	Seabed	
	231272	254775	173.2	Open coast	High ground		Cliff		Shore platform			
	231278	254719	173.3	Open coast	High ground		Cliff		Beach	*mixed*	Seabed	
	231232	254668	173.3	Open coast	High ground		Cliff		Shore platform			
	231232	254571	173.4	Open coast	High ground		Cliff		Beach	*sand*	Seabed	
	231110	254500	173.6	Open coast	High ground		Cliff		Shore platform			
	231120	254399	173.7	Open coast	High ground		Cliff		Beach	*sand*	Seabed	
	231039	254348	173.8	Open coast	High ground		Cliff		Shore platform			
Llangrannog	231024	254201	173.9	Bay	High ground		Seawall		Beach	*sand*	Seabed	
	230582	254023	174.4	Open coast	High ground		Cliff		Shore platform			
	230358	253738	174.8	Open coast	High ground		Cliff		Beach	*gravel/cobble*	Reef?	
Carreg-y-ty	230089	253703	175.0	Open coast	High ground		Cliff		Shore platform			
	230053	253494	175.3	Open coast	High ground		Cliff		Beach	*sand*	Seabed	
Carreg y Nodwydd	229809	253388	175.5	Open coast	High ground		Cliff		Shore platform			

Chainage	Centroid			Feature	Elements								
	x_os	**y_os**	**km**		**Hinterland**		**Backshore**		**Foreshore**		**Nearshore**	**Offshore**	
Traeth Penbryn	229337	252570	176.5	Open coast	High ground		Dune		Beach	*sand*	Seabed		
	229230	252483	176.6	Open coast	High ground	*incised valley*	River	*alluvium*	Beach	*sand*	Seabed		
	229180	252428	176.7	Open coast	High ground		Dune		Beach	*sand*	Seabed		
	228910	252219	177.0	Open coast	High ground		Cliff		Beach	*upper-gravel; lower-sand*	Seabed		
	228585	252031	177.4	Open coast	High ground		Cliff		Beach	*gravel/cobble*			
	228194	251864	177.8	Open coast	High ground		Cliff		Shore platform	*with occasional rock fall veneer*			
Tresaith	227798	251584	178.3	Bay	High ground		Cliff		Beach	*sand*	Seabed		
Aberporth	226787	251533	179.3	Open coast	High ground		Cliff		Shore platform				
	225928	251457	180.2	Bay	High ground		Rock revetment		Beach	*sand*	Seabed		
	225872	251447	180.2	Bay	High ground	*incised valley*	River	*alluvium*	Beach	*sand*	Seabed		
	225857	251620	180.4	Headland	High ground		Cliff		Beach	*sand*	Seabed		
	225761	251569	180.5	Bay	High ground		Seawall		Beach	*sand*	Seabed		
	225715	251594	180.6	Bay	High ground	*incised valley*	River	*alluvium*	Beach	*sand*	Seabed		
	225537	252006	181.0	Headland	High ground		Cliff		Shore platform				
Cribach Bay	225192	252026	181.4	Bay	High ground		Cliff		Beach	*sand*	Seabed		
	225131	252138	181.5	Bay	High ground		Cliff		Shore platform				
	225049	252189	181.6	Bay	High ground		Cliff		Beach	*sand*	Seabed		
Pencribach	225105	252433	181.8	Headland	High ground		Seawall		Shore platform				
Pen-Peles	221823	252385	185.1	Open coast	High ground		Cliff		Shore platform	*with occasional rock fall veneer*			
	219127	252134	187.8	Headland	High ground		Cliff		Shore platform				
Mwnt	219389	251930	188.2	Bay	High ground		Cliff		Beach	*sand*	Seabed		
Pen yr Hwbyn	218175	251785	189.4	Headland	High ground		Cliff		Shore platform				
Cardigan Island	216227	251361	191.4	Headland	High ground		Cliff		Shore platform			Island	*Cardigan Island*
Craig y Gwbert	215836	250239	192.6	Headland	High ground		Cliff		Shore platform				
Gwbert	216095	249528	193.3	Bay	High ground		Cliff		Channel				
	216023	248718	194.0	Bay	Low ground	*Towyn Warren*	Rock revetment		Channel		Seabed		
	216000	248620	194.1	Spit	Low ground		Beach ridge		Channel		Inlet-associated banks		
Teifi Estuary	215968	248432	194.4	Estuary		*Afon Teifi*			Channel		Inlet-associated banks		

Chainage	**Centroid**			**Feature**	**Elements**							
	x_os	**y_os**	**km**		**Hinterland**		**Backshore**		**Foreshore**		**Nearshore**	**Offshore**
	215468	248742	195.0	Bay	Low ground		Dune		Beach	*Poppit Sands*	Inlet-associated banks	
	214658	248940	195.8	Bay	High ground		Cliff		Beach	*with shore platform outcrops*	Seabed	
Penrhyn Castle	214372	249131	196.2	Headland	High ground		Cliff		Breakwater			
Cemaes Head	213118	250147	197.8	Headland	High ground		Cliff		Shore platform	*with occasional rock fall veneer*		
	212801	249282	198.7	Headland	High ground		Cliff		Beach	*mixed*		
Pen yr Afr	211928	248662	199.8	Open coast	High ground		Cliff		Shore platform	*with occasional rock fall veneer*		
	212253	248289	200.3	Open coast	High ground		Cliff		Beach	*gravel/cobble*		
	212245	248154	200.4	Open coast	High ground		Cliff		Shore platform			
Gernos	212269	248035	200.5	Open coast	High ground		Cliff		Beach	*boulder/cobble*		
Foel Hendre	211556	247424	201.5	Open coast	High ground		Cliff		Shore platform			
Ceibwr Bay	211023	245729	203.3	Inlet	High ground	*incised valley*	Beach Ridge	*alluvium*	Beach	*gravel/cobble*		
	211016	245640	203.4	Inlet	High ground	*incised valley*	River		Channel			
Careg Yspar	209918	245018	204.6	Open coast	High ground		Cliff		Shore platform			
Cell Howel	208737	243748	206.3	Open coast	High ground		Cliff		Beach	*boulder/cobble*		
Pwll Coch	206502	243367	208.6	Headland	High ground		Cliff		Shore platform	*with occasional rock fall veneer*		
Carregedrywy	205041	242160	210.5	Headland	High ground		Cliff		Shore platform			
Newport Bay	205409	240592	212.1	Bay	High ground		Rock revetment		Beach	*sand*		
	205206	240242	212.5	Spit	Low ground		Dune		Beach	*sand*	Inlet-associated banks	
	205213	239912	212.9	Estuary		*Afon Nyfer*			Channel		Inlet-associated banks	
	204851	239791	213.2	Bay	High ground		Cliff		Beach	*with shore platform outcrops*	Channel	
	203892	239950	214.2	Bay	High ground		Cliff		Shore platform			
Aber Rhigian	203244	239544	215.0	Bay	High ground	*incised valley*	Beach Ridge	*alluvium*	Beach	*sand*		
	202933	239709	215.3	Bay	High ground		Cliff		Shore platform			
Aber Fforest	202565	239563	215.7	Bay	High ground	*incised valley*	Beach Ridge	*alluvium*	Beach	*sand*		

Chainage	Centroid x_os	y_os	km	Feature	Elements Hinterland		Backshore		Foreshore		Nearshore	Offshore
	202387	239728	216.0	Bay	High ground		Cliff		Shore platform			
	202038	239753	216.3	Bay	High ground		Cliff		Beach	*boulder/cobble*		
Trwyn Isaac	201904	240071	216.7	Headland	High ground		Cliff		Shore platform			
	201765	240065	216.8	Bay	High ground		Cliff		Beach	*mixed*		
	201682	240045	216.9	Bay	High ground		Cliff		Shore platform			
Cwm-yr-Eglwys	201593	240058	217.0	Bay	High ground	*incised valley*	Seawall		Shore platform			
	201504	240090	217.1	Bay	High ground	*incised valley*	Seawall		Beach			
Pig y Baw	201657	240293	217.3	Headland	High ground		Cliff		Shore platform			
	201587	240338	217.4	Headland	High ground		Cliff		Beach	*mixed*		
Dinas Head	200469	241404	219.0	Headland	High ground		Cliff		Shore platform	*with occasional rock fall veneer*		
Pwllgwaelod	200425	239982	220.4	Bay	High ground	*incised valley*	Beach Ridge	*alluvium*	Beach	*sand*		
	200463	239918	220.4	Bay	High ground	*incised valley*	Rock revetment		Beach	*sand*		
	200209	239633	220.8	Bay	High ground		Cliff		Shore platform	*with occasional rock fall veneer*		
	199917	239334	221.2	Bay	High ground		Cliff		Beach	*mixed*		
Cerrig Duon	199675	239201	221.5	Bay	High ground		Cliff		Shore platform			
Aber Bach	199688	238636	222.1	Bay	High ground		Cliff		Beach	*mixed*		
Penrhyn Ychen	198240	238483	223.5	Bay	High ground		Cliff		Shore platform	*with occasional rock fall veneer*		
	196767	237645	225.2	Bay	High ground		Cliff		Beach	*mixed*		
	196729	237690	225.3	Bay	High ground		Cliff		Shore platform			
	196653	237677	225.4	Bay	High ground		Cliff		Beach	*mixed*		
Castle Point	196189	237842	225.9	Bay	High ground		Cliff		Shore platform			
	196088	237448	226.3	Bay	High ground		Seawall		Breakwater			
	196253	237302	226.5	Bay	High ground		Seawall		Channel			
Afon Gwaun	196253	237144	226.7	Bay	High ground	*incised valley*	River	*Afon Gwaun*	Channel			
	196202	237182	226.7	Bay	High ground	*incised valley*	Seawall		Beach	*mixed*		
Penyraber	195954	237442	227.1	Bay	High ground		Cliff		Shore platform			
	195795	237537	227.3	Bay	High ground		Cliff		Beach	*boulder/cobble*		
	195738	237779	227.5	Bay	High ground		Cliff		Shore platform			

Chainage	Centroid x_os	y_os	km	Feature	Elements Hinterland		Backshore	Foreshore		Nearshore	Offshore	
Fishguard	194932	237740	228.3	Bay	Low ground		Rock revetment	Beach	*sand; with groynes*			
	194811	237950	228.6	Bay	Low ground		Seawall	Jetty				
	194703	238090	228.7	Bay	Low ground		Seawall	Rock revetment				
	195103	238693	229.5	Bay	High ground		Seawall	Rock revetment				
	195446	239391	230.2	Headland	High ground		Seawall	Breakwater				
Pwll Hir	195129	239531	230.6	Headland	High ground		Cliff	Beach	*with shore platform outcrops*			
Y Penrhyn	194379	240579	231.9	Headland	High ground		Cliff	Shore platform				
Llanwnda	192836	240096	233.5	Headland	High ground		Cliff	Beach	*mixed*			
	191985	240820	234.6	Headland	High ground		Cliff	Shore platform				
Porthsychan	190550	240757	236.0	Headland	High ground		Cliff	Beach	*mixed*			
Strumble Head	189103	241322	237.6	Headland	High ground		Cliff	Shore platform				
Porth Maenmelyn	188868	239214	239.7	Headland	High ground		Cliff	Beach	*boulder/cobble*			
Ynys Ddu	188715	238826	240.1	Headland	High ground		Cliff	Shore platform				
Pwll Deri	189103	238363	240.7	Headland	High ground		Cliff	Beach	*boulder/cobble*			
	188023	237582	242.1	Headland	High ground		Cliff	Shore platform				
Pwlldawnau	187991	237061	242.6	Headland	High ground		Cliff	Beach	*mixed*			
Trwyn Llwyd	187820	236604	243.1	Headland	High ground		Cliff	Shore platform				
Pwllcrochan	188550	236464	243.8	Headland	High ground		Cliff	Beach	*mixed*			
Llech Dafad	188036	235791	244.7	Headland	High ground		Cliff	Shore platform				
Aber Bach	188379	235048	245.5	Bay	High ground	*incised valley*	Beach Ridge	Beach	*gravel/cobble*			
	188271	234908	245.7	Headland	High ground		Cliff	Shore platform				
Aber Mawr	188182	234610	246.0	Bay	High ground	*incised valley*	Beach Ridge	Beach	*gravel/cobble*			
Trwyn Llwynog	186810	234477	247.4	Headland	High ground		Cliff	Shore platform	*with occasional rock fall veneer*			
Abercastle	185242	233651	249.1	Inlet	High ground	*incised valley*	Beach Ridge	Beach	*mixed*		Island	*Ynys y Castell*
	184226	233981	250.2	Headland	High ground		Cliff	Shore platform				
Pwll Whiting	184207	233613	250.6	Bay	High ground		Cliff	Beach	*mixed*			

Chainage	Centroid			Feature	Elements						
	x_os	y_os	km		Hinterland		Backshore	Foreshore		Nearshore	Offshore
	183972	233416	250.9	Headland	High ground		Cliff	Shore platform			
Pwll Llong	184118	233302	251.1	Bay	High ground		Cliff	Beach	*mixed*		
	183724	233187	251.5	Headland	High ground		Cliff	Shore platform			
Pwll Olfa	183756	232978	251.7	Bay	High ground		Cliff	Beach	*mixed*		
	182194	232667	253.3	Headland	High ground		Cliff	Shore platform	*with occasional rock fall veneer*		
Porth-gain	181381	232641	254.1	Headland	High ground		Seawall	Breakwater			
	181444	232559	254.2	Inlet	High ground	*incised valley*	Seawall	Beach	*mixed*		
	181425	232540	254.2	Inlet	High ground	*incised valley*	Seawall	Breakwater			
	181394	232533	254.2	Inlet	High ground	*incised valley*	Seawall	Beach	*mixed*		
	181368	232603	254.3	Headland	High ground		Seawall	Breakwater			
	180416	232819	255.3	Headland	High ground		Cliff	Shore platform			
Ynys Barry	180117	232165	256.0	Bay	High ground		Cliff	Beach	*mixed*		
	180035	232108	256.1	Bay	High ground		Cliff	Shore platform			
	180225	231975	256.4	Bay	High ground		Cliff	Beach	*sand*	Seabed	
Trwyn Castell	179241	231549	257.4	Headland	High ground		Cliff	Shore platform			
Abereiddi Bay	179666	231244	257.9	Bay	Low ground		Seawall	Beach	*sand*	Seabed	
Carreg yr Afr	175813	229180	262.3	Headland	High ground		Cliff	Shore platform	*with occasional rock fall veneer*		
St David's Head	172034	227765	266.4	Headland	High ground		Cliff	Shore platform			

Figure 6.18 and 6.19 illustrate the compartmentalised nature of this coast. Within the broader confines of the bay as defined in the north by the headland of Braich y Pwll and in the south by St David’s Head, complex sequences of smaller headlands, bays, and estuaries can be identified. The northern section (Braich y Pwll to the Mawddach estuary), and southern section (New Quay to St David’s Head) are characterised by particularly fine-scale bay-headland sequences, which necessitate some subjective decisions on the resolution of the system mapping process. High resolution aerial imagery reveals a multitude of minor bays and rocky headlands. Some of these extend over only 100 to 200 metres or so, and many present no obvious management issues. Accordingly, the most minor features have been amalgamated into larger units, with small-scale bays and inlets resolved only where human interventions or obvious management issues are present.

Figure 6.20 illustrates the need to choose an appropriate mapping resolution with reference to a short section of coast in the vicinity of Newport (approximately 210 km down-coast of Braich y Pwll and the Llŷn Peninsula). High-level mapping might here recognise only a simple headland-bay-headland system, with the additional influence of a small estuary. At the other extreme, a detailed study might pick out a multitude of minor headlands and bays. A more general purpose mapping exercise (as undertaken here for the whole of Cardigan Bay) might resolve an intermediate level of detail, including the small bay at Cwm-yr-Eglwys, where a seawall protects infrastructure landward of the beach. The necessity for this kind of judgement reinforces the fact that there is no unique coastal system map for a given stretch of coast. Rather, a variety of maps may be produced to suit particular management applications, and to reflect and represent alternative expert opinions.

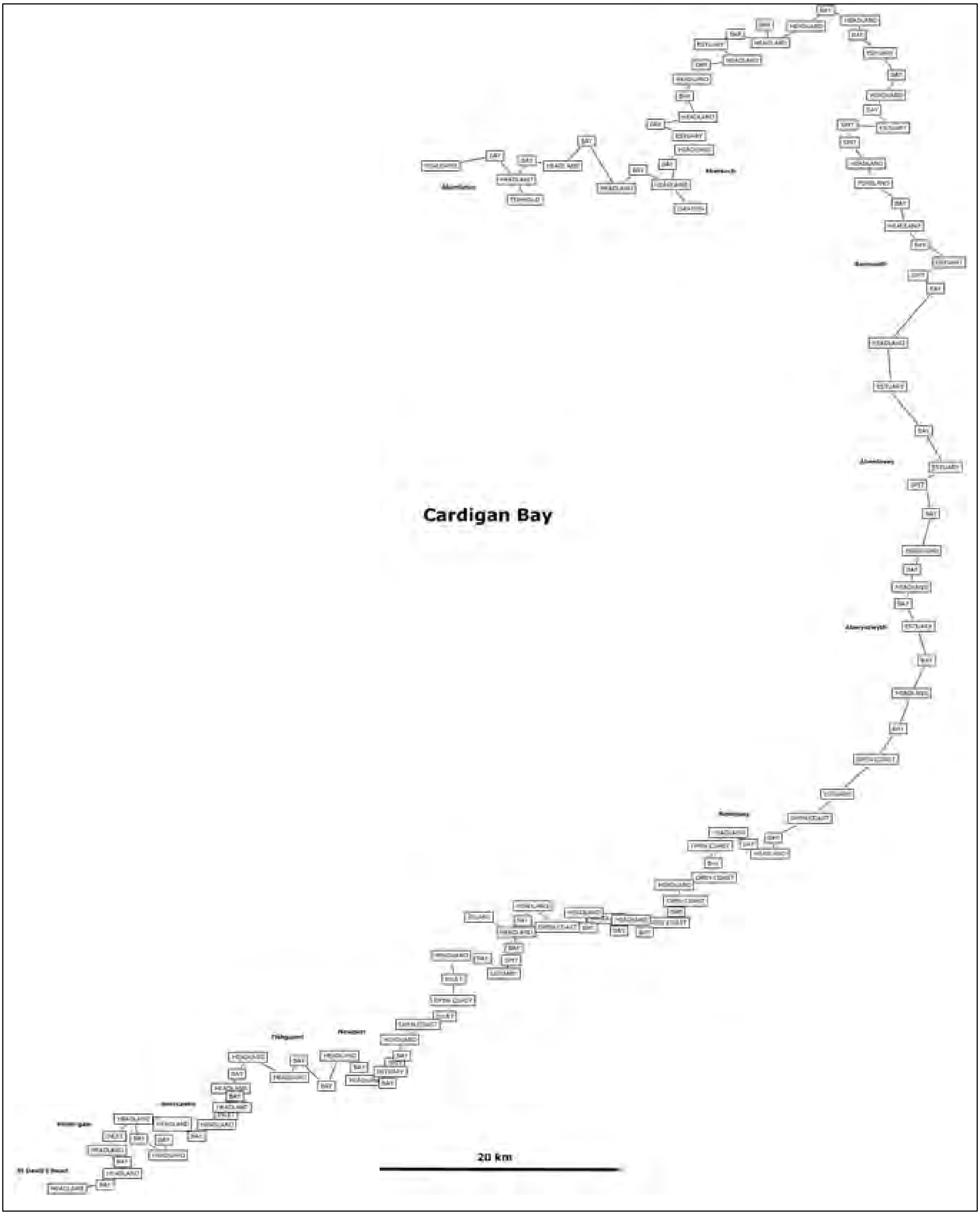


Figure 6.18 Feature-level coastal system map for Cardigan Bay between Braich y Pwll and St David's Head.

Offshore linkages omitted for clarity.

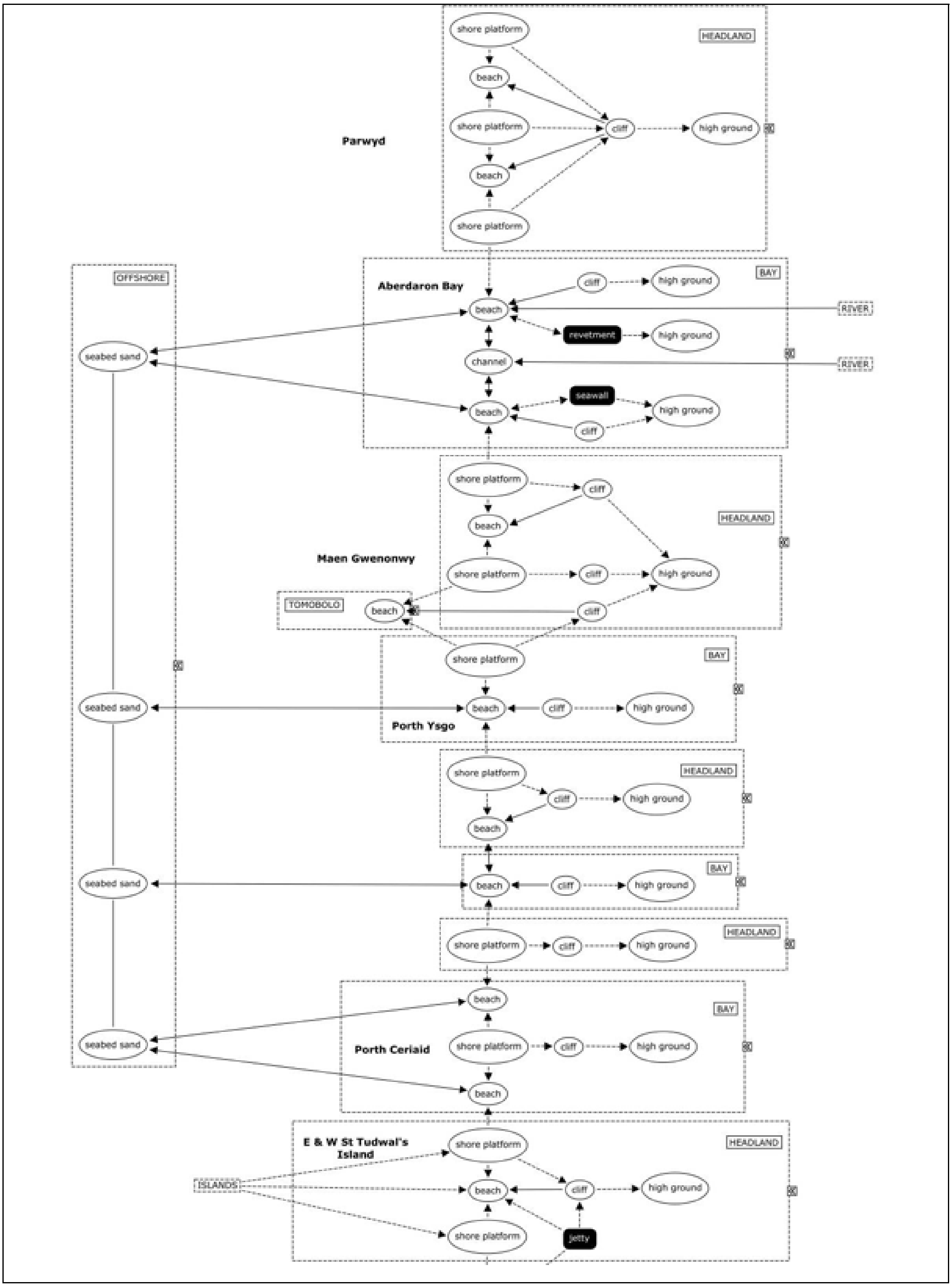


Figure 6.19A System map for Cardigan Bay between Braich y Pwll and St Tudwal's Islands.

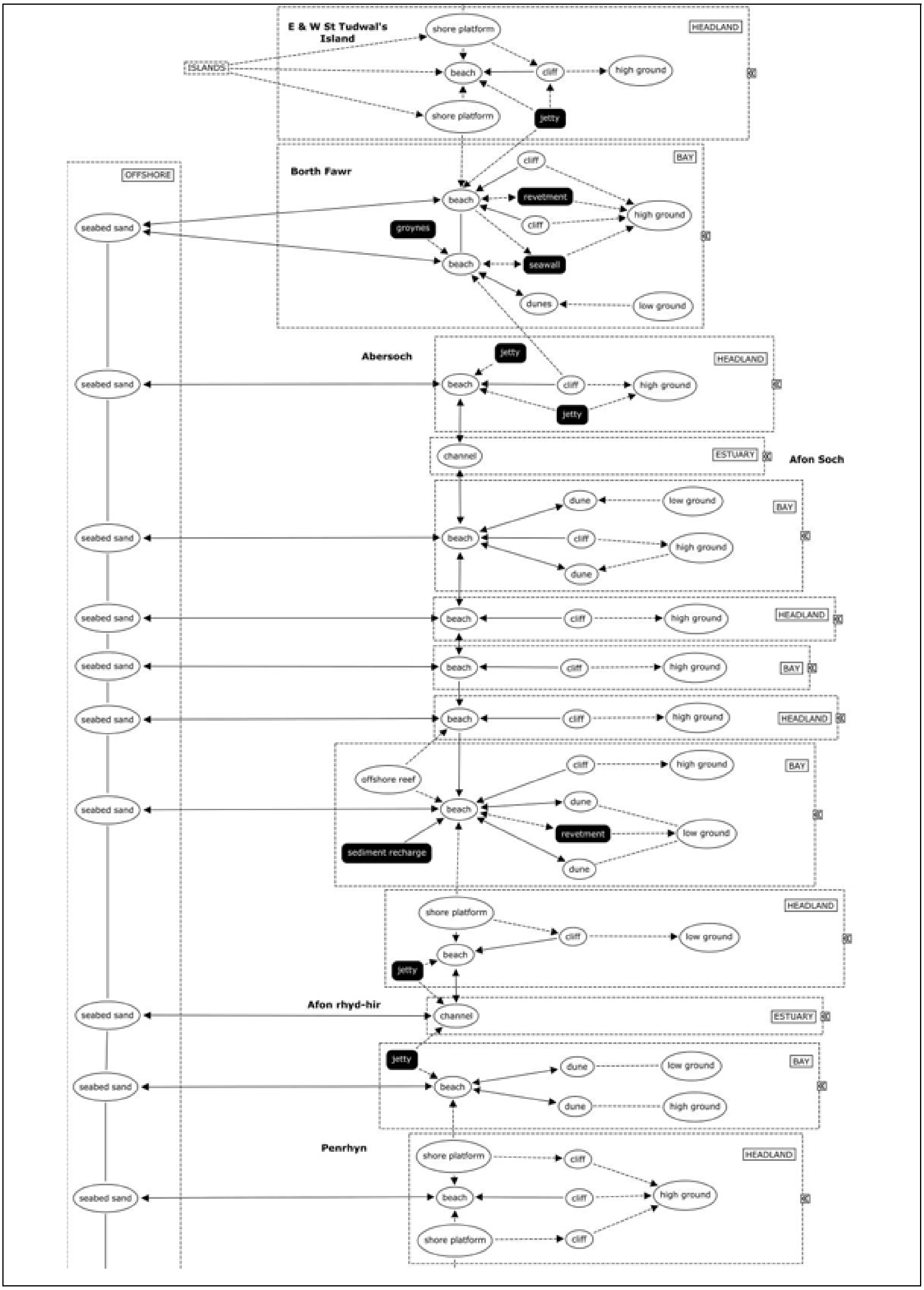


Figure 6.19B System map for Cardigan Bay between St Tudwal's Islands and Penrhyn.

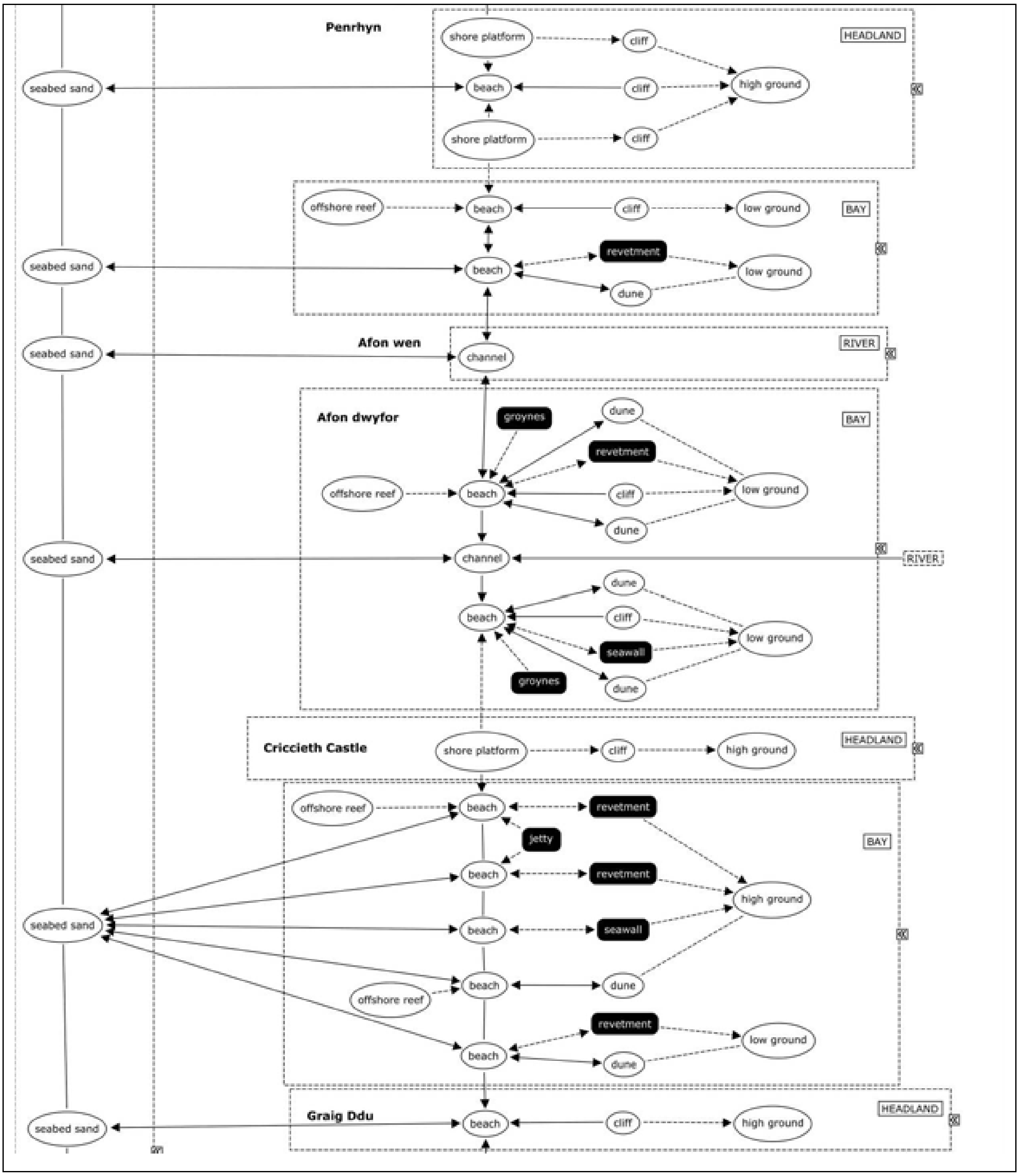


Figure 6.19C System map for Cardigan Bay between Penrhyn and Graig Ddu.

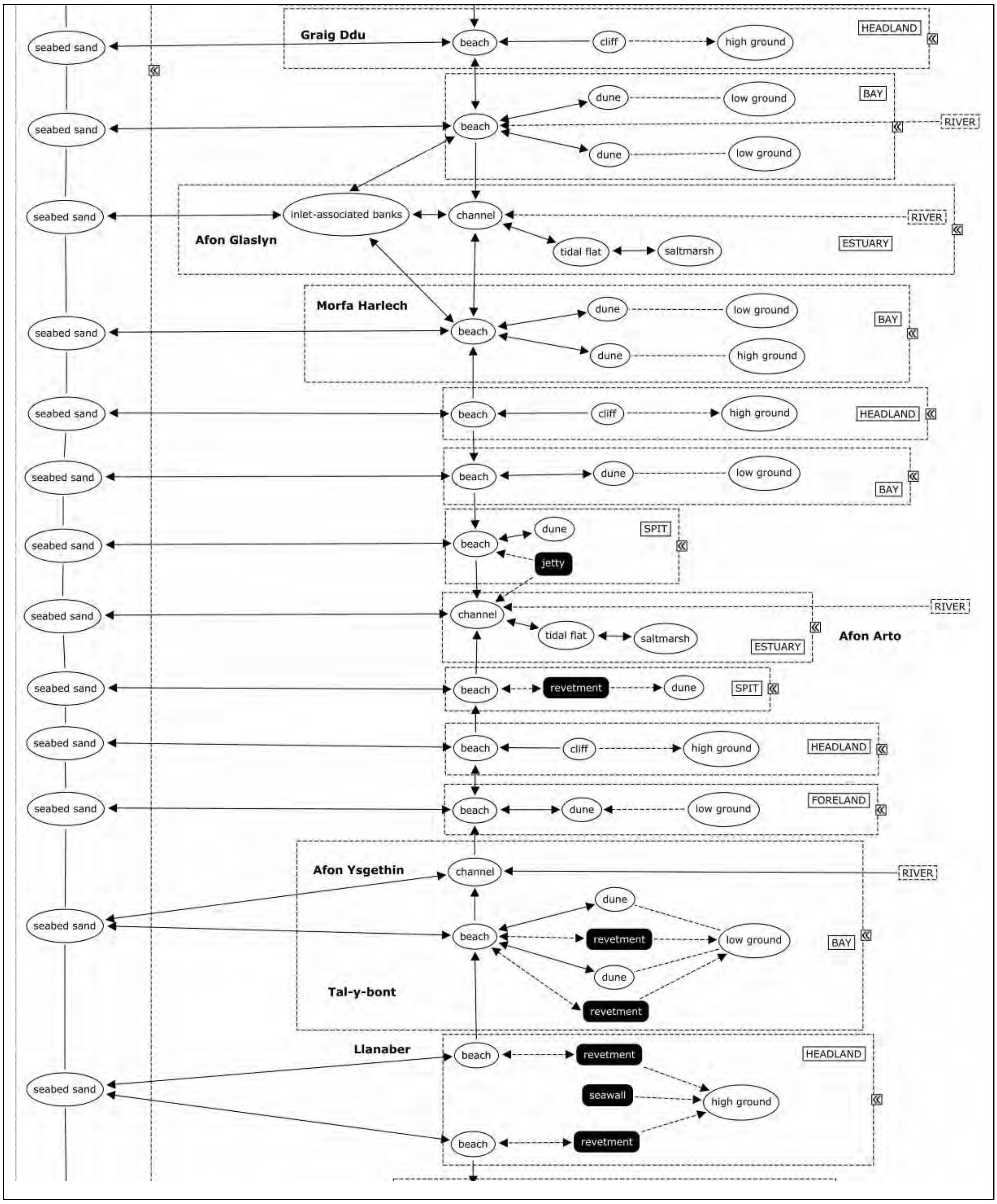


Figure 6.19D System map for Cardigan Bay between Graig Ddu and Llanaber.

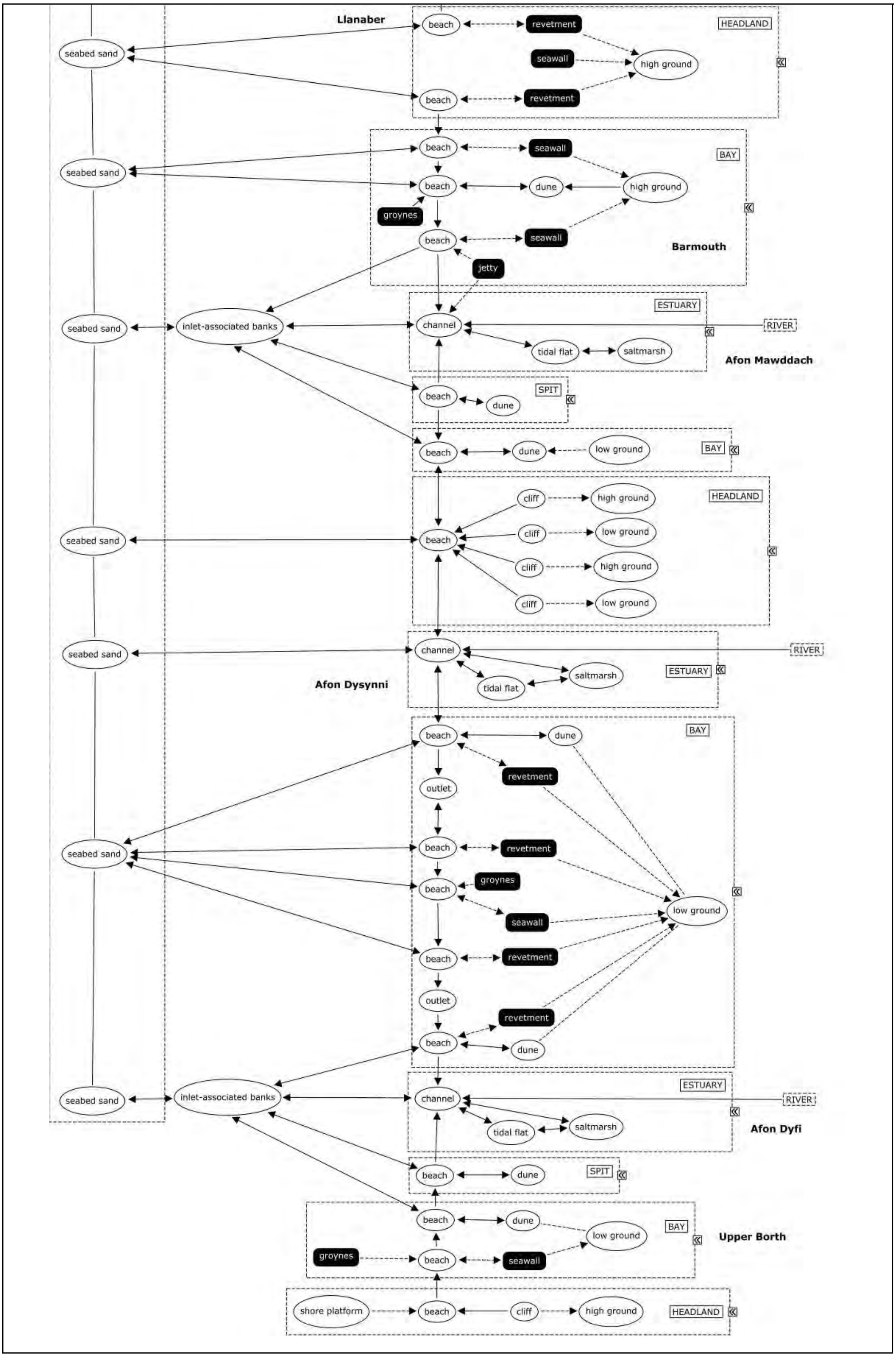


Figure 6.19E System map for Cardigan Bay between Llanaber and Borth.

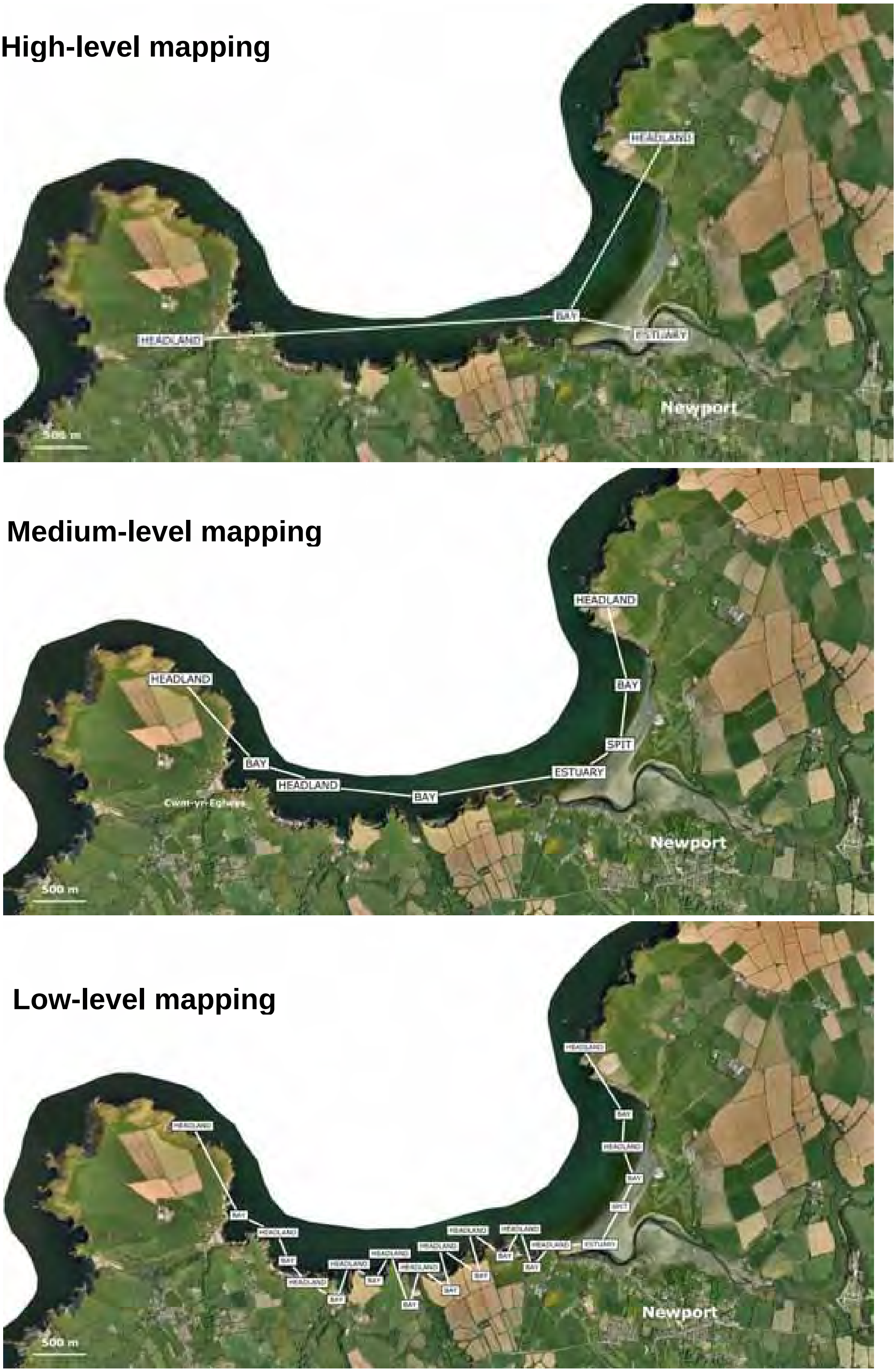


Figure 6.20 Alternative levels of coastal system mapping resolution, illustrated with reference to short section of coast in the vicinity of Newport, south Cardigan Bay.

Medium-level mapping was attempted in this study.

Table 6.9 presents summary statistics extracted from the element-level system map of the northern half of the bay presented in Figure 6.19. These show a system that is intermediate between the Suffolk and Alnmouth Bay examples in terms of the proportion of known bi-directional links, both for sediment and influence interactions. However, in contrast to both Suffolk and Alnmouth Bay, the system map for the northern portion of Cardigan Bay has a much larger influence network, such that only 54 per cent of the links function as part of the sediment budget system.

Table 6.9 Summary information for system map shown in Figure 6.19 (northern part of Cardigan Bay, between Braich y Pwll and Afon Dyfi).

System comprises 298 elements and element-level interventions:
36 cliff
30 dune
59 beach
16 shore platform
5 tidal flat
5 saltmarsh
11 channel
5 offshore reef
31 high ground
21 low ground
37 seabed sand
9 seawall
17 revetment
8 jetty
6 groyne
2 outlet

These elements are grouped into 53 features:
2 offshore
17 headland
20 bay
4 spit
1 foreland
1 tombolo
7 estuary
1 river

These elements are also linked to 10 unmapped feature-level subsystems:
10 river

Sediment transfer system pathways:
Number of components in sediment transfer system = 187
Number of sediment pathways = 225
Number of sediment pathways (incl. both directions of bi-directional paths) = 343
Fraction of bi-directional links = 52.4%

Influence network pathways:
Number of components in influence network = 308
Number of influence pathways = 416
Number of influence pathways (incl. both directions of bi-directional paths) = 559
Fraction of bi-directional links = 34.4%

Ratio of N(sediment links)/N(all links) = 0.54

Figure 6.21 shows the element-level interaction matrix. Interactions between cliff, dune and beach are all prominent, as are beach-seabed interactions. The extent of structural interventions is also evident, especially in the form of the revetments that back many of the beaches in the region. The importance of cliff-beach-seabed sediment exchanges is further highlighted in Figure 6.22, which shows the element-level interactions for sediment transfers.

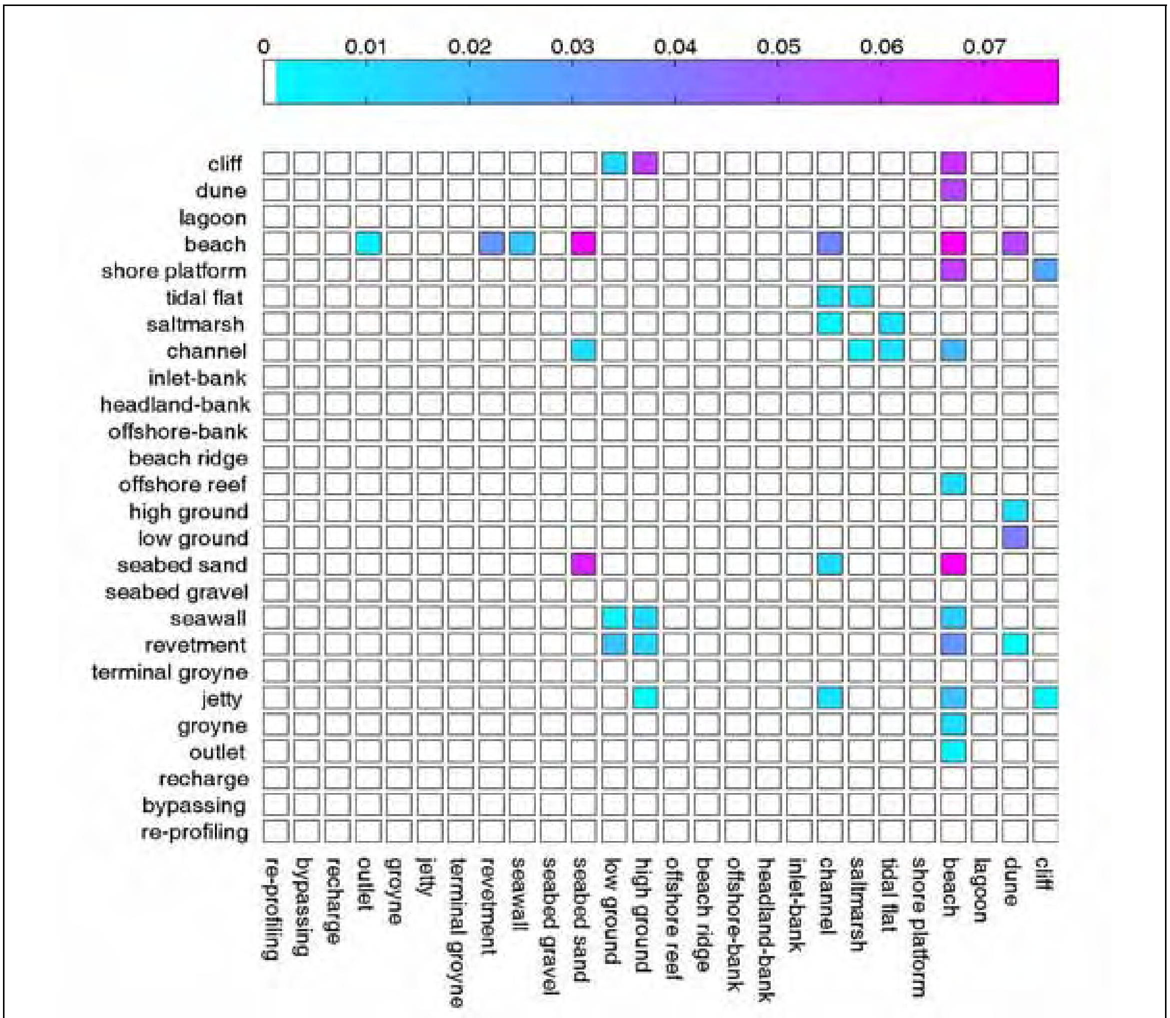


Figure 6.21 Interaction probability matrix for the system map in Figure 6.19.

White cells indicate interactions that do not occur in this system map, colour-coded cells show the varying probability of the interactions that do occur. This analysis includes both directions of any bi-directional links.

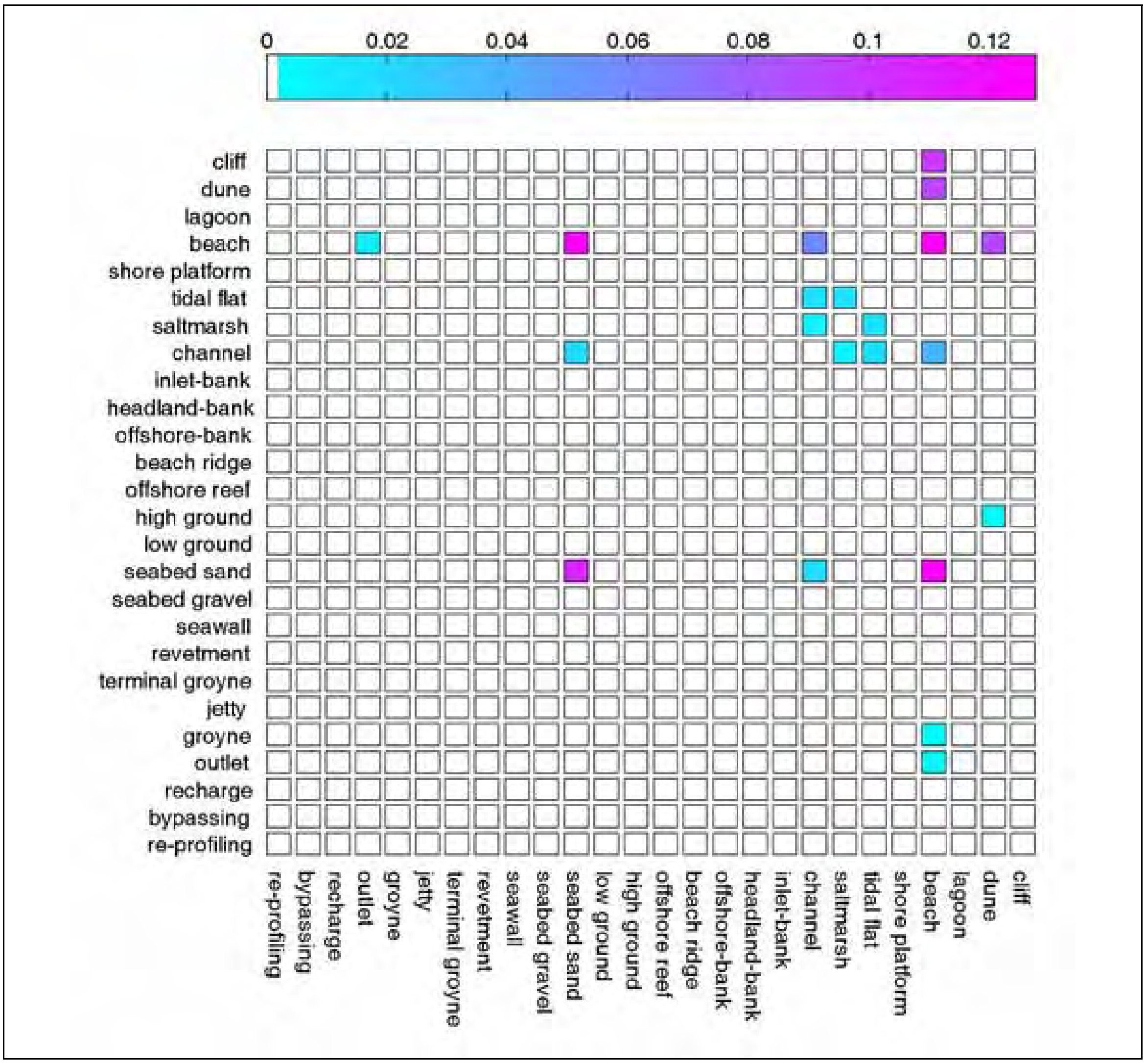


Figure 6.22 Interaction probability matrix for the system map in Figure 6.19, for sediment transfers only.

White cells indicate interactions that do not occur in this system map, colour-coded cells show the varying probability of the interactions that do occur. This analysis includes both directions of any bi-directional links.

6.3. Operator variance

Although effort has been made to develop a logically consistent mapping procedure, there is clearly scope for interpretation and maps produced by different ‘experts’ will invariably differ. Such differences might originate in various ways. First, a degree of subjective judgement is required on the resolution at which discrete features and elements are identified. For example, a headland at one scale might be mapped as a composite set of headlands and minor bays at a smaller scale (Figure 6.20 illustrates this). It is clearly desirable for the resolution to be informed by specification of the management application, but care is still needed to ensure a consistent level of detail across the region of interest. Second, there may be minor differences of opinion over the classification of a few system components, particularly where mapping is not supplemented by field knowledge. In the Cardigan Bay case study a full field reconnaissance was not possible, so the classification of some shore platform or offshore reef elements, and a few structural interventions, remains tentative. A richer set of features and elements can help here, although increasing complexity ultimately becomes counter-productive. A third area where there is scope for differences of interpretation is the rationalisation of elements within features. Rationalisation of some kind is advocated on the grounds that this emphasises the system structure in a way that tabulation of data does not. The main criteria for rationalisation used here is the recognition of a minimum set of components that defines the alongshore continuity of the coast whilst incorporating local variability in cross-shore (including offshore) landforms and processes. Strict adherence to this guiding principle should minimise variability of this kind.

Probably the most important source of variation between maps produced by different experts is that due to differences of opinion and interpretation on how the coast actually behaves. Different experts will have access to their own stores of knowledge (first hand experience, research literature, datasets and so on) and will bring these to bear on their classification of a given coastal system and its behaviour.

In an effort to prove the reliability of the underlying procedure, mapping of the Alnmouth Bay site was performed separately by the University of Southampton, which was not provided with advance sight of the original UCL-produced map. This was quite a stern test, since the second team of mappers had no first-hand experience of the field site and had no prior experience of the CmapTools software.

Superficially, the Southampton map (Figure 6.23) is similar to the UCL-produced map (Figure 6.14). The feature-level mapping is essentially identical, apart from the omission of Coquet Island (inclusion of which is subjective in any case). The real differences emerge at the element level. These appear to originate for all of the reasons highlighted above. Notable differences are as follows:

- Subjective decisions on the detail at which complex headlands are mapped give rise to differences at the northern and southern ends of the study area. In the case of the Amble and Hauxley headland, the University of Southampton map does not extend as far south as in the UCL map (hence its simplified representation in the former), whilst the UCL map picks out more of the detail on the Boulmer Headland. The distinction between cliff and dune units also differs, and this is probably a consequence of relying on aerial imagery in the absence of any fieldwork.

- Shore platforms are placed within the offshore zone in the University of Southampton map, whilst they are considered to be an extension of the nearshore in the UCL map. This subjective judgement is probably of little consequence.

- Detailed mapping of the estuary systems is quite different between the two maps, most likely due to differences in opinion on how these sub-systems are likely to function (reinforced by the limited information available), as well as uncertainty in how best to map this functional behaviour using the tools available.

- One or two aspects of the University of Southampton map deviate from the supplied procedure. An attempt is made to introduce the idea of urban areas, effectively at the element level. Also, the idea of river inflows being controlled by a weir is introduced in the case of the River Coquet. Other minor deviations (refer to Figure 6.5) include incorrect/inconsistent use of the object outlines (such as for interventions), the placement of feature labels, and use of plural and singular feature and element descriptors (which is important if the maps are to be analysed statistically to extract feature and element abundance information).

There will always be scope for subjective differences in interpretation, although this source of 'operator variance' can be minimised through the use of workshops on the production of consensus-based maps. The numerous minor differences of detail, including departures from the procedure, indicate the need for high quality training materials. To this end, we have produced an electronic tutorial, based around the mapping of part of the Alnmouth study region. This includes more detailed guidance on how to use the CmapTools software in conjunction with the mapping procedure to produce the kind of maps contained in this report. These tutorial materials are available from the project website (www.coastalgeomorphology.net as well as from www.geog.ucl.ac.uk/ceru/cmap).

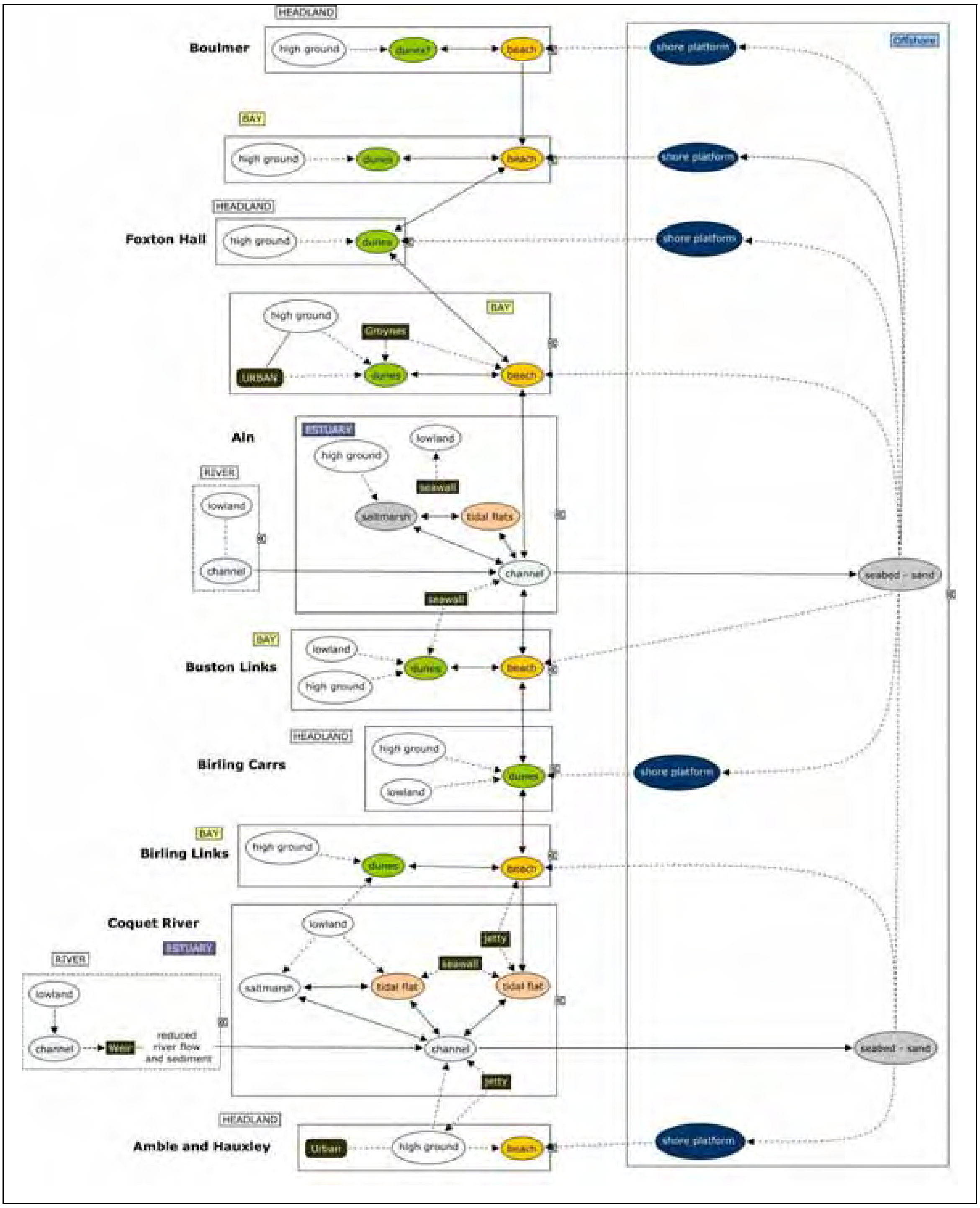


Figure 6.23 System map for Alnmouth Bay produced by independent team, based on supplied mapping procedure and solely on analysis of aerial imagery.

6.4. Discussion

The formal system mapping procedure presented here allow important components of large-scale coastal geomorphological systems to be mapped in a way that emphasises the structure of their interactions within a two-level hierarchy of features and embedded elements. In applying and refining the mapping procedure, it was necessary to revise the initial generic feature and element classification (Tables 6.1 and 6.2). Most of these revisions were at the element level, and included new geomorphological elements to capture the geomorphological diversity of the coastline of England and Wales, and a set of human interventions (both structures and non-structural management practices).

The process of applying the feature and element classification, and transferring this to a system-level representation using CmapTools software afforded insights into factors influencing medium-term coastal behaviour across a range of spatial scales. The three case studies ranged from a single, though fairly complex, headland-bay-headland system (Alnmouth Bay, 15 km) through a coastal sub-cell (Lowestoft to Landguard Point, 73 km) up to an entire coastal cell (Cardigan Bay, 267 km). The classification scheme proved reliable across all scales, and between contrasting coastline types.

In each of the case studies, geomorphological reconnaissance accomplished using online aerial photographs provided the basis for identification of alongshore and cross-shore assemblages of coastal features and elements and likely modes of interaction, with the latter cross-checked against research literature. Google Maps (http://maps.google.co.uk/) proved useful as a source of freely available high resolution aerial photography, although offshore features are not well resolved on these images. Aerial imagery alone is sufficient for a first-order mapping exercise, although in all of the case studies described here it was supplemented by reference to the scientific literature and available research reports and inputs from individuals with first-hand knowledge of the areas.

Training is essential on the underlying principles of geomorphological system mapping and the use of software such as CmapTools. There will always be scope for interpretation, of course, and maps produced by different individuals will invariably differ in detail. Rather than being seen as a limitation, 'operator variance' of this kind should be viewed as a valuable aspect of the knowledge formalisation process.

Knowledge formalisation using the coastal system mapping approach might be performed in one of two ways. First, through comparison and subsequent merging of maps produced in isolation by a small team of experts. This appears to work well for small systems where mapping effort is not demanding in terms of time and supporting resources. Second, as a group activity where two or more experts work together to produce a map that reflects their shared opinions. This is probably better for larger systems, where creation of the map involves more time and effort. A mini-workshop might be required to build a consensus on a system on the scale of Cardigan Bay.

Consensus-derived coastal system maps provide a clear indication of the underlying structure of the influences and sediment transfer paths that govern system behaviour in the medium- to long-term. As such, they are an effective means of formalising various forms of geomorphological knowledge. The resulting understanding can then be used to inform the choice of predictive modelling tools, such as historical trend analysis or numerical coastal morphodynamic models. In particular, a system map can provide the framework for more quantitative analysis of the sediment budget, and can aid the specification of process modules in a numerical simulation package (such as modules handling soft rock cliff erosion, inlet morphodynamics, onshore-offshore exchange, offshore banks and so on) and their boundaries.

System maps are also useful in the later stages of the conceptualisation-modelling process. In electronic form, CmapTools project files can function as a repository for the results of quantitative analyses and predictive modelling. For example, the system links can be annotated to include estimates of the sediment mass fluxes, and model results files and research reports can be linked to system components. Some of these results may suggest revisions of the original system map, such that the process of knowledge formalisation, conceptualisation, and modelling becomes an iterative one.

7. Proof of concept for a linked coastal-estuary system model

7.1. Introduction

A demonstration modelling exercise for a linked coast and estuary system was done in this study (Walkden and Rossington, 2009). This was carried out as a proof of concept modelling (PoC) exercise to explore how to use and move beyond coastal mapping (Chapter 6) and Expert Geomorphological Assessment (EGA) (Chapter 9). This work incorporated aspects of quantified process-based understanding into models of coastal systems with the capacity to predict variables of relevance to coastal management decision-making.

The proof of concept is a partial example of how (with adequate follow-on research) systems models could be used to support the difficult problem of long-term management of a changing coastline. It also demonstrates the way in which links between existing models can be established and used for both pilot testing and demonstration of management scenarios. In addition this work was undertaken to generate insights into the relative importance and roles of estuary inlet features (such as channels, deltas and flats) in regulating the exchange of sediment between an open coast and an estuary.

The proof of concept comprised coupled broad-scale, long-term models describing a notional coast/estuary region. **Although the coupled models did not represent specific locations, they were intended to be realistic.** They were therefore selected and adapted to describe conditions typical for the east and south of the UK. To ensure relevance for coastal management, the coupled models were used to represent spatial scales of the order of tens of kilometres and time periods from years to one century. Both climate change and coastal management changes were represented.

The modelling tools Soft Cliff And Platform Erosion (SCAPE) and Aggregated Scale Morphological Interaction between Tidal basin and the Adjacent coast (ASMITA) were used since they were able to represent large scales, climate change and engineering interventions. To allow rapid development of the links and to ensure realism, the simulations were based on existing models. **These modelling tools do not represent all types of geomorphological elements, but can be used to represent the geomorphological elements within the case study.** SCAPE describes beaches, cliffs and shore platforms and ASMITA represents channels, ebb deltas (inlet-associated banks) and tidal flats.

The system comprised three features: two open coasts on either side of an estuary (see Figure 7.1). These were driven by tides, wave action and sea-level rise and were coupled through the movement of sand which could pass from the updrift coast to the estuary and from the estuary to the downdrift coast.

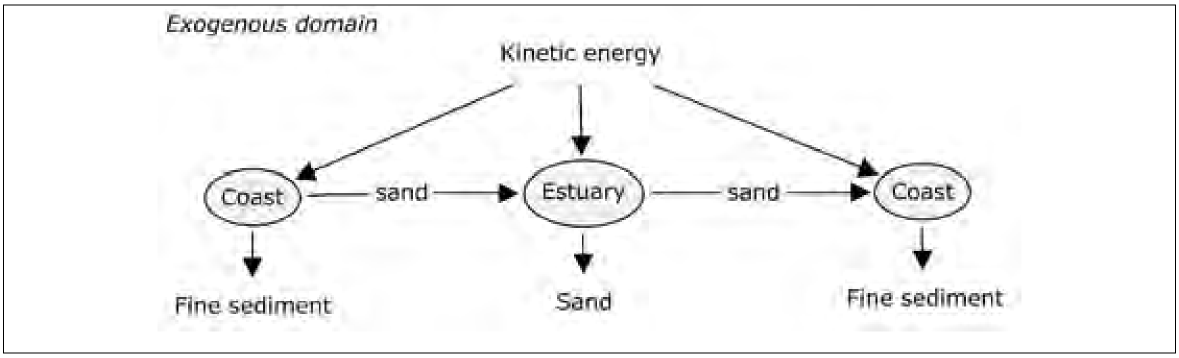


Figure 7.1 Simulated relationship between the system's features.

This section begins with descriptions of SCAPE and ASMITA. It then explores how behavioural systems models can be constructed from formalised systems maps, drawing on EGA. The coast and estuary models are described, along with the manner in which they were linked and driven, and the scenarios under which they were run. Some model outputs are presented and used to illustrate how such results might inform management questions. Finally, behavioural systems modelling is discussed in the light of the proof of concept findings, and recommendations for further work are made. Extensions to these types of models to represent other elements (such as marshes, dunes, mixed sediment, beaches, spits), for example through implementation of different geomorphological storages and mechanistic links, will be required, or possibly new models will ultimately be required to enable fuller representation of more coastal and estuary systems.

7.2. Relationship with expert geomorphological assessment

Numerical models based on behavioural systems ideas are closely related to EGA. The conceptual models on which the numerical models are based are normally developed through EGA processes. In addition, the modelling process encapsulates EGA tools and techniques. Finally, EGA provides the information required for calibration and validation (see for example Walkden and Hall, 2005, Dickson *et al.*, 2007 and Rossington, 2008).

The automation and integration involved in the modelling process adds significant value to individual EGA methods. To illustrate this, alternative methods for predicting the repose of soft rock cliffs to accelerated sea level rise are compared below, including an EGA method (historical trend analysis), behavioural EGA models (the modified Bruun Rule and the Walkden and Dickson equation) and a behavioural system model (SCAPE) are compared below.

Historical Trend Analysis, in isolation, provides statistics on prior recession rates (R_1). Future rates can not be assumed to be the same because the coast is undergoing the systemic change of accelerated sea level rise. Some additional information on processes is required to account for the likely increase in recession.

The modified form of the Bruun Rule (a behavioural EGA model) described in Section 8.3 encapsulates some understanding of shore processes to represent sensitivity to rate of sea level rise. It requires variables representing 'length of active profile' and 'closure depth', which are normally difficult to establish. It is further limited by its assumption that changes in the net sediment budget over time are small, that the rock profile form remains constant and that it responds immediately to changes in the rate of sea level rise.

Walkden and Dickson (2008) encapsulate a large number of numerical model simulations to provide an EGA behavioural model. This recognises that the rock profile form varies with the rate of sea level rise and does not require a closure depth or active profile length. It is limited by its assumption that the beach is relatively small in volume. It further assumes that response to changes in the rate of sea level rise is immediate.

In comparison, the behavioural systems model SCAPE encapsulates broader knowledge of the coastal system, including the dynamics of rock profile evolution and alongshore beach movement. Being computer-based, it can be readily time-stepped and used to simulate a series of sections along shore. This allows the sediment budget to be quantified through time and along the coast, avoiding the sediment budget assumptions of the previous two methods. Time-stepping allows quantification of change through time, avoiding the assumptions of instantaneous response.

The temporal and spatial interactions allowed by the behavioural numerical model allow much richer representation of coastal behaviour and its response to change than is possible by EGA alone. These strengths mean that the model is able to provide much greater insight into soft cliff response to sea level rise. Dickson *et al.* (2007) compare such SCAPE simulations to predictions made using the modified Bruun Rule. They showed that longshore transport had a strong influence on soft cliff response to increased sea level rise, even causing sections of shore to erode less under higher sea level rise. In addition Walkden and Hall (2005) and Dickson *et al.* (2007) used SCAPE simulations to show shore profiles taking more than 50 years to fully respond to an increase in sea level rise rate.

7.3. Relationship with system mapping

The SCAPE modelling tool was based on systems concepts similar to those applied by project partners at UCL to produce coastal systems maps (Chapter 6). One of the purposes of that mapping work was to lay foundations for subsequent numerical model development. It therefore seemed worthwhile to simulate the development of SCAPE using the formalised mapping methodology as a starting point. This was done with the intention of providing a tentative road map that could inform future development of other models, and perhaps provide useful feedback to the mapping protocol.

7.3.1. System map

Figure 7.2 shows the coast upon which the PoC model was based and a formalised map of the geomorphological system following the methodology developed in the project. The nodes and links conform to the formal project classification, for example the solid lines show flow of sediment whilst dotted lines indicate another type of influence.

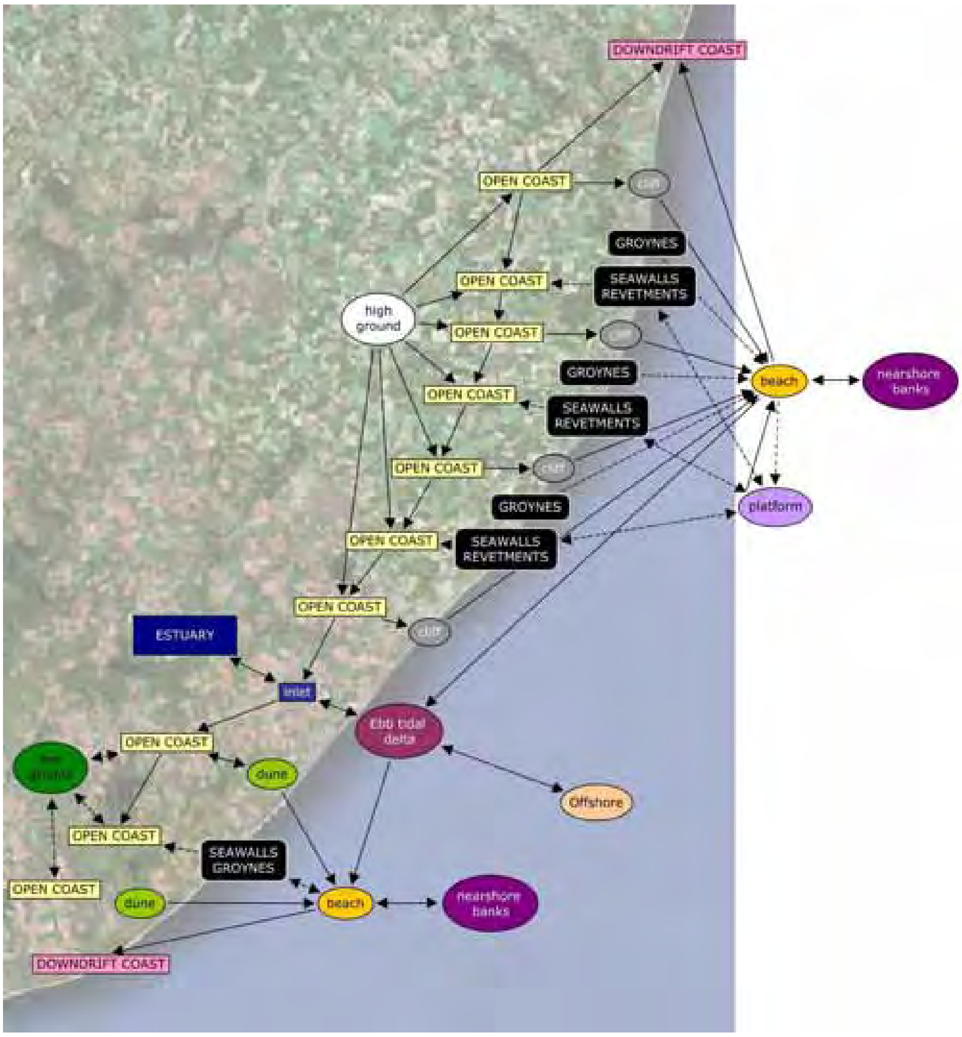


Figure 7.2 Formalised geomorphological mapping of proof of concept open coast.

The map represents the key features, elements, sediment flows and influences involved in the functioning of this coast. Human influence is captured in the black 'structure' cells. The resulting figure is quite easy to read and informative, effectively communicating the pattern of sediment flow and influence around this coast and formally capturing its elements. At the top of the figure the coast has important vertical interaction between platform and beach which produces some congestion in this essentially 2D horizontal mapping. At the bottom of the image the platform is not active and the map is clearer.

From the numerical modelling perspective the map has some redundancy that might be eliminated. This occurs where variation along the coast might be described by model parameters, such as cliff height or sediment content, whilst fundamental behaviour remains the same. The coastal system above the estuary inlet was selected as such an area.

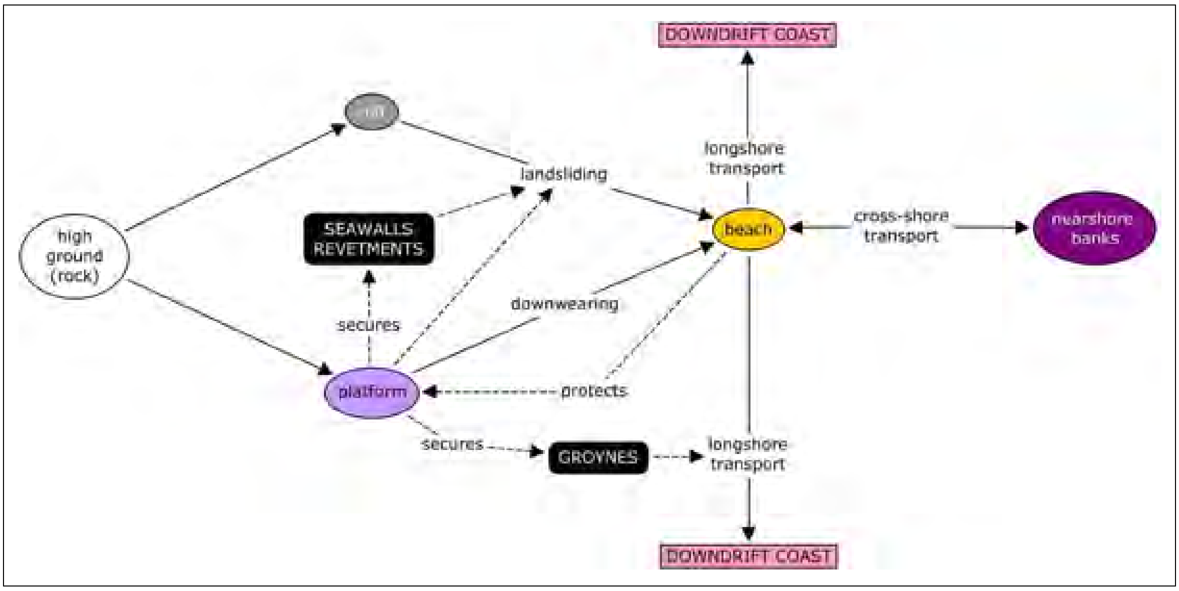


Figure 7.3 **Spatially non-explicit influence map.**

Figure 7.4 represents this area with redundancy removed. This effectively removes spatial information, allowing representation of the vertical dimension. This results in a more focussed and generic map. The feature 'Open Coast' has been removed as this is now implicit. Processes have been added to build information needed for numerical model development. Structures are included as artificial influences on natural processes and the role of the shore platform in securing the structures is explicit.

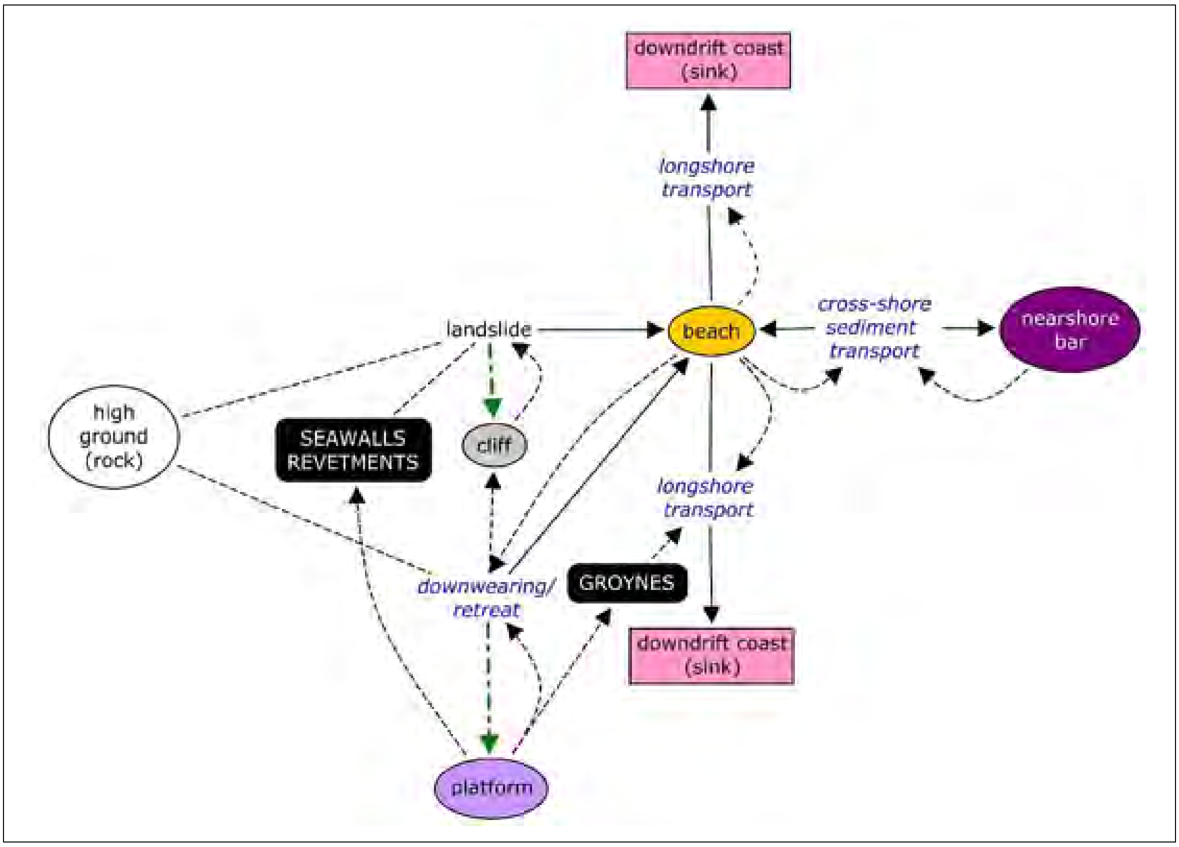


Figure 7.4 **Process focussed map.**

Systems methods work with interactions between elements. Accordingly Figure 7.4 develops the map to focus on processes through which the elements are formed. This forces two structural changes in the map to recognise that landsliding forms the cliff and downwearing forms the platform. A new line style (green, dot-dash) has been introduced to represent formation/activation; the alternative 'influence' (dotted) line seems too weak in this context. Assembly of this map drives more detailed thinking about the processes, and this results in more influence lines, examples include:

- Changes in the cross-shore extent of the beach influences both longshore and cross-shore transport rates.
- The beach protects some of the platform against downwearing.
- The nearshore bar volume affects the rate at which sediment can pass across shore to the beach.
- Platform shape influences breaker shape and therefore downwearing rates. Properties of the cliff height have a strong influence on landsliding.

The resulting map is informative. For example, rock is the only source of sediment for the system, and the processes of landsliding and downwearing are crucial for its supply. Longshore transport is the only process moving material out of the system (to sinks). Also, if it is reasonably assumed that no element in the system is unstable (has a trend in size), the 'downstream' elements depend on those further up the influence diagram and *all must be included in the model if this coast's behaviour is to be captured*.

The next step is the identification of model parameters and variables, as shown in Figure 7.5. These allow the system state to be described and track model behaviour, including the sediment budget. At this stage particular attention has to be paid to the management questions that the model is intended to address. So, for example, cliff top position must be an explicit variable if erosion costs are to be quantified. Also beach volume and platform profile are important determinants of coastal defence structure stability and so are also needed.

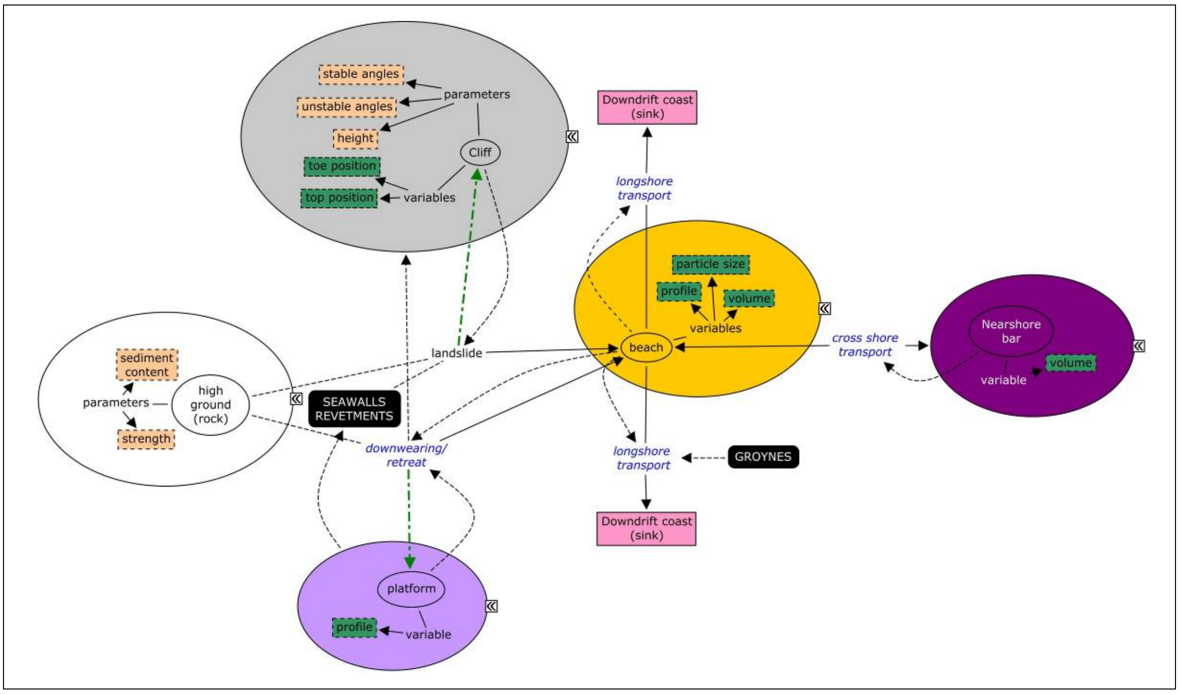


Figure 7.5 Inclusion of parameters and variables.

7.3.2. Behavioural descriptions

Having found the processes crucial to the system's behaviour, it is possible to identify potential model components to represent them. Many coastal processes are poorly understood and many existing descriptions deal with scales that are too small to be meaningfully built into a broad-scale model.

The systems approach recognises that approximate representations are valuable, and often superior, when describing systems. Therefore in this work we describe processes with abstract terms. The degree of abstraction varies and depends strongly on:

- availability of prior work;
- modelling speed;
- the importance of the process in determining the behaviour of the coast.

In some cases these descriptions may have a clear basis in more precise theory (such as linear wave theory); in others where little evidence is available, 'rules of thumb' may be used. Examples taken from the existing SCAPE model are described below.

7.3.2.1. Landsliding

Landsliding has received much attention in the literature, and this provided a range of possible approaches for model representation. It was deduced from system mapping that landsliding processes do not regulate the behaviour of this type of coast, instead landsliding follows coastal retreat. Consequently, a simple and fast approach was needed. Given the importance of cliffs to coastal management issues, the approach should include cliff height and slope as parameters. A simple approach was therefore developed based on concepts of a stable and unstable cliff angle, both of which were described probabilistically.

7.3.2.2. Longshore transport

The one-line approach was selected because of its extensive track record and short run times. Opinions are divided on the classification of this approach since it is based on process-based arguments, but is quite abstract in its application. It also relies on behavioural assumptions, for instance in the profile of the beach. In SCAPE the Bruun beach profile was used, which is essentially a behavioural rule for the beach surface with implicit assumptions regarding cross-beach fluxes.

7.3.2.3. Cross-shore transport

As can be deduced from Figure 7.5, the cross-shore sediment motion between the beach and bar elements does not regulate the overall behaviour of the coast. The nearshore bar is a temporary store of material rather than a sink. Given this and the fact that little appropriate related work was found in the literature, this transport was described with behavioural rules. Seaward flux rates were approximated with the results of more detailed numerical modelling (using a coastal profile model – see Section 8.6) which were stored in a look-up table. Landward fluxes were represented with a simple behavioural rule, based on expert judgement. This assumed that one per cent of the bar volume returned to the beach every tide when wave conditions were not stormy.

7.3.2.4. Downwearing

No suitable model was identified capable of capturing the dynamic feedback between wave hydrodynamic loading and profile evolution. System mapping revealed that this behaviour played an important role in regulating coastal behaviour, and so efforts were invested in developing a new module. This was derived using existing theory and model data. The resulting adaptive slope module relied on process-based arguments, but was applied in relatively abstract terms.

7.3.3. Iterative development

Coding the above modules represents the first stage in writing the model. The process proceeds iteratively, using insights gained from each stage to improve the model and learn about the coastal system in question. Model behaviour is often unexpected, and can reveal shortcomings in the original understanding of the system as well as model insufficiencies.

7.3.4. Observations

The UCL conceptual mapping (Chapter 6) provides a sound starting point for the development of formal quantified behavioural numerical models. Importantly, it provides a holistic framework for the model. This exploration has provided the tentative roadmap for model development illustrated in Figure 7.6.

The tasks within the frame ‘model assembly’ illustrate the model developmental sequence described above. ‘Spin-up’, ‘calibration’ and ‘validation’ are discussed below. The whole process is founded on expert geomorphological assessment and supports quantified coastal risk assessment and uncertainty analysis, as is discussed in Section 7.9.

Data provided by coastal monitoring are crucial for model application, calibration and validation. Model assembly must also be linked to the management process. Existing management structures and other interventions must be represented in the systems map, to include their effect on coastal behaviour. Understanding of pertinent coastal issues must also be gained for the model to generate relevant system variables. Finally, when the model is applied to the study site, it is necessary to represent the range of potential management strategies (such as when and where to build/remove structures). After validation, the model can be used to test the performance of potential management options through processes of quantified risk assessment and uncertainty analysis. This is discussed further in Section 7.10.

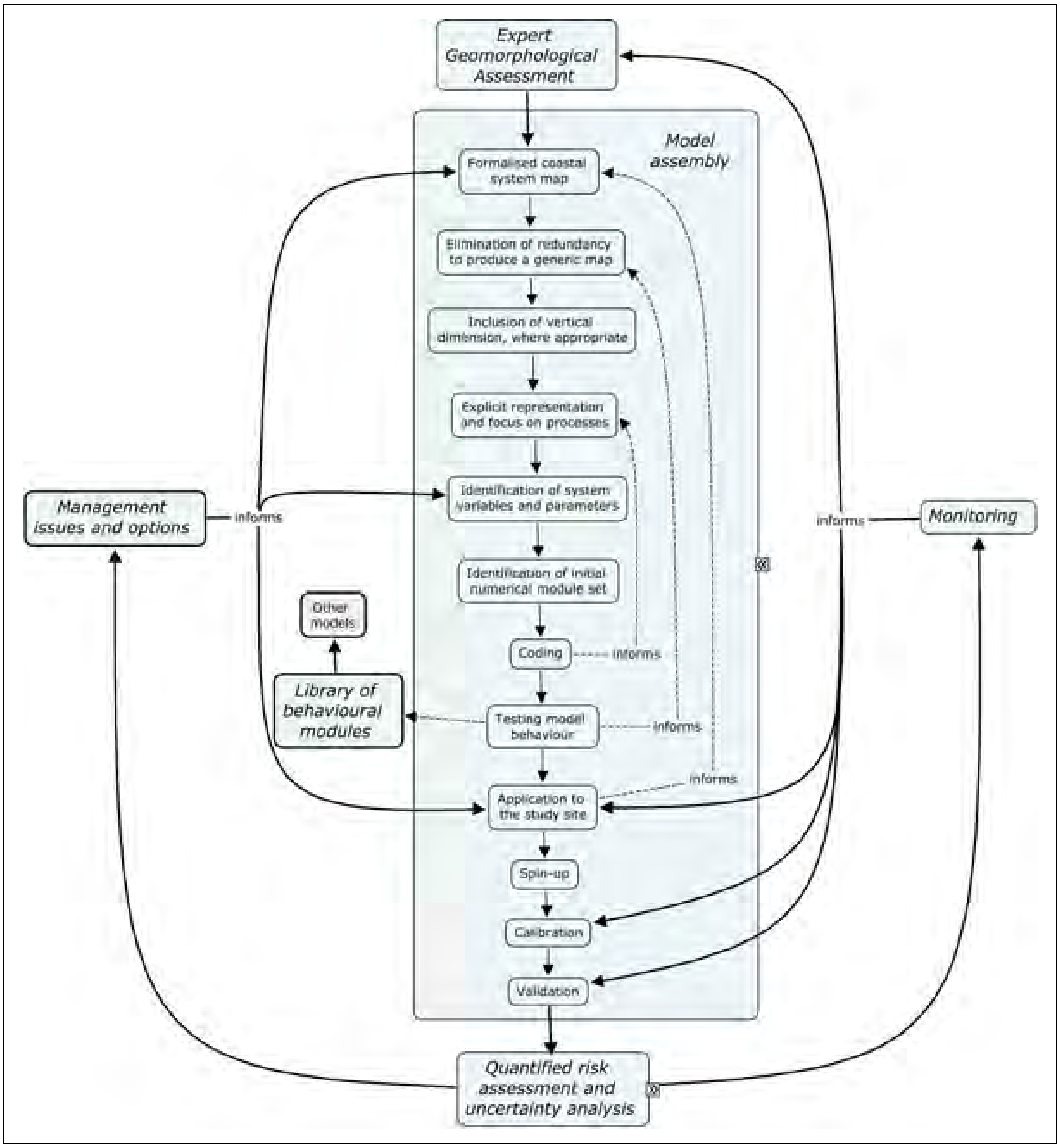


Figure 7.6 Tentative roadmap for model development.

7.4. Behavioural systems modelling tools

7.4.1. SCAPE

Open coast evolution was modelled using SCAPE (Soft Cliff And Platform Erosion, Walkden and Hall, 2005), which was developed specifically to describe large scales, coastal management interventions and climate change. To meet these criteria SCAPE was designed to be holistic and more abstract than most numerical models. Though abstract SCAPE is remarkably stable, due to negative feedback allowed by its systemic scale and multiple internal pathways, and it has shed new light on coastal large-scale geomorphological behaviour (see Walkden and Hall, 2005, Dickson *et al.*, 2007, Walkden and Dickson, 2008). A typical model profile is illustrated in Figure 7.7.

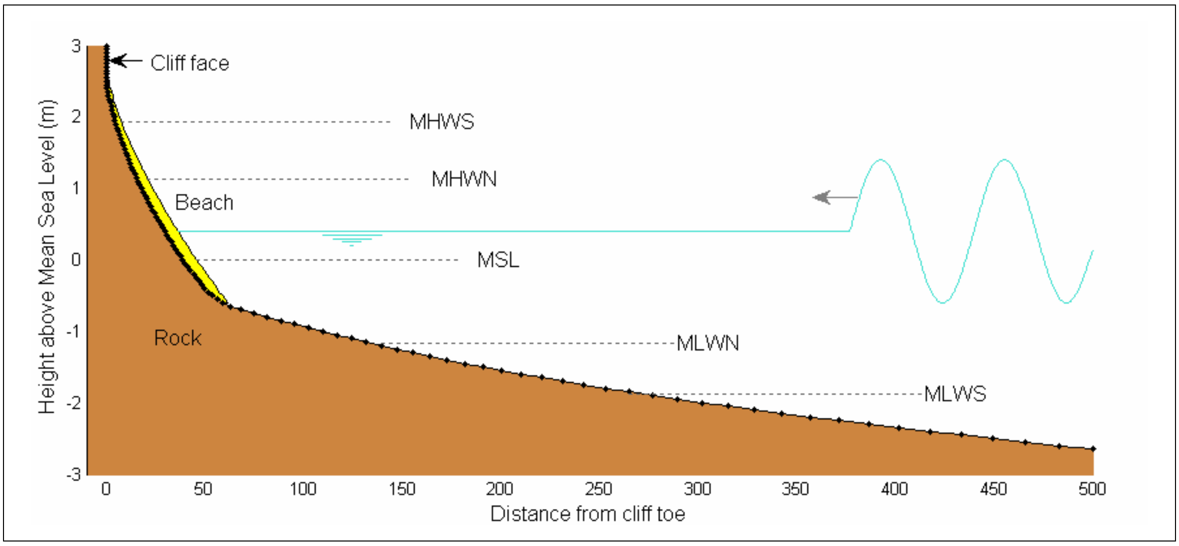


Figure 7.7 Schematic representation of a typical SCAPE model profile.

The two most important feedback processes that regulate model behaviour act to modulate the beach volume and platform profile. They are:

- Higher coastal retreat leads to (→) beach growth (→) greater protection (→) lower coastal retreat.
- Higher coastal retreat (→) flatter platform profiles (→) greater wave dissipation (→) less platform downwearing (→) lower coastal retreat.

SCAPE simulates the emergence of soft rock shore profiles. Walkden and Hall (2005) describe its development, structure and application, including calibration and testing at the Naze Peninsula, in Essex. The components of the system described by SCAPE are illustrated in Figure 7.8.

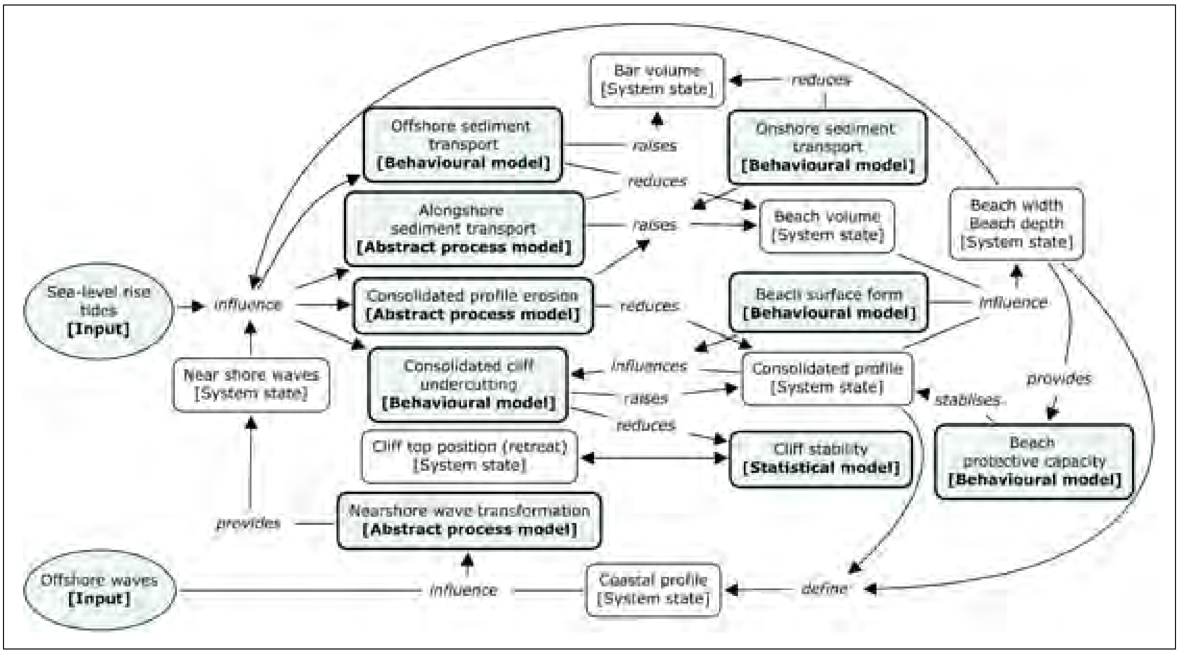


Figure 7.8 SCAPE system map.

SCAPE has process-based and behavioural modules representing platform, cliff and beach, as well as hydrodynamic loads. Such holistic representation is necessary to capture interaction and feedback that regulates the behaviour of such coasts. The process descriptions are relatively abstract to minimise run times and so allow simulation of long periods and exploration of model sensitivities.

Every model timestep (one tidal period), data describing wave height, period and direction, tidal amplitude, and rate of sea level rise are read from input files and the system state (rock profile, beach width, beach depth, nearshore wave conditions) is recalculated.

The wave conditions are assumed to be constant throughout a tidal timestep. Wave transformation due to shoaling and refraction is calculated using linear wave theory. A beach is represented as a surficial layer on the rock, as illustrated in Figure 7.7. Quasi three-dimensional beach volumes are determined from the erosion and composition of the rock and from losses through wave driven sediment transport. The beach is assumed to follow a Bruun profile (Bruun, 1954). As the model runs, and the platform surface evolves, the beach surface is translated horizontally until the correct beach volume is encompassed. The beach profile rises with long-term sea level rise.

Beaches generally protect the shore platforms that they cover. Based on observational data (Ferreira *et al*., 2000) a behavioural rule was adopted whereby beach depths greater than $0.23H_b$ (where H_b is the height of the breaking wave) were assumed to be fully protective. It was further assumed that this protective capability decreased linearly for shallower beaches.

7.4.1.1. Consolidated profile erosion module

The SCAPE rock profile is represented as a vertical stack of horizontally aligned elements of height *dz*, the seaward edge of which make up the exposed face of the shore platform and cliff. No differentiation is initially made between the cliff face and shore profile, this boundary emerges through model iteration.

Figure 7.9 illustrates the conceptual shore profile and the integration of erosive potential for a single tidal timestep. At every stage of the tidal oscillation, the breaking wave field has the potential to erode the rock surface. This is represented by a function f_1. The seaward extent of f_1 is approximately equal to the water depth at which waves begin to break. To obtain the total erosive potential over a tidal cycle, the instantaneous distribution of erosion must be integrated over the tidal period. As can be seen in Figure 7.9 the integrated erosive potential tends to be concentrated at the tidal extremes, simply because this is where the water level spends the most time. Importantly, the actual erosion experienced by any exposed rock element also depends on (the tangent of) its slope. This means that gently sloping elements (generally lower in the profile) tend to erode less than the (typically higher) steeper elements.

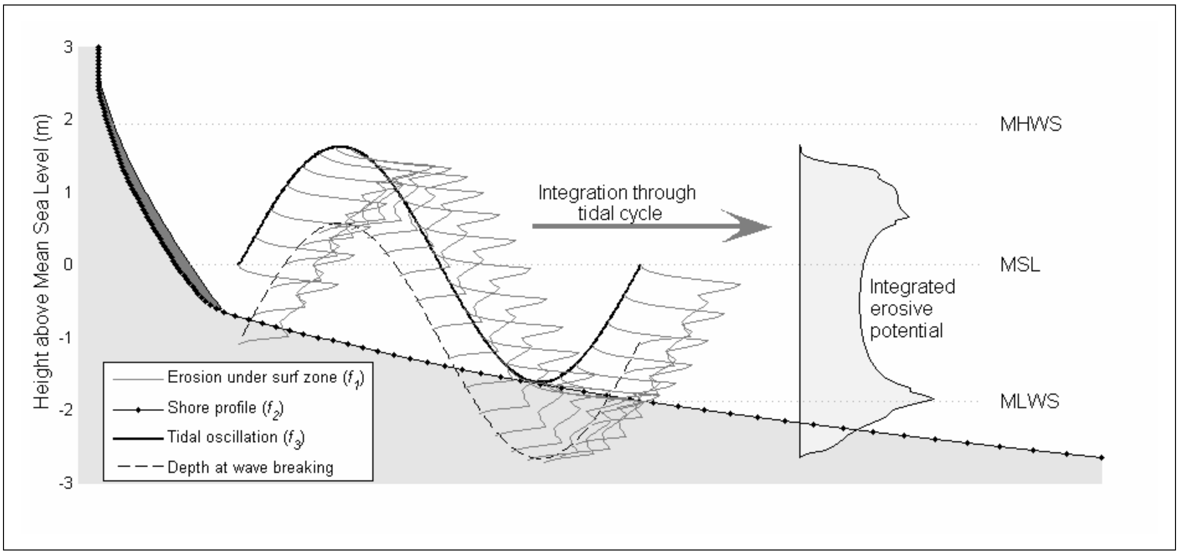


Figure 7.9 Integration of the erosion pattern of a breaking wave field during a tidal timestep (tidal amplitude = 1.62 m, water depth at wave breaking = 1.04 m).

More formal descriptions of this modelling tool can be found in Walkden and Hall (2005) and Walkden and Dickson (2008).

This coastal system, and therefore the dynamically stable emergent profile form, is regulated through feedback. This may be illustrated by considering the interaction of the cliff and shore platform. A sequence of events that cause high cliff toe retreat tends to widen the platform and raise the cliff toe. This reduces the erosive capability of subsequent waves at higher sections of the profile. This negative influence continues until ongoing processes narrow and lower the platform. Thus a period of unusually high cliff toe retreat is followed by a period of unusually low retreat, and the long-term average is stabilised. Such behaviour also regulates smaller scale profile morphology.

The consolidated profile erosion module in SCAPE can therefore be classified as abstract and process-based.

7.4.1.2. Longshore transport

Longshore transport was represented in SCAPE using the one-line approach because of its extensive track record and short run times. Opinions are divided on the classification of this approach since it is based on process-based arguments, but is quite abstract in its application. The approach also relies on behavioural assumptions, for instance in the profile of the beach. In SCAPE the Bruun beach profile was used, which is essentially a behavioural rule for the beach surface with implicit assumptions regarding cross-beach fluxes.

7.4.1.3. Cross-shore transport

Cross-shore sediment motion between the beach and a bar is represented in SCAPE. The nearshore bar is a temporary store of material rather than a sink and does not regulate the overall behaviour of the coast. Given this and the fact that little appropriate related work was found in the literature, this transport was described with behavioural rules. Seaward flux rates were approximated with the results of more detailed numerical modelling (using COSMOS) which were stored in a look-up table. Landward fluxes were represented with a simple behavioural rule, based on expert judgement. This assumed that one per cent of the bar volume returned to the beach every tide when wave conditions were not stormy.

7.4.1.4. *Landsliding*

Landsliding has received much attention in the literature, and this provided a range of possible approaches for model representation. It was deduced from system mapping that landsliding processes do not regulate the behaviour of this type of coast, instead landsliding follows coastal retreat. Consequently a simple and fast approach was needed. Given the importance of cliffs to coastal management issues, the approach should include cliff height and slope as parameters. A simple approach was therefore developed based on concepts of a stable and unstable cliff angle, both of which were described probabilistically.

7.4.2. ASMITA

Estuary evolution was modelled using ASMITA (Version1.3) (Aggregated Scale Morphological Interaction between Tidal basin and the Adjacent coast), which was originally described by Stive *et al*. (1998) and subsequently developed within project FD2107 (Huthnance *et al.*, 2008). ASMITA uses a schematised representation of an estuary comprising the morphological elements tidal flats, ebb-tidal delta and channels (Figure 7.10). Reduced element models can be applied in cases where morphological elements are not present.

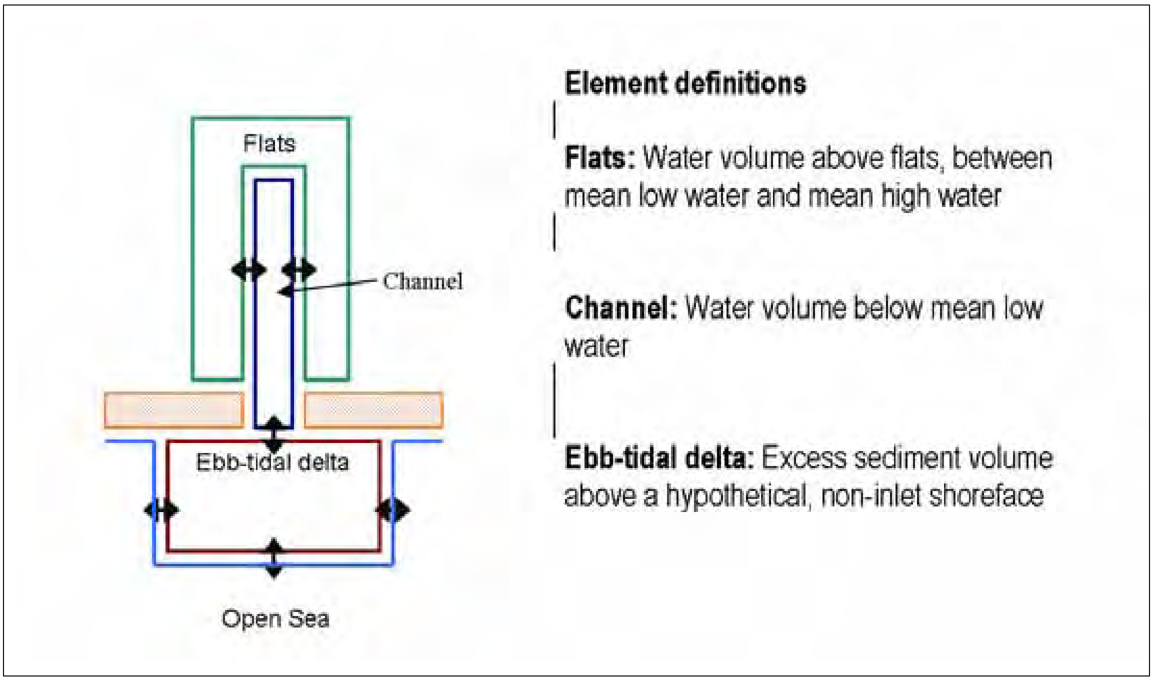


Figure 7.10 Typical three-element schematisation of estuary as used in ASMITA.

These elements and the interactions between them are characterised using mathematical expressions to derive equilibrium volumes and areas, the evolution of each element towards equilibrium, and the long-term residual sediment exchanges between elements (which is assumed to occur by diffusion).

Equilibrium volumes and areas for each element are defined by a linear relationship with tidal prism, which is empirically derived for each element. This means that changes in tidal prism, for example caused by accretion, dredging, managed realignment or reclamation, alter the equilibrium volumes and areas of the elements and cause sediment exchange as the elements evolve towards their new equilibrium. The estuary cross-section and equilibrium equations are shown in Figure 7.11. Further details of the model can be found in Walkden and Rossinngton (2009).

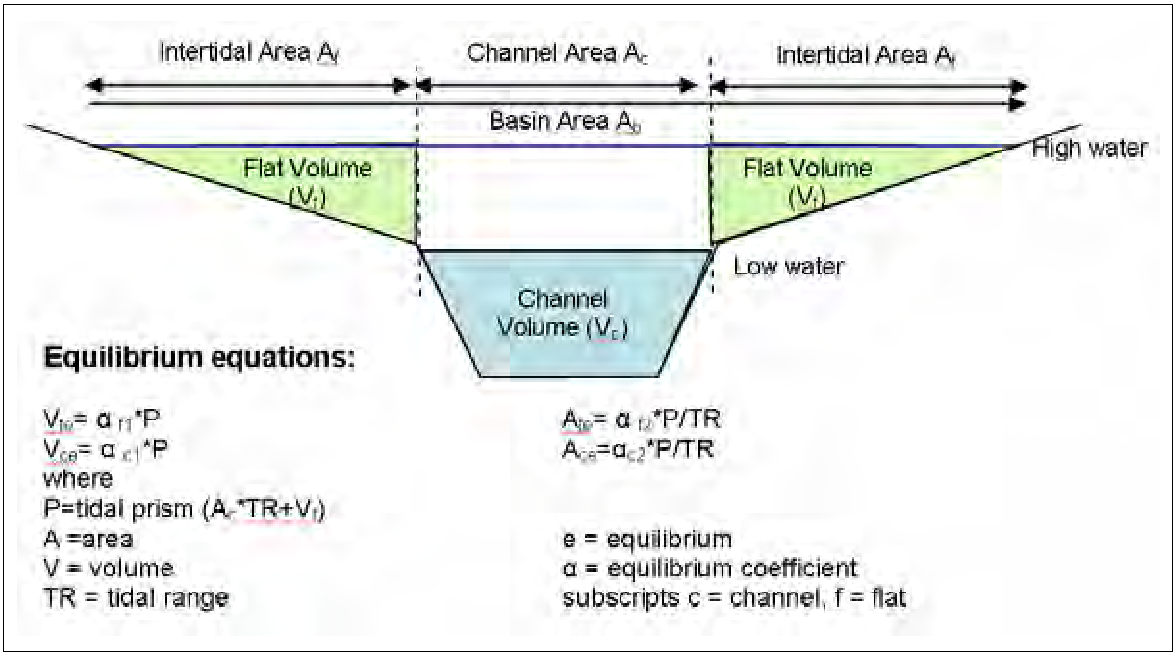
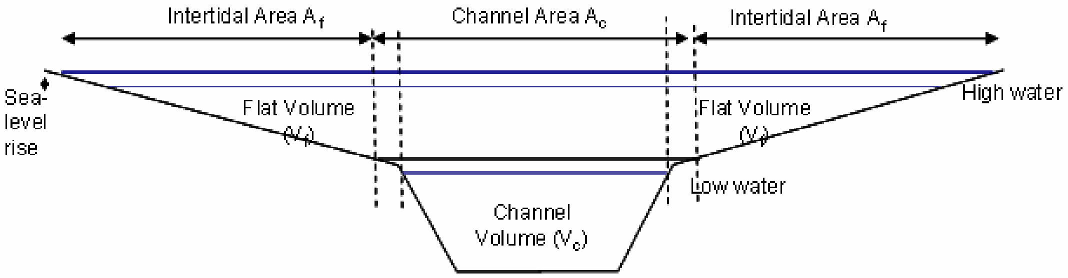


Figure 7.11 Element equilibrium definitions used in ASMITA.

Applying ASMITA to model estuary evolution requires a number of inputs, derived directly from physical properties of the Estuary and more aggregate parameters outlined below. Measurable inputs include element volumes, areas and tidal range. Equilibrium equations can be estimated directly from area and volume data. The sediment exchange coefficients used in ASMITA are not measurable properties of the real system and were estimated for each estuary (Walkden and Rossinngton, 2008).

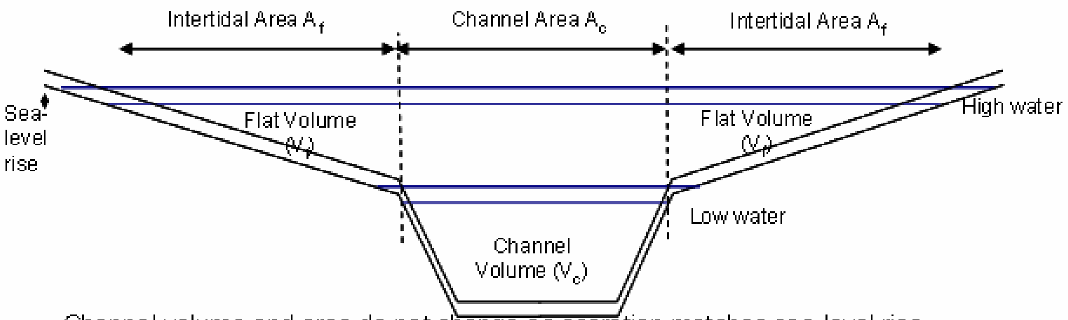
Typical ASMITA responses to sea-level rise and accretion, caused by changes in tidal prism and hence equilibrium volume and area, are shown in Figure 7.12. Behaviour predict by the model depends on the balance between sea-level rise, management interventions and sediment supply and is not always obvious as these factors can interact to produce quite complex behaviours.

Sea-level rise, no morphological change



- Channel volume increase, Channel area increases
- Flat volume increases, flat area increases (due to inundation)
- Tidal prism increases
- Equilibrium volumes and areas are proportional to tidal prism and therefore increase. Actual areas and volumes are too small and try to increase to reach equilibrium.
- Channel area increases by replacing flat area at low water. Flat area increases by erosion at high water.

Sea-level rise, morphological change (exactly matches sea-level rise)



- Channel volume and area do not change as accretion matches sea-level rise
- Flat volume and area do not change
- Tidal prism does not change
- Equilibrium volumes and areas do not change, so actual volumes are close to equilibrium and no further change is triggered.
- If accretion is greater than sea-level rise (i.e. with very high sediment supplies), prism is decreased, equilibrium volumes decrease and actual volumes decrease to follow equilibrium. In this case it is possible to set up positive feedback that will ultimately end up with the estuary infilling completely.

Figure 7.12 Typical ASMITA responses to sea-level rise and accretion, caused by changes in tidal prism and hence equilibrium volume and area.

7.5. Models

7.5.1. Background

The coast-estuary-coast system was represented by coupling a SCAPE model with an ASMITA model. These were intended to be realistic without describing a real system. Consequently, two existing models were used that had previously been calibrated and validated, but which described sites that were unconnected in reality. The model results are therefore demonstrative of realistic behaviour, but do not represent the evolution of a real place. The SCAPE model was split to form a pair of coasts and the estuary inlet was assumed to exist between them, as illustrated in Figure 7.13.

7.5.2. Open coast

The existing SCAPE model that was adopted for this study describes the evolution of the coast of north-east Norfolk (Dickson *et al.,* 2007). This was selected because it represents a long coast and had already been used to explore responses to management and climate change scenarios.

The model comprises 101 sections describing an east facing coast approximately 50 km long comprising a glacial till cliff and shore platform, with a beach. The beach is fed by the erosion of the till. Wave conditions, the tidal range, sea-level rise, cliff height and rock sediment volumes were set to levels typical for the southern North Sea. The dominant beach drift direction was towards the south, although there was also drift towards the northern boundary due to the presence of a drift divide.

The original model planshape and sections can be seen in Figure 7.13, along with the assumed location of the estuary inlet. In this application the model was split to form coasts on either side of the estuary inlet, which was assumed to exist between model sections 27 and 28.

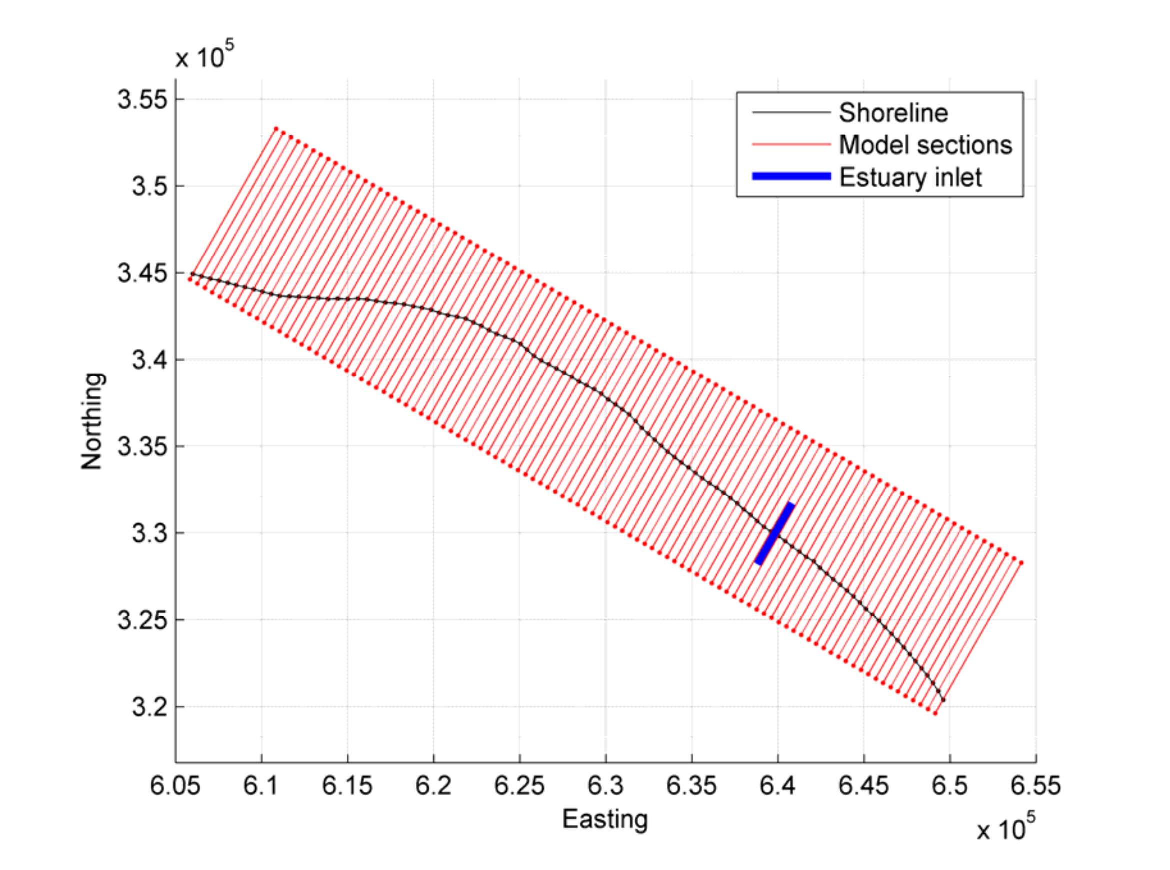


Figure 7.13 Norfolk model sections and shoreline.

7.5.3. Estuary

Selection of an existing ASMITA model was based on three criteria: dynamism and responsiveness to coastal sediment input, inclusion of an ebb-tidal delta to facilitate the implementation of coastal interaction and similarity of tidal characteristics with those of the SCAPE model. The estuary was represented as a macrotidal bar-built symmetrical tidal inlet comprising an intertidal flat, a channel and an ebb-tidal delta, with a dominant sediment type of (fine) sand. This sand may be introduced from the open coast via the ebb-tidal delta or may come from the exogenous domain (the open sea). Sediment supply from rivers was assumed to be negligible.

Sediment arriving from the updrift coast reduced the water volume of the ebb-tidal delta. This forced the delta out of equilibrium and in response ASMITA redistributed the sediment by diffusion with adjacent elements, in this case either the channel or the exogenous domain.

In addition to sediment received from littoral drift, ASMITA can import or export sediment by diffusion between the ebb-tidal delta and the exogenous domain, based on concentration gradients between the two. The concentration in the exogenous domain is assumed to be constant and is unaffected by the development of the inlet. The volume of sediment exchanged by diffusion can be calculated. All of the sediment export by diffusion (if any) is assumed to be available for the development of the downdrift coast.

7.5.4. Coupling

Conceptually, sediment was supplied by SCAPE to the ebb-tidal delta in ASMITA via beach longshore drift, and then redistributed internally by the estuary, where required, to its elements. No sand was assumed to move in the opposite direction. Any sediment exported from the estuary was assumed to pass to the downdrift coast; no material moved from the downdrift coast to the estuary.

The models were run sequentially, starting with the SCAPE updrift coast, then ASMITA, and lastly the SCAPE downdrift coast, using the outputs from the earlier models to drive the later ones. The first SCAPE runs (updrift coast) were used to produce a text file containing the annual volume of sediment input into the ebb-tidal delta in ASMITA. Similarly, ASMITA output the annual import/export volume for use in the downdrift SCAPE model. As the SCAPE model timestep (one tide) is much shorter than that of ASMITA (order of one year), the longshore drift from SCAPE was summed annually to provide the input for ASMITA. The ASMITA code was adapted to output element sediment concentrations and these were used to calculate the diffusive exchange at the boundary.

7.5.5. Inputs

The SCAPE and ASMITA models were driven by similar tide and sea level rise conditions; SCAPE also required wave input.

Sea level rise was implemented as an ongoing linear increase in sea level. Tidal range was input to ASMITA explicitly, whilst SCAPE was provided with discrete recorded tidal amplitudes. Wave conditions were also described once per tide in SCAPE, and were hindcast from wind records.

Details of SCAPE’s parameters and coefficients are given in Walkden and Rossington (2009). Hydrodynamic inputs are described in more detail below.

7.5.5.1. SCAPE wave conditions

Offshore wave conditions were estimated by HR Wallingford (2002). The Norfolk coastline is exposed to waves generated within the North Sea from directions between approximately 300°N and 90°N, but particularly from between North (0°N) and 70°N, since the fetch lengths for this sector are all greater than 500 km.

The offshore wave conditions were predicted using the numerical model HINDWAVE. This models wave growth under wind action and requires information on measured winds and the fetch over which waves are created.

Sequential land-based wind data from Gorleston, which is near Great Yarmouth, were input with speeds appropriately increased to represent over-water conditions, and extended in duration using seven years of synthetic wind data from a UK Met Office weather model. In total 23 years of wind data were used, from 1978 to 2001. The largest waves are likely to arrive from about 030°N, but the most frequent wave directions are from the north-west (330°N).

Nearshore wave conditions, at specific points, were calculated by means of a set of transfer functions. These described nearshore wave heights and directions for all offshore conditions and water depths. They accounted for the bathymetry of the region and were developed for use under rising sea-level conditions. A fuller description of these transfer functions may be found in Kuang and Stansby (2004).

7.5.5.2. SCAPE water levels

Water levels were estimated by HR Wallingford from ten years of sequential hourly water level data recorded at Cromer and extreme values derived using the method of Dixon and Tawn (1996).

7.5.5.3. Joint probabilities

The analysis and handling of joint probabilities (of waves and water levels) was done by HR Wallingford using the method described in Section 3.5.3 of CIRIA (1996). This approach allows combinations of extreme water level predictions with extreme wave predictions in order to derive overall extreme sea conditions with given joint return periods. In general terms, the wave and water level data were matched by date and time and then used as input to a process of long timeseries generation (see below), involving the resampling of months of data. Extreme wave and water levels within this extended timeseries were then resampled from distributions identified using the CIRIA method. For further details see HR Wallingford (2002).

7.5.5.4. Timeseries extension

Very long (1,000-year) timeseries of input data were required for the ‘spin-up’ stage of the morphological modelling. Temporal extension of the data was done by HR Wallingford (2002). The process began with compilation of sets of months of the observed data describing coupled waves and water levels. A long timeseries of joint wave and water level conditions was then generated by randomly sampling complete months, retaining annual progression (a ‘January’ was first chosen, then a ‘February’ and so on) and joining them to form a 12,000-month series. Extreme values in the extended dataset were resampled from the joint distributions produced using the CIRIA method.

SCAPE was then driven by the resulting wave and water level conditions that:

- were derived from observations;
- were statistically coupled in their extreme values;
- represented seasonal changes;
- were extended to represent conditions over 1,000 years.

7.5.6. Outputs

Coupled models were used to produce a large number of output data over a period of 100 years after the ‘spin-up’ stage. The period of 100 years corresponds to the current assessment horizon of Shoreline Management Plans. Outputs included the following:

Coast

- beach volumes;
- shoreline (cliff toe) position and recession rates;
- volumes of sand released from the cliff and platform;
- alongshore sediment transport rates;

- shore platform levels;
- width of intertidal zones.

Estuary

- water volumes of channels and flats;
- sediment volume of ebb-tidal delta;
- surface areas of channels, flats and ebb-tidal delta.

7.5.7. Test conditions

7.5.7.1. Model tests

A matrix of tests explored the system's response to twelve different coastal and estuarial management policies and two rates of sea level rise. Each test simulated one hundred years of development. This period was chosen as an appropriate management timeframe, although the models used can be applied over much longer time periods. For example, the spin-up period (described in the next section) was six hundred years.

Although storm conditions could have been varied, by modifying the wave and water levels input to SCAPE, these were assumed to be constant to keep the size of the test matrix manageable. Before realistic coupled simulations could be run, a period of model 'spin-up' was required.

7.5.7.2. Spin-up

System-based models tend to be highly dynamic. ASMITA functions by continually adapting its elements towards local and overall equilibrium. Changes in its exogenous drivers (such as sea level or sediment input) perturb these equilibria and the whole model responds. Similarly, SCAPE constantly adapts in response to changes in its drivers. Shore profile shapes develop towards equilibrium forms in response to wave, tide, sea level rise and beach conditions. At the same time, diffusive beach behaviour tends to spread sediment along the coast and equilibrate shoreline trends. These dynamic processes may develop over centuries in reality. It is a strength of the systems approach that such models require similar simulated periods to do the same thing. Consequently, such simulations normally have an initial period of 'spin-up' in which equilibria develop.

The PoC models were spun-up for six hundred years. This allowed the shore profile shape and beach conditions to settle along the open coast, and for the estuary to develop towards equilibrium with the coastal sediment influx. Although the models probably do not equilibrate entirely, they do at least achieve relatively steady behaviour against which management and sea level rise perturbations can clearly be seen.

7.5.7.3. Sea level rise

Two rates of sea level rise were simulated, (low) two mm/year and (high) six mm/year. The two rates of sea level rise were used to explore sensitivity in model simulations, and were applied instantaneously at the start of the simulations (the transition from two mm/year to six mm/year was not graduated). The instantaneous change was implemented to minimise transitional and time lag effects in the model output.

The models could have been driven with curved time histories of sea level rise, such as those provided by Defra (2006b). If the Defra sea level rise curve had been used, the overall effects would have been similar but a time lag would have been introduced to the models' response. Sea level rise effects would have been weaker at the start of the century and stronger at the end. Given the form of the Defra curve (for example, four mm/year at the start of the century and 15 mm/year at the end, for south east England) the strongest effects would have occurred after the simulation period. The coupled response of the models may be quite complex and in a real flood and coastal risk management application, the specific sea level curve (Defra, 2006b – or whatever was current at the time) would need to be implemented.

7.5.7.4. Representation of management policy

Six ASMITA models were run without being coupled to an open coast model. Their output was used to demonstrate the dependency of the estuary on the coast. 'Natural' SCAPE and ASMITA simulations were used to identify the behaviour of the open coast and estuary in the absence of human intervention. Engineering interventions were simulated along the coast and within the estuary. These were assumed to be constructed simultaneously. Interventions comprised the addition of seawalls, revetments and groynes to simulate measures to protect four settlements. Estuary interventions simulated the loss of 380 hectares of the tidal flat area through reclamation and also fixing of the estuary circumference with seawalls. Realignment was implemented as the instantaneous removal of structures. The test matrix is given in Table 7.1.

Table 7.1 Scenarios of management and sea-level rise.

('N', 'E' and 'R' indicate 'natural', 'engineered' and 'realigned', '2' and '6' indicate the rate of sea level rise, in mm/year, coast 'Absent' indicates no coastal input to ASMITA)

Coast	**Absent (A)**			**Natural (N)**			**Engineered (E)**			**Realigned (R)**		
Estuary	**N**	**E**	**R**	**N**	**E**	**R**	**N**	**E**	**R**	**N**	**E**	**R**
Low (2 mm/year) sea level rise	AN2	AE2	AR2	NN2	NE2	NR2	EN2	EE2	ER2	RN2	RE2	RR2
High (6 mm/year) sea level rise	AN6	AE6	AR6	NN6	NE6	NR6	EN6	EE6	ER6	RN6	RE6	RR6

The timings of the interventions and reporting periods are shown in Figure 7.14. Because of the requirement for an engineered period preceding any realignment, the reporting periods for the realigned scenarios are 100 years later than for other scenarios.

Figure 7.14 Timings for coast and estuary scenarios with reporting periods outlined in red.

7.5.7.5. Engineering the open coast and estuary

Management of the open coast was implemented by representing typical coast protection structures at four notional settlements, one of which was situated on the downdrift coast. The settlement locations are illustrated in Figure 7.15.

Structures are represented in the model through their effect on natural processes in the following ways:

- Seawalls prevent recession (but not downwearing) of the rock profile.
- Revetments reduce heights of waves passing through them by 50 per cent.
- Groynes reduce the coefficient of longshore transport.

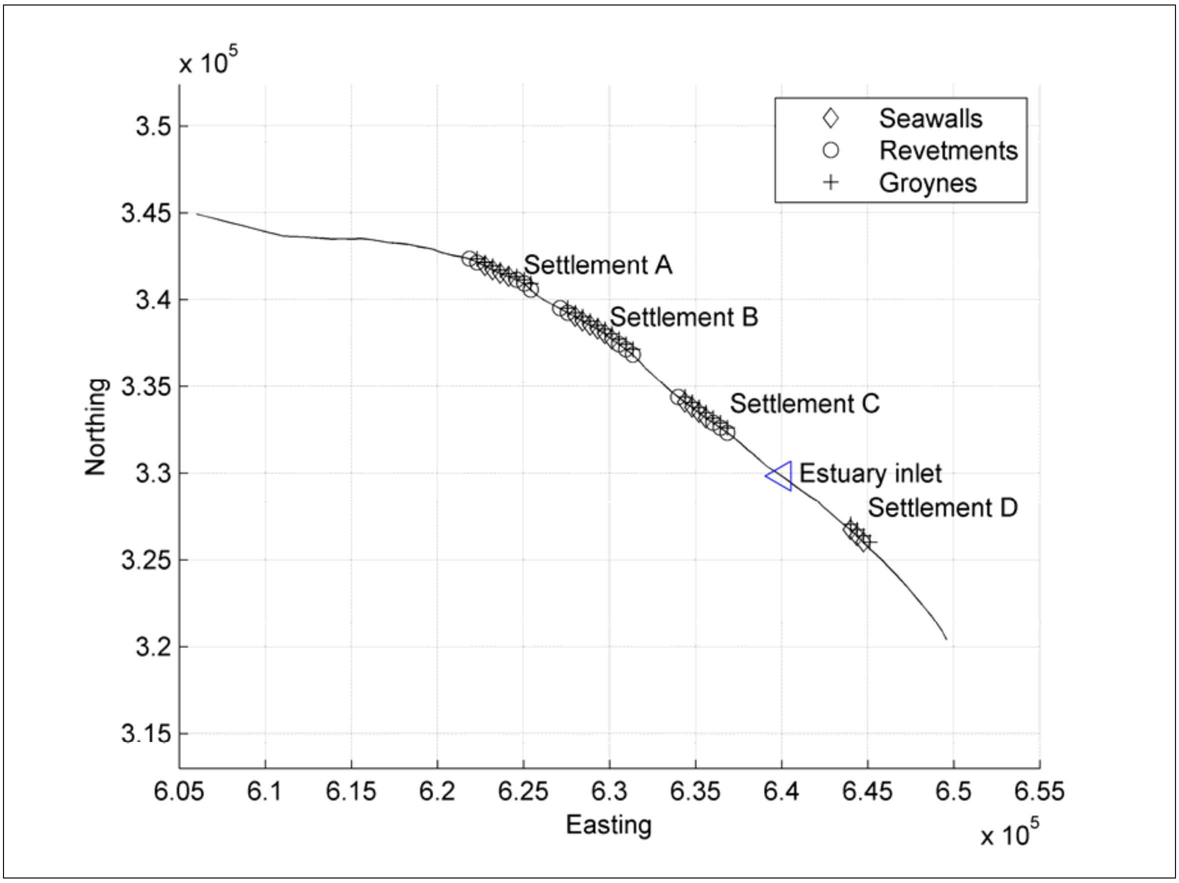


Figure 7.15 Settlement locations on the open coast.

Engineering of the estuary was simulated as reclamation (reduction) of approximately 10 per cent of the intertidal flat area (380 ha), coupled with the construction of seawalls around the whole estuary. The seawalls acted to constrain the high water circumference, preventing flooding of hinterland.

Estuary realignment was simulated as though the seawalls had been set back to allow the estuary to expand to its previous area (380 ha of expansion was allowed).

7.6. Model output for coastal management

This section includes a selection of model results to demonstrate their usefulness for coastal management issues. These are presented as responses to a series of hypothetical but realistic questions. A more detailed description of model outputs is provided in the report by Walkden and Rossington (2009).

The 'proof of concept' models were designed to answer specific types of management questions. New models could be designed to answer others.

The SCAPE model was designed to respond to the following management interventions:

1. Seawall construction/removal
2. Revetment construction/removal
3. Groyne construction/removal
4. Nourishment

The ASMITA modelling tool was designed to respond to:

5. Reclamation
6. Realignment

In addition, both tools respond to changes in:

7. Sea level rise

Whilst SCAPE also responds to changes in:

8. Wave and surge conditions

The SCAPE model simulates, amongst other things:

A. Three-dimensional cliff/shore platform surface
B. Three-dimensional beach form

The ASMITA model simulates the volume of:

C. Intertidal flat
D. Channel
E. Ebb-tidal delta

Having linked the SCAPE and ASMITA models it is possible to *quantify* the effects of changes in Points 1 to 8 on Points A to E. Such changes could be implemented in isolation or combination and could be synchronised or staged. The proof of concept simulations were intentionally simplistic for the purposes of demonstration, and could have been made arbitrarily complex.

In the following examples, proof of concept results are presented to illustrate how such models might be used to answer (in this case hypothetical) management questions.

7.6.1. If existing structures fail at settlement A, how much cliff recession will occur over the next century?

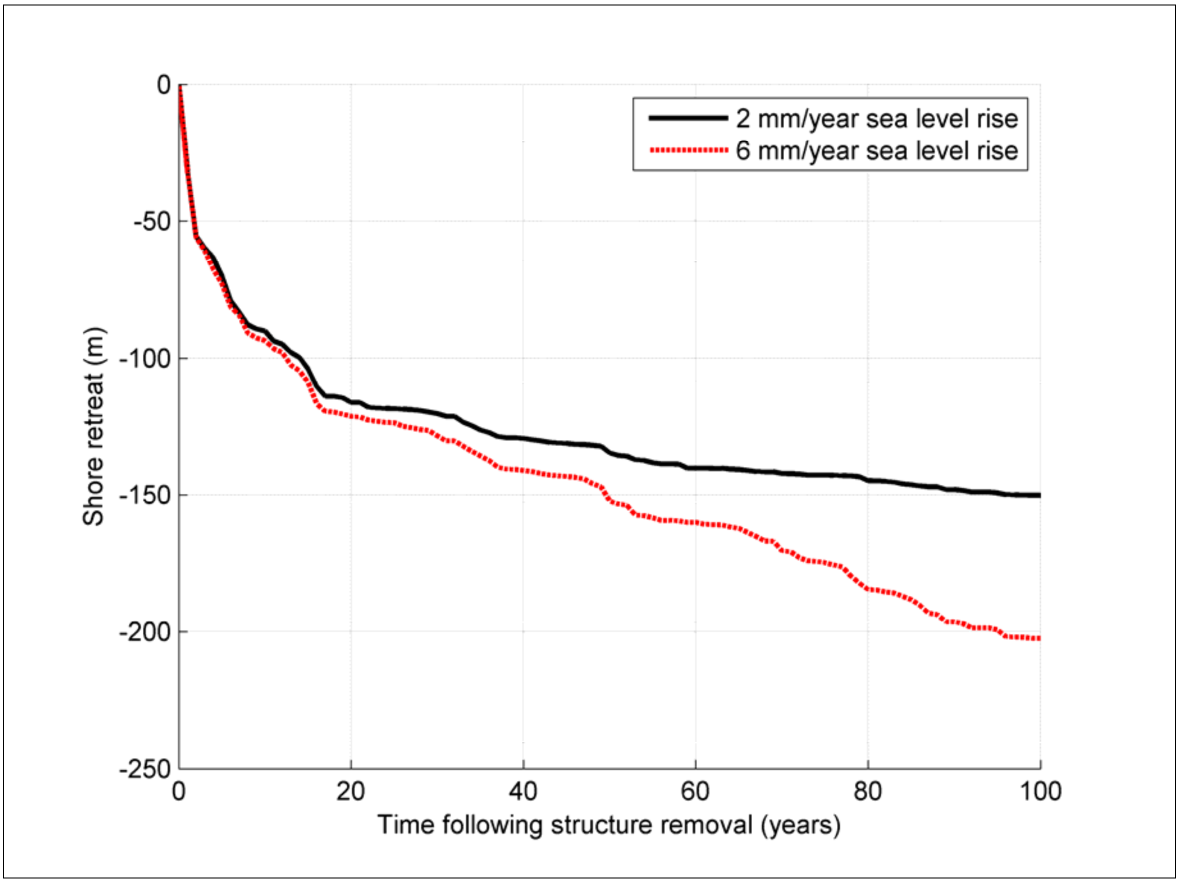


Figure 7.16 Cliff recession at settlement A following structure removal/failure.

Between 150 and 250 metres of shore recession will occur at settlement A in the century following structure removal, depending on rate of sea level rise. Most of this recession will occur in the first twenty years.

Clearly such projections could be combined with asset information to estimate damages. In addition, multiple simulations could be performed to explore response to uncertain variables to produce a distribution of recession distance (as opposed to a range) to allow risk quantification.

7.6.2. If present management policy (defend) is continued at settlement A, how will shore platforms evolve over the next century?

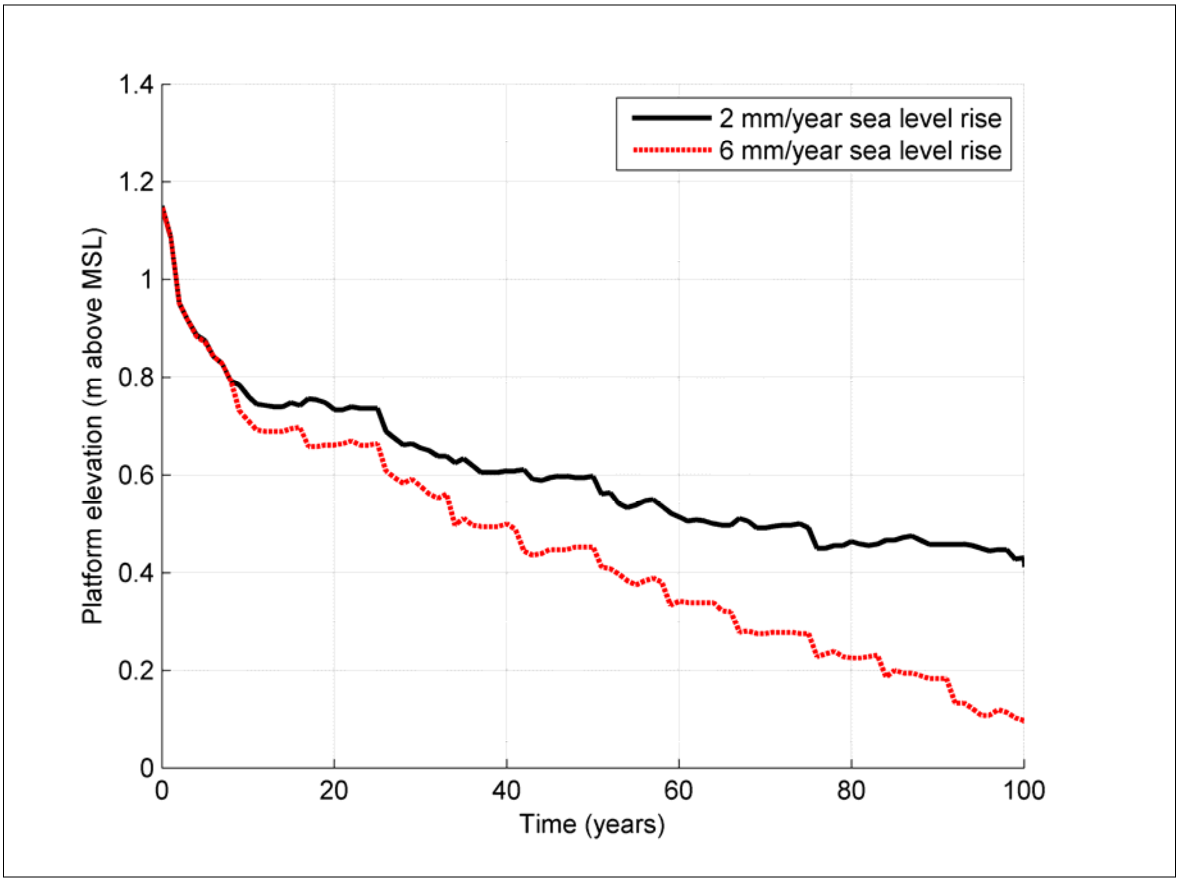


Figure 7.17 Relative platform elevation at settlement A following coast protection.

The shore platform close to the defence structures will drop by approximately 0.8 to 1.1 metres. Such information is of value in determining stability of coastal structures and foreshore trends.

7.6.3. If present management policy (defend) is continued at settlement A, will wave loading on the existing structures change over the next century?

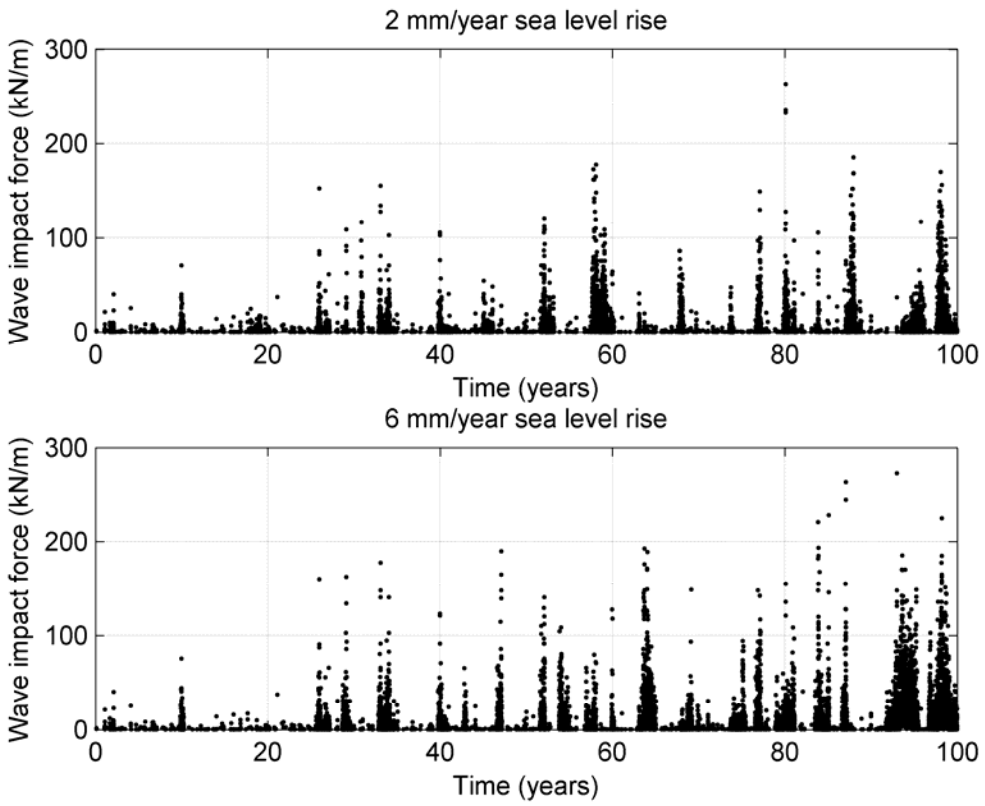


Figure 7.18 Wave impact forces at settlement A following coast protection.

Wave impacts on coastal structures were included in the assessment; force per unit length of seawall. The method of Blackmore and Hewson (1984) was used to estimate wave impact forces for every event in which the high tide reached the seawall and waves broke onto the structure. This method requires the water depth and the wave height, period and celerity. Wave period was already known. Water depth at the structure was found by comparing the levels of the beach and high tide. The breaking wave condition and height at the seawall was established by relating the incident wave height to the water depth via the breaker index.

In the present case wave impact forces will grow to approximately four times their current levels over the century. A similar exercise could be carried out for wave overtopping using existing prediction methods.

7.6.4. If settlements A, B, and C are defended for one century, will this affect sediment flux to the estuary?

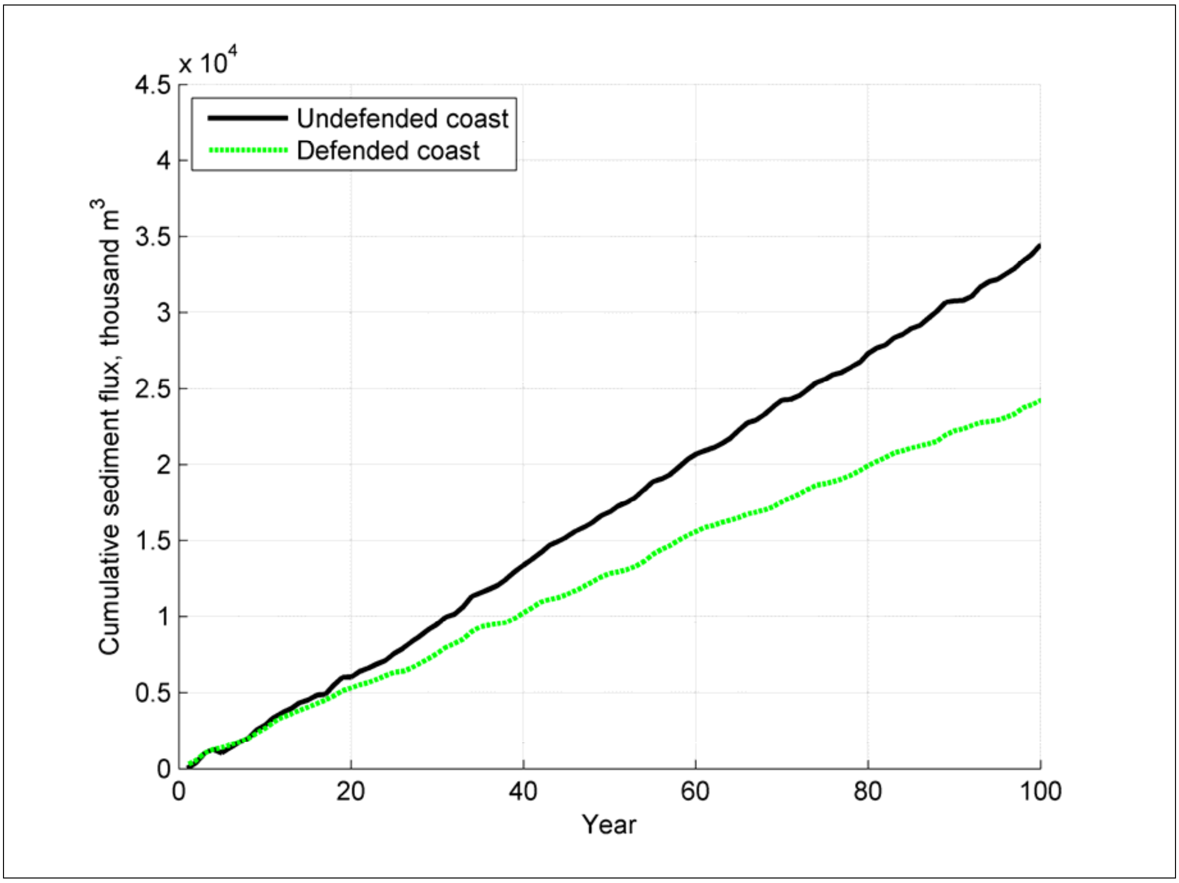


Figure 7.19 Cumulative sediment flux to the estuary.

Defence construction and maintenance will, over the course of the century, produce approximately ten million cubic metres less sediment which is potentially available to the estuary.

7.6.5. If 380 hectares are reclaimed from the estuary what will be the resulting loss of intertidal habitat?

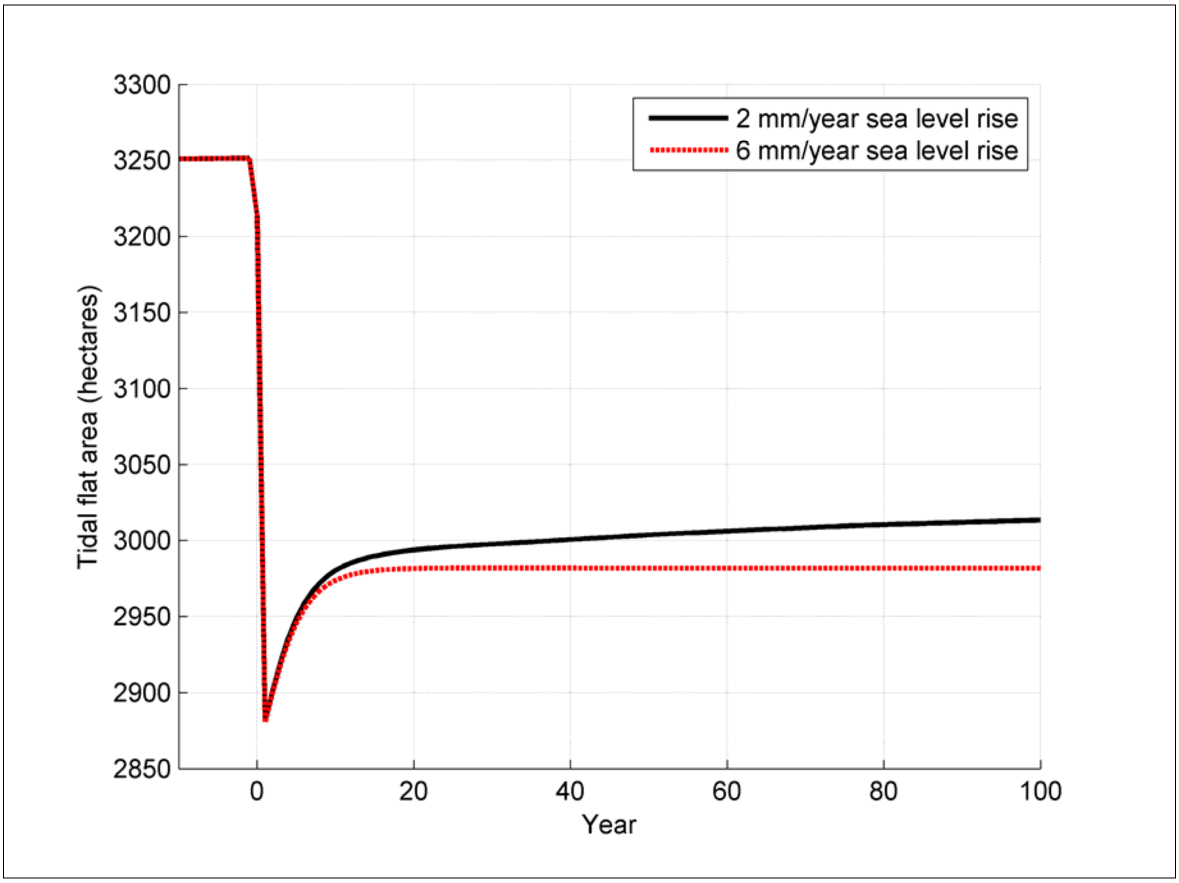


Figure 7.20 Change in intertidal flat area following estuarial reclamation.

Reclaiming 380 hectares will result in the loss of approximately 240 to 270 hectares of intertidal habitat. Initial losses are partially mitigated by estuarial sedimentation.

7.6.6. If 380 hectares are reclaimed from the estuary and simultaneously settlements A, B and C are defended what will be the resulting loss of intertidal habitat?

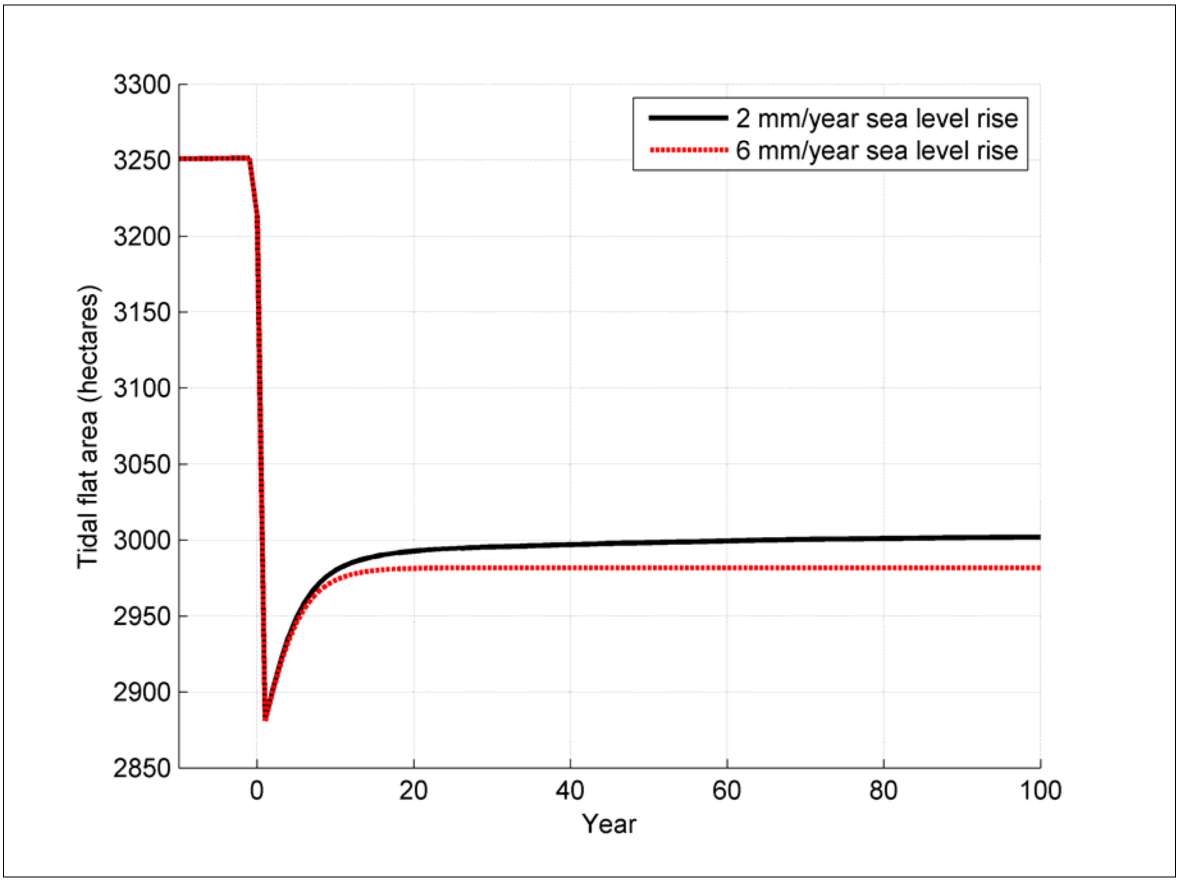


Figure 7.21 Change in intertidal flat area following estuarial reclamation with coastal defence.

Between 250 and 270 hectares of intertidal habitat will be lost. Coast protection increases the loss, on average, because less sediment is available to support growth of intertidal flat.

7.6.7. Would such interventions affect the downdrift shoreline at settlement D?

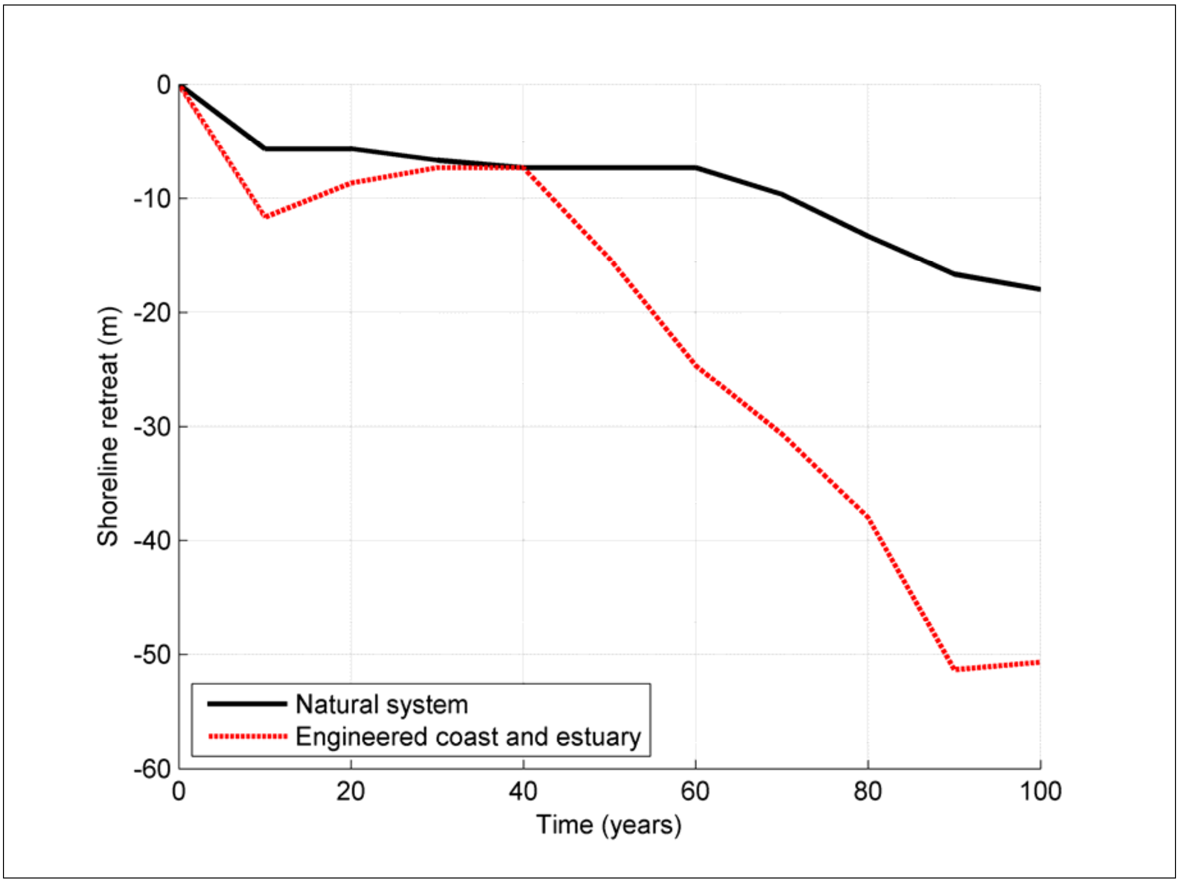


Figure 7.22 Shoreline retreat at settlement D (for simplicity only the results from the two mm/year sea level rise are shown).

The shoreline at settlement D, downdrift of the estuary, would have retreated regardless of whether the estuary or updrift coast was defended, however the defences increase shoreline retreat considerably.

7.6.8. Which of the options (1) retreat estuarial seawalls or (2) retreat estuarial seawalls and allow coast protection structures to fail causes least flooding?

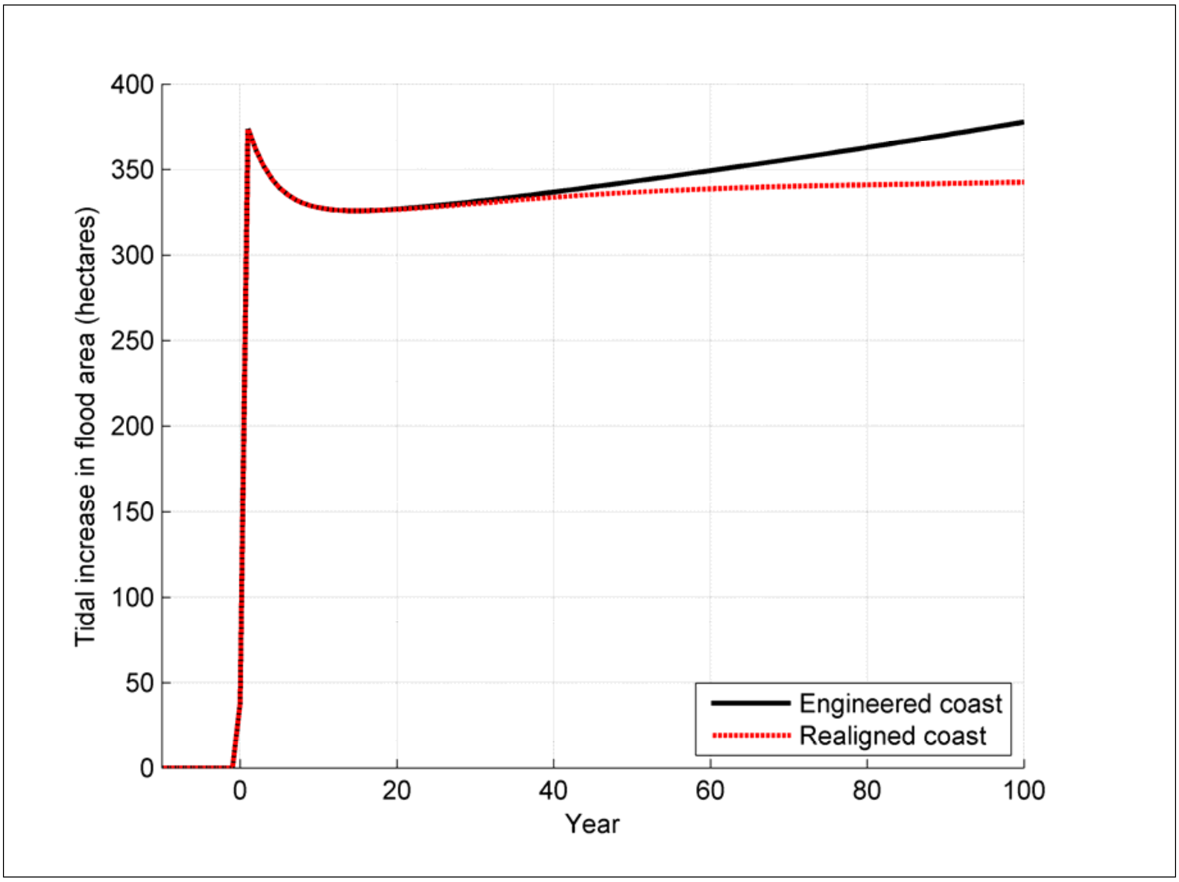


Figure 7.23 Increases in flood area following estuarial realignment.

Retreating the estuarial seawalls to the original perimeter of the estuary results in growth of flood area of approximately 380 hectares if defences on the open coast are maintained (option 1), or approximately 345 hectares if the coast is realigned (option 2). Therefore, allowing realignment of the open coast reduces estuarial (tidal) flooding by approximately 10 percent.

7.6.9. Comments

The examples presented in Section 7.6 are a small and simplified subset of the numerous and potentially complex 'what if' management questions that could be explored with the coupled models.

As noted above, the modelling tools have been constructed to simulate specific types of management interventions; new models could be developed to represent others.

All the proof of concept model runs used deterministic scenarios, since probabilistic simulation was beyond the scope of the existing work. Probabilistic application is feasible for both models since they have short run times. The one-hundred year simulations take the ASMITA model approximately ten seconds and the SCAPE model approximately twenty minutes. Probabilistic application of a similar SCAPE model involving 1,250 simulations has been demonstrated by the Tyndall Centre.

7.7. Discussion

This proof of concept work has linked two behavioural systems models and used them to explore the long-term development of a notional coast/estuary system under scenarios of climate change and management.

Coupling between the models was represented by passing material delivered by longshore transport from the updrift coast to the ebb-tidal delta, and all material exported from the estuary passing to the downdrift coast. Real situations are likely to be more complex. This complexity could be written into the model using additional behavioural descriptions. For example, if an expert believes that the estuary exports a proportion of its sediment offshore under certain tide conditions, this judgement can be explicitly represented. Formally capturing it in this way allows sensitivity testing of such belief and reveals knock-on effects that might otherwise be missed.

If more complex behaviour controls the coupling, such as the dynamics of a spit, then this will require a more sophisticated behavioural representation. Importantly the framework demonstrated in this proof of concept provides boundary conditions for such a model.

The coupled coast estuary system is atypical in that the sediment exchanged is sand, rather than mud. This sediment was chosen to constrain the size of the coastal system dealt with. Fine sediments tend to travel further and so muddy estuaries may be coupled to coastal evolution at extended distances. This implies that real studies would (a) need to encompass larger areas and (b) probably show lower sensitivity to changes in their neighbouring coasts than was seen in this study.

The models used in the proof of concept were designed to operate over temporal scales longer than one year; there is little reason to expect good performance over shorter periods. The spatial scales are also large, although more variable. ASMITA was designed to describe estuary scale development, whilst SCAPE describes processes on a grid, which can be adapted to suit the site. For the proof of concept the grid was 500 m in the horizontal dimension and 0.05 m in the vertical. Despite this short vertical resolution when describing a long stretch of coastline the model representation is essentially coarse.

The benefits of this work do not come from the model projections *per se*, since they do not describe the future of a real coastal system. They come instead from the light they shed on larger issues surrounding the strengths and weaknesses of the approach. The two models are equilibrium models but additional insights into the geomorphological behaviour of the coast and estuary system can be determined by coupling such models.

7.8. Modelling issues

The following questions were raised during the study and have been answered based on the proof of concept results.

7.8.1. Can the behavioural system approach provide the kind of information needed by decision makers?

The answer to this question is clearly yes. Behavioural systems models are typically designed to understand geomorphological behaviour at the scales most appropriate for large-scale, long-term coastal management. In addition, as was illustrated in

Section 2.1, system parameterisation should explicitly account for the needs of decision-makers. For example the models in this study were designed to simulate, amongst other things, cliff top position, beach volume, sediment fluxes, shore platform level, and the changing sizes of estuarial channels and flats.

7.8.2. Can confidence reasonably be had in their predictive simulations?

The level of confidence that it is appropriate to assign to an individual model will vary from case to case. Confidence can be associated with the behavioural systems modelling approach in general since, fundamentally, they are encapsulations of expert knowledge. For example ASMITA represents, to some degree, Stive and co-authors' understanding of estuary dynamics (Stive *et al.*, 1998). In addition the formal model expressions should have some physical basis, though they are likely to be abstract.

Confidence can be improved and gauged during application. Specific models should be calibrated and validated to gauge their performance. The models described here had been through such processes, although not within this study (Dickson *et al.*, 2007, Rossington 2008).

The validation process is essentially the same for models regardless of whether they are based on reductionism or systems approaches. After calibration the model should be run to hindcast coastal change so that the results can be tested against observations. The validation of long-term behavioural models is inherently superior in that it can be performed over longer timescales (where observational data is available). For example the SCAPE model used here was tested against 117 years of observed cliff toe location (Dickson *et al.*, 2007). Successful testing over such temporally extended periods lends considerable confidence to model predictions.

It is possible to validate behavioural systems models more rigorously than conceptual geomorphological models. Calibration of SCAPE requires data on the sediment budget and the historic recession rate of the shoreline. Calibration of ASMITA requires data on the variables it simulates such as intertidal area and channel volumes. Clearly these datasets need to be collated and analysed as part of any study and if they are not available or of poor quality or limited coverage in time (decades) and space (kilometres), it will not be possible to make a reasonable calibration of the model and expert judgement will be required in setting model parameters.

The quantification and consistency checking involved in numerical model assembly brings rigour to the conceptual models upon which they are based. Moreover, having encapsulated a conceptual model in an automated numerical form, its performance may then be tested under far more varied input conditions than would otherwise be possible.

In addition to a validation stage, model behaviour should be scrutinised for plausibility (many examples of this are described in Section 4). Finally confidence can be more formally gauged through sensitivity testing and uncertainty handling. This is discussed further in Section 5.2.

7.8.3. What are the strengths and weaknesses of the behavioural systems approach relative to reductionist modelling and expert geomorphological assessment?

Because the process descriptions of behavioural models are abstract, they cannot be expected to provide the accuracy possible from a reductionist model. However reductionist models have not been very successful at representing geomorphological processes over large scales. Even when reductionist models are applied at small and short scales their results can disagree by orders of magnitude. By comparison behavioural systems-based models are capable of being approximately right over large and long scales. Their approximate nature should be dealt with when they are used, for example through sensitivity testing and probabilistic application.

Expert geomorphological assessment is also capable of long-term prediction, and is generally quicker than a modelling exercise. The relative strength of behavioural systems models is that they can handle more complex interactions between system elements, improve consistency between and within studies and quantify knock-on effects. These strengths allow the expert to explore the implications of their beliefs, test sensitivity to their uncertainty and account for more system elements. In addition the formalisation processes involved in model assembly improve evidence quality.

7.9. Uncertainty

All forecasts of complex natural systems are subject to uncertainty, regardless of the model used. It is now well recognised that quantification of this uncertainty can bring valuable information to the decision-making process and is crucial for risk quantification.

Uncertainty quantification methods typically involve multiple simulations within which model sensitivity to uncertain parameters and input conditions is mapped. In this way the consequences of uncertainty in, amongst other things, model calibration, structure fragility and future climatic drivers can be accounted for during policy making.

In the related field of flood risk, methods of uncertainty quantification developed to support decision-making have employed models of reduced complexity. These simpler models have shorter run times, enabling the necessarily high number of simulations. They also allow the inclusion of broader systems, which is necessary for integrated risk analysis. There is a straightforward parallel with behavioural systems models of coastal geomorphology. They have shorter run times and are more holistic than reductionist models and can therefore be employed in quantified risk analysis and uncertainty assessment.

Behavioural systems models may be perceived to be inherently less valid than reductionist models because of their abstract content. There is a fundamental difference between the basis of inherent belief in behavioural systems models compared with traditional reductionist models. To some extent we believe models have inherent validity, prior to their testing; that is, we have some confidence that they emulate reality. We have confidence in reductionist models because they (in principle at least) describe fundamental physical processes. This reasoning lends less, though still some, confidence to the abstract terms of behavioural systems models.

The philosophical strength of the behavioural systems approach arises from its holism. It is clearly unreasonable to attempt to predict the future behaviour of a complex system, such as an open coast of the type represented here, by modelling only one of its components in isolation. It is necessary to model the beach, shore platform and cliff, as well as the hydrodynamic processes that drive them. The interaction and inter-regulation that arise when the whole set of components are modelled control overall response and prevent unnatural behaviour.

The traditional reductionist approach recognises that it is necessary to describe processes. The ‘systems’ approach also recognises that the whole system must be described, and that it is normally necessary to reduce the precision of process descriptions to achieve this. This more symmetrical balance between description of the components and the whole lends long-term stability.

In summary, over the short term reductionist models are more inherently valid; beyond this, behavioural systems models should be more reliable. Behavioural systems models are therefore not recommended for coastal management over short timescales. They are applicable to annual to decadal timescales; in the current project, the simulation period was 100 years.

7.10. Decision support

The potential value of such models lies in their capacity to inform the management decision-making process. As noted above, models should be designed to respond to management interventions (such as nourishment, sea defence, realignment) and to output the system states required for risk analysis (such as cliff top position, flood depths). Such models should also be designed to have short run times, to enable the multiple simulations typically required during risk analysis. Figure 7.24 (note that the frame '*Model assembly*' has been described in detail above) suggests how the process of constructing and applying behavioural systems models could be coupled with processes of uncertainty quantification and risk analysis to test management options.

The frame 'Quantified risk assessment and uncertainty analysis' follows a process developed for the regional coastal simulator of the Tyndall Centre. The validated model(s) is run multiple times, each with a unique set of inputs and parameters that represent (1) the management option being tested and (2) uncertainty. The predicted future system states are integrated to produce probability distribution functions (of cliff top position, flood depth and so on). These can be integrated with data on shore assets (such as type and location of structures in the floodplain/along the cliff top) to calculate economic risk. This risk can be integrated and compared with cost to identify those options that are preferable, in economic terms. The spatial distribution of risk can also be examined to locate areas of high vulnerability.

The modelling described here can be used to inform Decision Support Systems of the type outlined in Section 2.4.

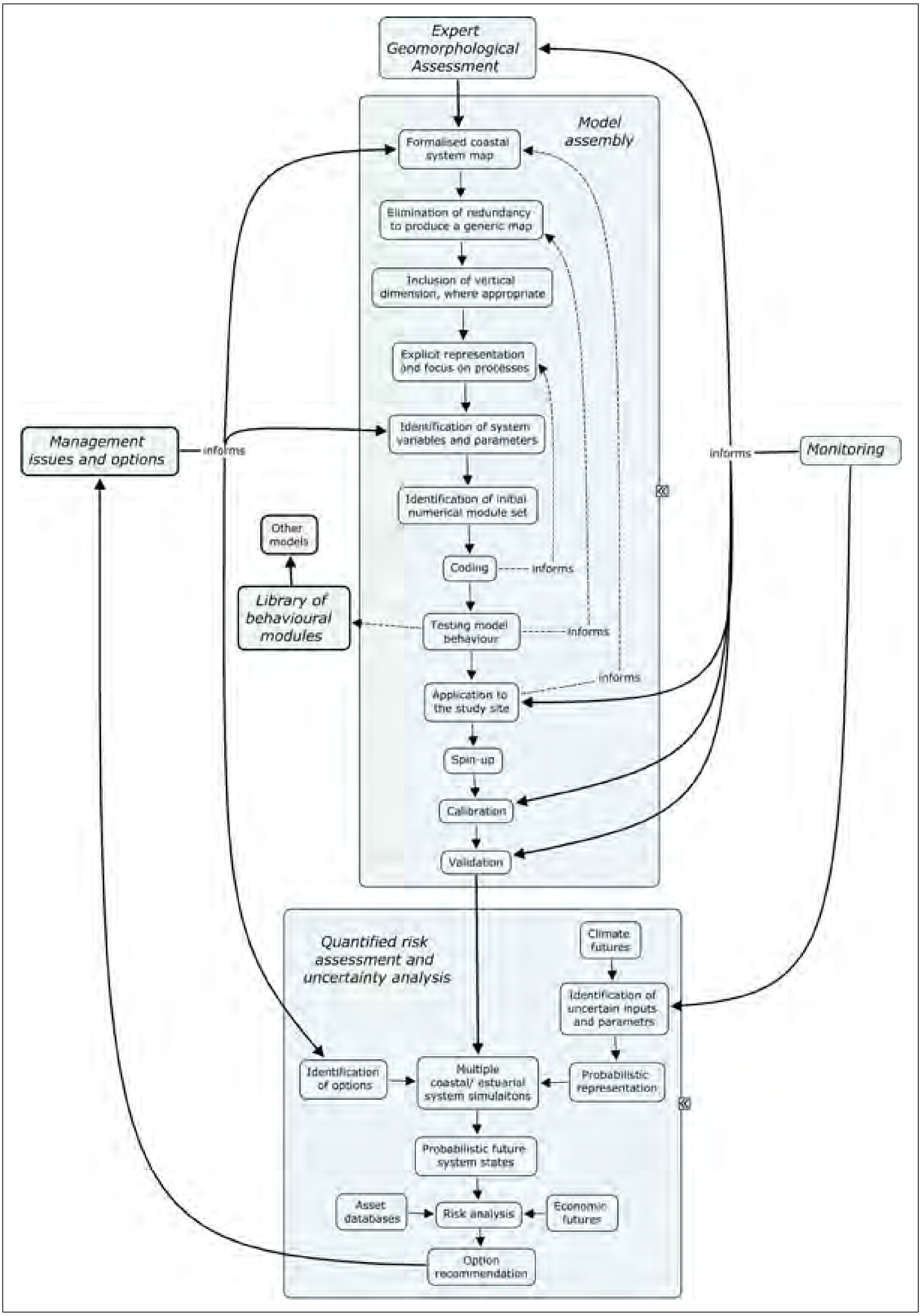


Figure 7.24 Behavioural systems model development for management options testing.

7.11. Geomorphological insights

Our simulations demonstrated a broad set of geomorphological behaviours. For example, responses to coast protection measured included: reduced sediment release, relative platform lowering, reduced longshore transport, estuarial hinterland loss and intertidal gain and increased recession of the downdrift coast. These examples are all unsurprising, however a strength of the behavioural approach is that they are quantified and, moreover, their inter-relationships are explicitly handled. For example the increase in downdrift coastal recession referred to above was explicitly modified by (1) the reduction in sediment release caused by the updrift seawalls and revetments, (2) the rate of platform lowering, (3) lower longshore transport caused by groynes, (4) the loss of hinterland and accretion of the estuary flat, and (5) other model behaviours.

Other insights provided by the models are less obvious. For example, the relative importance of estuarial reclamation compared with coast protection for erosion of the downdrift coast was revealed. The estuarial reclamation caused a sharp but transient fall in the supply of beach sediments to the downdrift coast, whereas coastal protection of the updrift coast caused a smaller immediate effect, but much more serious long-term starvation of the beaches.

The ebb-tidal delta proved to be a crucial link between the coast and estuary and its behaviour, as simulated by ASMITA. It regulated the capacity of the estuary to respond to management policy changes both internally and on the open coast. The major difference between the coupled model scenarios and the absent coast scenarios is that, when present, the coastal sediment supply forces the ebb-tidal delta away from equilibrium, thus driving morphological change throughout the system. The absent coast scenarios do not have this drive and morphological change is driven by changes to tidal prism within the estuary.

One additional feature that arose from early (unreported) model runs was the size of estuary that can remain open for a given rate of littoral drift. Initial tests used an estuary one-third of the size of the test estuary, and this was observed to infill completely within 1,200 years. The size of estuary that can be maintained will therefore depend on the rate of sediment supply from the updrift coast, and on the efficiency of estuarine processes in expelling sediment through flushing.

7.12. Conclusions

This proof of concept is a brief and partial exploration of the development and application of behavioural systems models. It demonstrates their feasibility and shows that the concept can usefully be exploited for coastal management purposes. The direction and magnitude of change are both useful output parameters.

This project explored how to use and move beyond coastal mapping and expert geomorphological assessment to build and apply broad-scale coastal models. Coastal systems models with the capacity to predict variables of relevance to coastal management were constructed by incorporating relevant aspects of quantified process-based understanding.

Although the approach is not new, it has received relatively little attention from the scientific community, probably because it is non-reductionist. As a result the library of available models and behavioural descriptions is small. The proof of concept work involved description of elements including cliffs, beaches, shore platforms, intertidal flats, channels and ebb-tidal deltas. New modules are needed to describe other elements, such as spits, nesses, marshes and dunes. A ‘toolbox’ is also required to store new models for reuse at other sites.

The behavioural systems approach differs from reductionism in that it (1) accepts approximate (as opposed to precise) descriptions of processes and (2) aspires to represent whole systems. The loss of local precision is accepted to gain broader scale realism and stability. Interactions of the system elements constrain model behaviour to prevent instability. The use of approximate process descriptions brings the long-term predictive capacity needed for decision-making, but this comes at the cost of short-term precision. Over shorter and smaller scales reductionist models should be superior, because of their more fundamental process descriptions.

The SCAPE model cannot be used in its present configuration for hard rock shores and does not deal with mixed sediments. It does not simulate alongshore tidal currents and only has a parameterised cross-shore sediment exchange. The methods are not appropriate for short timescales of less than one year.

This approach requires expert geomorphological assessment to create the conceptual model of the coastal system, which forms the basis of the numerical model. Representation of the conceptual model with formalised coastal system maps provides a template upon which the numerical model can be assembled.

Behavioural systems models have the inherent benefit for coastal management in that they tend to describe longer timescales. However, to properly use them coastal managers should influence model development so that the model is designed to: (1) represent the effects of existing human interventions on the coastal system, (2) output system variables most relevant to the management problem (such as cliff top position, flood depths), and (3) allow the full range of future strategies envisaged by the manager. In addition the model should be designed to have run times short enough to allow the multiple simulations necessary for uncertainty analysis and risk quantification. Essentially the model is constructed for the purposes of coastal management, rather than to describe detailed processes.

With additional work these strengths of the behavioural systems approach can be more fully realised and put to good use in coastal management.

7.13. Further work

This proof of concept has shown how to move beyond coastal mapping to incorporate relevant aspects of quantified process-based understanding into models of coastal systems that have some capacity to predict variables of relevance to coastal management decision-making.

It is a partial example of how systems models could be used to support the difficult problem of long-term management of a changing coastline. This can only be achieved with adequate follow-on research.

To develop and further establish the approach, it should be pilot tested with a real coastal site, following the stages illustrated in Figure 7.24. This should involve collaboration with coastal managers and include elements of model development and application, options testing and risk analysis.

Given the difficulty of the problem and the lack of attention to such broad scale work, many geomorphological features and elements have not previously been represented at appropriate scales. Models are needed to represent features such as dunes, spits, sandbanks, marshes, mixed sediment beaches and nesses. This should not necessarily inhibit the development of a pilot test since the study site could be selected to minimise the number of new modules required.

Particular effort should be focused on uncertainty quantification. The short run times and holistic basis of such models should allow more thorough uncertainty quantification than has been possible with traditional reductionist coastal/estuarial models. Such a study should deal with, amongst other things, uncertainty in model assembly, calibration, defence residual life and future climate.

Inclusion of realistic management issues and options, and quantification of risk will ensure the contribution of the work to coastal management and more fully test the behavioural systems approach.

8. Evaluation of methods

8.1. Introduction

This section contains a summary of eight methods for assessing coastal change and predicting future changes in morphology. These methods are:

- Historical Trends Analysis (HTA) and Future Trends Extrapolation (FTE)
- Bruun Rule and related methods
- Equilibrium bay shape
- One-line beach model
- Coastal profile model
- Coastal area model
- Shingle and barrier inertia methods to predict breaching of shingle barriers
- Tidal inlet stability.

For each method a description, summary of metadata and example applications are provided. The models described fall broadly into three types:

1. Behavioural models of coastal change: historical tend analysis and future change extrapolation, the Bruun Rule and equilibrium beach shape. These models reproduce the observed behaviour of a feature of the morphology – in these cases the position of the shoreline – without attempting to reproduce the physical processes that cause the observed changes. These models are simple, quick and robust, but rely on future behaviour being similar to the behaviour the model was calibrated with.

2. Process-based models: one-line models, coastal profile models and coastal area models. A considerable amount of research has been carried out over the last 20 years to develop predictive process-based numerical models of coastal evolution covering periods ranging from storms to decades. These models include one-line models (Section 8.4) coastal profile models (Section 8.5) and coastal area models (Section 8.6). They are based on representations of physical processes and typically include forcing by waves and/or currents, a response in terms of sediment transport and a morphology-updating module. In practice, all models straddle the boundary between behavioural and process-based representation as no model includes all the physics involved. For example, even a detailed sediment transport model goes from knowledge of input conditions (waves, currents, sediment characteristic, bedforms and so on) to sediment concentration and flux without calculating the full details of the turbulence or force balance on each grain. However, there are still major gaps in our understanding of long-term morphological behaviour (de Vriend *et al*., 1993, Southgate and Brampton, 2001, de Vriend, 2003, Hanson *et al*., 2003) which mean that modelling results are subject to a considerable degree of uncertainty. Their use requires a high level of specialised knowledge of science, engineering and management. Southgate and Brampton (2001) provide a guide to model usage, which considers the engineering and management options and the strategies that can be

adopted, while working within the limitations of our scientific knowledge and data.

3. Change of state models: SHINGLE and barrier inertia models for the breaching of barrier beaches and the inlet stability tools. Behavioural and process-based models assume that the feature or elements being modelled will be preserved and will not change state during the course of the modelling. In practice, a shingle/gravel barrier may be breached and the breach may remain open creating a new tidal inlet (a new feature) where none existed before. A suite of models of long-term large-scale coastal behaviour must include the possibility for changes of state.

A range of methods are available (Table 8.1) and some of these are analysed in more detail in this section of the report.

Table 8.1 Summary of tools and methods available.

Element	Tool/Method	Data requirements	Limitations
Seacliffs	Historical trend analysis (HTA)	Historic maps Aerial photos Profiles	Records change, not reasons for change. Uncertainty over which parameter is captured (eg cliff line, cliff top). Trend vs episode. Accuracy (x, y, z).
	Expert geomorphological assessment (EGA) leads to conceptual model	Geology Geotechnical data Geomorphological map Site visit Remote sensing Recent evidence Exposure to waves	Needs surface and sub surface data. Degree of expertise. Trend vs episode. Antecedent conditions.
	Empirical models (e.g. Bruun/ Balson)	Profiles Rate of relative sea level rise	No account of geology. Assumes equilibrium profile. No process information.
	Slope stability	Profiles Material - Fabric - Strength Hydrogeology	Not good for marine domain. 1D may not capture along-coast variation.
	Systems-based models (e.g. SCAPE, Walkden and Dickson, 2008; Trenhaile, 2009)	Profiles along and offshore Waves Tides % mud:sand:gravel in cliff Material strength of platform Defences	Single value of material strength and % m:s:g on profile. Assumes alongshore uniformity. Only used on soft cliffs.

Element	Tool/Method	Data requirements	Limitations
Dunes	Historical trend analysis (HTA)	Historic maps Aerial photos Profiles	Records change, not reasons for change. Uncertainty over which parameter is captured (toe, crest). Trend vs episode. Accuracy (x,y,z)
	Expert geomorphological assessment (EGA) leads to conceptual model	Geology - Stratigraphy Sedimentology (particle size distribution) Dating of deposits Geomorphological map Site visit Remote sensing Recent evidence Exposure – wind energy regime, wave energy regime	Needs surface and sub surface data. Degree of expertise. Trend vs episode. Antecedent conditions.
	Empirical models (Bruun type)	Profile to 10-20 m depth Relative sea level rise	No account of geology or sediments. Assumes equilibrium profile. Limited process information.
	Parametric models (Dutch)	Profiles Material Particle size distribution	No stratigraphy. Uniform sand body assumed. Application to UK dunes.
Lagoons	Historic trends analysis (HTA)	Historic maps Aerial photos Profiles Rainfall data Groundwater levels Freshwater inflow	Records change, not reasons for change. Accuracy of maps. Episodicity may not be mapped.
	Expert geomorphological assessment (EGA) leads to conceptual model	Geology Geomorphology Site visit Remote sensing Recent evidence	Needs surface and sub surface data. Degree of expertise. Trend vs episode. Antecedent conditions.
Beaches	Historical trend analysis (HTA)	Historic maps High water Low water Aerial photos Profiles	Records change, not reasons for change. Uncertainty over which parameter is captured. Lack of detail. Trend vs episode. Accuracy of HW and LW lines. Needs long-term data sets.

Element	Tool/Method	Data requirements	Limitations
	Expert geomorphological assessment (EGA) leads to conceptual model Sediment budget analysis	Geology Geomorphological map Site visit Remote sensing Recent evidence Exposure to waves Data on erosion and accretion, sediment type, source, pathway, sink	Needs surface and sub surface data. Degree of expertise. Trend vs episode. Antecedent conditions. Qualitative Quantitative is difficult
	Empirical models (e.g.Bruun, Dean Equilibrium Profile) Shingle (Powell, 1990) Planshape (e.g. Hsu and Evans,1989)	Profiles Relative sea level rise Water level datum Grain size Closure depth As above Beach angle Wave angle Refraction point and end point of bay	No account of geology. Assumes equilibrium profile. No process information. Cannot deal with profile landward of the crest. Fixed "headland" Does not deal with 'moving' (eroding) refraction or end point.
	Systems-based models (e.g. SCAPE, Walkden and Dickson, 2008)	Profiles along and off shore Wave data Tide data Cliff % mud:sand:gravel Material strength of platform Defences	Single value of material strength and % mud:sand:gravel on profile. Assumes alongshore uniformity. Only used on soft coasts.
	Numerical profile models (e.g. COSMOS – Southgate and Nairn, 1993; Nairn and Southgate, 1993) Planshape (e.g. Beachplan, Osaza and Brampton, 1980)	Initial beach profile Water levels Wave climate Grain size Initial shore line Defences	Generally can only erode. Lack of validation data due to length of records needed.
Shore platform	Historical trend analysis (HTA)	Historic maps High water Low water Aerial photos Characteristic profile Bespoke measurements of downcutting	Records change, not reasons for change. Uncertainty over which parameter is captured. Trend vs episode. Platform coverage (by beach) varies. Rate of change is variable.

Element	Tool/Method	Data requirements	Limitations
	Expert geomorphological assessment (EGA) leads to conceptual model	Geology Geotechnical data Geomorphological map Site visit Remote sensing Recent evidence Exposure to waves Bio chem-phys-effects on material strength.	Needs surface and subsurface data. Degree of expertise. Trend vs episode. Antecedent conditions.
	Systems-based models (e.g. SCAPE)	Profiles along and off shore Waves Tides Cliff % mud:sand:gravel Material strength of platform Defences	Single value of material strength and % mud:sand:gravel on profile. Assumes alongshore uniformity. Only soft coasts. Complexity of representing beach cover in model (temporal change).
	Empirical (Bruun)	Profile Relative sea level rise Gives you lowering rate once recession is known (need to know the profile)	No account of geology. Assumes equilibrium profile. No process information. No material input. Episodicity not considered. Lags not represented.
Tidal flats, saltmarsh	Historical trend analysis (HTA)	Historic maps and charts Repeat topographic surveys/LiDAR surveys Aerial photo and remote sensing – give information on vegetation cover and type Core data Sediment stratigraphy Particle size distribution Geotechnical information	Spatial accuracy. Temporal resolution. Only ~10 years of LiDAR data. Limit on time of year taken. Density of coverage for core data.

Element	Tool/Method	Data requirements	Limitations
	Expert geomorphological assessment (EGA) leads to conceptual model Including: sediment budget analysis, vegetation analysis.	Microfossils Morphology, profiles etc Drivers Water level Waves Sediment supply Sediment distribution Biology	Needs surface and subsurface data. Degree of expertise. Trend vs episode. Antecedent conditions. Lack of data e.g. for waves in estuaries.
	Empirical approaches (Kirby typology – Kirby, 1992) (Dyer typology, Dyer, 1998)) Translation (Bruun concept)	Tidal datum and range Waves Morphology Channel width Relative sea level rise	Sediment type not represented. No account of sediment load, rate of transport.
	Analytical and numerical process models Friedrichs and Aubrey (1996), Roberts *et al.* (2000), Pethick (2002), Pritchard *et al.* (2002), Capucci *et al.* (2004) - 0D models	Tidal datum and range Waves Morphology Channel width Relative sea level rise	Concepts used need to be assessed for each application.
Banks, channels and inlet associated banks	Historical trend analysis (HTA)	Historic charts Bathymetric surveys	Datum for surveys. Positional accuracy (x,y). Vertical accuracy (z). Trend vs episode. Gap between survey in time too long or too short.
	Expert geomorphological assessment (EGA) including sediment trend analysis	Particle size distribution Surface and subsurface data (geophysics, cores) Surface features Process, waves, tides understanding Geological context	Expensive. Datum for survey. Positional accuracy (x,y). Vertical accuracy (z). Trend vs episode. Gap between survey in time too long or too short.
	Empirical methods based on volumes or prism	Morphology Estuary information including – volume and tidal prism	Crude (volume only). No information on form.

Element	Tool/Method	Data requirements	Limitations
	Numerical process modelling	Bathymetry Sediment particle size distribution Wave data Tide levels Currents	Infers bank behaviours from short-term process results. Requires one or more models with bathymetry based on charts/surveys and models that are calibrated and validated.
	Empirical models (Bruun and Gerittsen, 1960) for inlets O'Brien regime models	Freshwater flow Tidal prism Longshore drift Cross-section area	Categorisation through broad parameters. Simplistic. No timescale information.

8.2. Historical trend analysis and future change extrapolation

Historical analysis (Hooke and Bray, 1996), or historical trend analysis (Pye and van der Wal, 2000) has been employed in coastal geomorphological and engineering studies for many years, and is widely regarded as an essential component of any study aimed at understanding and projecting large-scale, long-term change. The historical data employed can be of various types: map and chart evidence is generally applicable over decadal to centennial timescales, ground-survey data are generally available over timescales of months to decades, and remote-sensing data such as satellite imagery, aerial photography and airborne LiDAR are generally available for more recent time periods of months to decades. The availability of such data, including frequency and reliability of coverage, varies greatly between different geographical areas, and over different time periods.

Maps and charts are amongst the most widely used data sources in historical trend analysis, but care must be taken in their use (Carr, 1980; Hooke and Kain, 1982; Hooke and Bray, 1997). Maps and marine charts prepared before the middle of the nineteenth century are generally less accurate than those produced by the Ordnance Survey and the Hydrographic Office from the 1840s inwards. Maps produced prior to the mid-eighteenth century are often schematic, but can sometimes provide useful qualitative information about general coastal morphology. The development of better triangulation methods by the Ordnance Survey in the 1830s opened the way for more accurate maps of the entire country, originally published at a scale of one inch to the mile and later at a scale of six inches to the mile and twenty-five inches to the mile.

While an understanding of the pattern and rates of past changes is useful in itself, there is also interest in using historical data to predict future changes. Accurate prediction of future behaviour in open systems is extremely difficult and may be impossible (Oreskes *et al*., 1994), but management planning in coastal and other environments generally requires forecasts of possible future changes. The uncertainties and limitations of such forecasts should always be borne in mind.

Simple extrapolation of historical trends over different time periods provides a frame of reference which can be compared to outputs from other models and expert assessments. Historical trends may be extrapolated to produce estimates of future change by assuming that typical past behaviour continues into the future (Hooke and Bray, 1996). This combined process has been referred to as historical trend analysis - future change extrapolation (HTA - FCE) by Blott *et al*. (2006). However, predictions based on different time periods of historical data may give very different results. This is due to the episodic, and sometimes cyclical, nature of many natural processes and the variable lags associated with morphological responses. The assumption of no future change in general system conditions may also be invalid.

However, it is possible to incorporate the potential effects of changes in some system conditions, such as sea level rise, into HTA-FCE calculations. For example, the future coastal retreat rate can be estimated using the following expression (National Research Council, 1987; Leatherman, 1990; Dean 1991) which is derived from the Bruun Rule (see Section 8.3):

$$R_2 = (R_1/S_1)S_2$$

where S_1 = historical rate of sea level rise indicated by tide gauge records

S_2 = projected future rate of sea level rise

R_1 = historical rate of coastal retreat

R_2 = projected future rate of coastal retreat

This assumes that sea level rise is the dominant control on retreat rates and that all other conditions (such as sediment budget) remain constant. It also takes no explicit account of geological controls or physical processes, such as sediment transport, in retreat rates as these aspects are only implicitly considered within the context of historic coastal retreat rates.

The historical trend analysis approach to predictions of future coastal change was used in the *Futurecoast* study (Defra, 2002). Five epochs of Ordnance Survey historical mapping were used to quantify historical trends in mean high and mean low water:

Epoch 1 - First County Series survey published between 1846 and 1901

Epoch 2 - First Revision Country Series survey published between 1888 and 1915

Epoch 3 - Second Revision County Series survey published between 1900 and 1949

Epoch 4 - Third Revision Country Series survey published between 1922 and 1969

Epoch 5 - First National Grid Re-survey published after 1945

Digital data were obtained from Landmark Information Group Ltd and the Ordnance Survey, with pre-1945 maps rectified to National Grid to allow comparison with later mapping. Four positions were recorded for each map year: mean low water (L), mean high water (H), back of beach (B) and top of cliff (C), along pre-defined profile lines with a spacing of one to five kilometres. Profile locations were chosen to be representative an entire length of coast - not necessarily the sites of most active change. Each profile was aligned normal to the coastline. The distance H-B was used as a measure of backshore width and the distance H-L as an indicator of foreshore width.

The OS suggest that an error band of five metres should be used for the Country Series Maps (pre 1945) and a band of 3.5 m for National Grid maps (post-1945). These uncertainties were taken into account using a sum of squares filtering routine. However, as Halcrow did not consult the original maps, their analysis relates to date of publication and not to actual dates of survey. This is an unquantified source of error in the Futurecoast analysis.

Halcrow used three parameters to assess the nature and rates of historical shoreline change and likely future implications for coastal defences: (1) change in position of MHW, (2) change in position of MLW, and (3) change in intertidal slope. Intertidal flattening was considered to reduce shoreline energy and therefore risk of shoreline erosion in most situations. Based on these parameters, a 13-point classification scheme was defined, ranging from -6 (most unhealthy beach trend), through zero (no change) to +6 (most healthy beach trend of foreshore progradation and reduced backshore exposure). The current beach width, defined from the most recent mapping, divided by the mean rate of historical beach width change, was used to define expected future 'life' values for shoreline features, including structures. These were classified as short (under 20 years), short to medium (20-50 years), medium to long (50-100 years), and long (over 100 years). One standard error around the mean rate of change was also used to provide an assessment of uncertainty.

An alternative approach to HTA-FCE was employed by Pye and Blott (2006, 2008a,b). These studies defined the positions (where possible) of mean low water (MLW), mean high water (MHW), and 'back of beach', which in most cases represents a cliff toe, dune toe, or concrete structure. Several different sources of information were used, including several different epochs of Ordnance Survey mapping, aerial photography, LiDAR surveys and ground surveys. A number of difficulties can arise in this process, including the fact that re-surveys of an area of interest may not provide complete coverage, there are differences in data representation on maps of different epochs, and water level positions have to be estimated from LiDAR digital terrain models and ground survey data. There are errors associated with the accuracy of the original surveys, data extraction from the resulting maps, and the data processing methods subsequently used.

8.2.1. Example Applications

8.2.1.1. Alnmouth Bay

The data sources used in the Alnmouth Bay study by Pye and Blott (2008b) are shown in Table 8.2. Selected historical shoreline positions, superimposed on a digital terrain model of the area compiled from LiDAR and synthetic aperture radar (SAR) data, are shown in Figure 8.1. A summary of the absolute changes and rate of erosion/accretion at 16 selected profile locations around the bay is provided in Table 7.2, and a graphical representation of trends at eight of the locations is shown in Figure 8.2. The historical data for the period 1898-1953 were used to predict changes over the period 1953-2000/7; these predictions show generally good agreement with the changes actually observed since 1953 (Table 8.4). Table 8.4 also shows the predicted changes for time periods 20, 50 and 100 years into the future, based on the record of historical change between 1953 and 2000-7.

Table 8.2 Dates and sources of information for historical shoreline and tideline positions at 10 profile locations in Alnmouth Bay, Northumberland.

Profile	Zero point		Epoch 1 (First Edition			Epoch 2 (Second Edition			Epoch 3 (1926 Edition			Epoch 4 (National Grid			Epoch 5 (National Grid			Epoch 6			Epoch 7 (interpolated		
			Six-Inch OS Maps)			Six-Inch OS Maps)			Six-Inch OS Maps)			Six-Inch OS Maps)			1:10,000 OS Maps)			(2002 air photos)			from topographic surveys)		
	Easting	Northin g	Back of Beach	HWM	LWM	Back of Beach	HWM	LWM	Back of Beach	HWM	LWM	Back of Beach	HWM	LWM	Back of Beach	HWM	LWM	Back of Beach	HWM	LWM	Back of Beach	HWM	LWM
P7	425324	611019	1864			1896	1896	1896	1922	1922	1922	1952	c. 1952	1953	1989	1959-73	1963	2002			2007	2007	2007
P7A	425178	610837	1864			1896	1896	1896	1922	1922	1922	1952	c. 1952	1953	1989	1959-73	1963	2002					
P8	425032	610632	1864			1896	1896	1896	1922	1922	1922	1952	c. 1952	1953	1989	1959-73	1963	2002			2007	2007	2007
P8A	424922	610489	1864			1896	1896	1896	1922	1922	1922	1952	c. 1952	1953	1989	1959-73	1963	2002					
P9	424802	610353	1864			1896	1896	1896	1922	1922	1922	1952	c. 1952	1953	1989	1959-73	1963	2002			2007	2007	2006
P10	424845	610036	1864			1896	1896	1896	1922	1922	1922	1952	c. 1952	1953	1989	1959-73	1963	2002			2007	2007	2007
P10A	424905	609811	1864			1896	1896	1896	1922	1922	1922	1952	c. 1952	1953	1989	1958-59	1953	2002					
P10B	424913	609592	1864			1896	1896	1896	1922	1922	1922	1952	c. 1952	1953	1989	1958-59	1953	2002					
P10C	424887	609412	1864			1896	1896	1896	1922	1922	1922	1952	c. 1952	1953	1989	1958-59	1953	2002					
P11	424967	609098	1864			1896	1896	1896	1922	1922	1922	1952	c. 1952	1953	1989	1958-59	1953	2002			2007	2007	2007
P11A	425152	608338	1864			1896	1896	1896	1921-22	1921-22	1921-22	1952	c. 1952	1953	1989	1958-59	1953	2002					
P12	425376	607304	1864			1896	1896	1896	1921-22	1921-22	1921-22	1952	c. 1952	1953	1989	1958-59	1953	2002			2007	2007	2004
P12A	425655	606701	1864			1896	1896	1896	1921-22	1921-22	1921-22	1952	c. 1952	1953	1989	1958-59	1953	2002					
P13	425860	606034	1864			1896	1896	1896	1921-22	1921-22	1921-22	1952	c. 1952	1953	1989	1958-59	1953	2002			2007	2007	2004
P13A	426215	605717	1864			1896	1896	1896	1921-22	1921-22	1921-22	1952	c. 1952	1953	1989	1958-59	1953	2002					
P14	426469	605264	1864			1896	1896	1896	1921-22	1921-22	1921-22	1952	c. 1952	1953	1989	1958-59	1953	2002			2007	2007	2004
		Note	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21

Note 1: The transition between beach and dunes is indicated by the 'High Water Mark of Ordinary Spring Tides' line.
Note 2: The high water mark is labelled 'High Water Mark of Ordinary Spring Tides' line. Mean high water is not shown.
Note 3: The low water mark is indicated by a faint line and the seaward limit of shading, but is not labelled.
Note 4: The transition between beach and dunes is indicated by a dashed line and a change from stippling to dune symbols on a white background.
Note 5: Line is labelled as High Water Mark of Ordinary Tides (HWMOT), and is assumed to be the same as Mean High Water (MHW).
Note 6: Line is labelled as Low Water Mark of Ordinary Tides (LWMOT), and is assumed to be the same as Mean Low Water (MLW).
Note 7: The transition between beach and dunes is indicated by a dashed line or cliff symbol, and a change from stippling to dune symbols on a white background.

Note 8: Line is labelled as High Water Mark of Ordinary Tides (HWMOT), and is assumed to be the same as Mean High Water (MHW).
Note 9: Line is labelled as Low Water Mark of Ordinary Tides (LWMOT), and is assumed to be the same as Mean Low Water (MLW).
Note 10: The transition between beach and dunes is indicated by a dashed line or cliff symbol, and a change from stippling to dune symbols on a white background.
Note 11: Line is labelled as High Water Mark of Medium Tides (HWMMT), and is assumed to be the same as Mean High Water (MHW).
Note 12: Line is labelled as Low Water Mark of Medium Tides (LWMMT), and is assumed to be the same as Mean Low Water (MLW).
Note 13: The transition between beach and dunes is indicated by a change from light grey shading to dune symbols on a white background.
Note 14: Line is labelled as Mean High Water.
Note 15: Line is labelled as Mean Low Water.
Note 16: Line is estimated from the photographs, principally from the transition between exposed sand and vegetation.
Note 17: Recent high water mark at time of surveyed can be indentified from strandline, but MHW cannot be determined as the state of the tide is unknown.
Note 18: Mean low water cannot be determined as the state of the tide at the time of survey is unknown.
Note 19: The transition between beach and dunes can be estimated, where beach profile data exist, from the break in slope.
Note 20: Mean High Water can be interpolated, where beach profile data exist, using the average of MHWS and MHWN data given in Admiralty Tide Tables (1.8 m OD).
Note 21: Mean Low Water can be interpolated, where beach profile data exist, using the average of MLWS and MLWN data given in Admiralty Tide Tables (-1.3 m OD).

Table 8.3 Absolute changes (a) and rates of change (b) in beach width and mean high and low water level positions between 1896 and 2007 at 10 profile locations in Alnmouth Bay, determined from Ordnance Survey maps (published 1898-1977), air photographs (flown 2002) and topographic surveys (2004-07).

(a) Absolute change

Profile	Zero point		Change in dune toe position (m)				Change in MHW position (m)				Change in MLW position (m)				Change in foreshore width (MHW-MLW) (m)				Change in backshore width (dune toe-MHW) (m)			
	Easting	Northing	1896 to 1921-22	1921-22 to 1952	1952 to 2002	1896 to 2002	1896 to 1921-22	1921-22 to 1958-59	1958-59 to 2004-07	1896 to 2004-07	1896 to 1921-22	1921-22 to 1953-63	1953-63 to 2004-07	1896 to 2004-07	1896 to 1921-22	1921-22 to 1953-63	1953-63 to 2004-07	1896 to 2004-07	1896 to 1921-22	1921-22 to 1952-59	1952-59 to 2002-07	1896 to 2002-07
P7	425324	611019	-4	2	-16	-18	3	-18	7	-8	-9	15	-65	-60	-12	33	-72	-51	7	-20	23	10
P7A	425178	610837	-3	-2	-1	-6	0	1			3	135			2	134			4	3		
P8	425032	610632	-15	-1	21	4	8	19	11	38	10	123	-115	18	1	104	-126	-20	24	20	-11	34
P8A	424922	610489	13	-4	19	29	37	32			65	63			28	31			24	36		
P9	424802	610353	14	-2	21	32	47	43	40	131	44	100	272	417	-3	57	232	286	34	46	19	99
P10	424845	610036	15	-9	1	7	-8	28	2	22	28	-30	-9	-11	36	-58	-12	-33	-24	37	1	14
P10A	424905	609811	111	-5	72	178	25	63			40	-28			14	-91			-86	68		
P10B	424913	609592	35	-4	26	57	28	16			39	-31			10	-48			-7	21		
P10C	424887	609412	-4	-4	4	-4	-2	10			31	-7			33	-17			2	14		
P11	424967	609098	4	-5	0	-1	-1	3	-11	-9	26	10	-14	22	28	7	-4	31	-5	8	-11	-8
P11A	425152	608338	5	-3	-4	-2	-5	-2			25	4			30	6			-10	1		
P12	425376	607304	9	-7	16	18	15	3	-22	-4	8	-18	15	6	-7	-21	37	9	6	10	-38	-22
P12A	425655	606701	13	-8	11	16	6	13			2	36			-4	23			-7	21		
P13	425860	606034	23	-4	-1	18	3	9	4	16	17	-25	-20	-28	15	-33	-25	-43	-20	13	5	-3
P13A	426215	605717	-2	-2	145	141	35	-2			1	-15			-34	-13			37	0		
P14	426469	605264	3	-1	20	22	-3	0	72	69	1	6	29	37	4	6	-43	-32	-6	1	52	47

(a) Rates of change

Profile	Zero point		Change in dune toe position (m/yr)				Change in MHW position (m/yr)				Change in MLW position (m/yr)				Change in foreshore width (MHW-MLW) (m/yr)				Change in backshore width (dune toe-MHW) (m/yr)			
	Easting	Northing	1896 to 1921-22	1921-22 to 1952	1952 to 2002	1896 to 2002	1896 to 1921-22	1921-22 to 1958-59	1958-59 to 2004-07	1896 to 2004-07	1896 to 1921-22	1921-22 to 1953-63	1953-63 to 2004-07	1896 to 2004-07	1896 to 1921-22	1921-22 to 1953-63	1953-63 to 2004-07	1896 to 2004-07	1896 to 1921-22	1921-22 to 1952-59	1952-59 to 2002-07	1896 to 2002-07
P7	425324	611019	-0.14	0.07	-0.33	-0.17	0.11	-0.49	0.14	-0.08	-0.35	0.41	-1.36	-0.54	-0.46	0.91	-1.50	-0.47	0.25	-0.59	0.47	0.09
P7A	425178	610837	-0.13	-0.06	-0.02	-0.06	0.02	0.03			0.11	3.74			0.09	3.72			0.15	0.08		
P8	425032	610632	-0.60	-0.05	0.43	0.04	0.32	0.51	0.23	0.35	0.38	3.42	-2.40	0.16	0.06	2.89	-2.63	-0.19	0.92	0.60	-0.22	0.31
P8A	424922	610489	0.50	-0.13	0.39	0.27	1.44	0.86			2.51	1.76			1.06	0.87			0.94	1.05		
P9	424802	610353	0.52	-0.08	0.42	0.30	1.82	1.17	0.86	1.19	1.69	2.79	5.67	3.79	-0.13	1.58	4.84	2.60	1.30	1.34	0.39	0.91
P10	424845	610036	0.59	-0.32	0.03	0.07	-0.32	0.75	0.05	0.20	1.08	-0.84	-0.19	-0.10	1.40	-1.61	-0.24	-0.30	-0.91	1.09	0.02	0.13
P10A	424905	609811	4.27	-0.16	1.44	1.68	0.98	1.70			1.52	-0.78			0.54	-2.53			-3.29	2.00		
P10B	424913	609592	1.36	-0.14	0.52	0.54	1.09	0.45			1.49	-0.87			0.40	-1.33			-0.27	0.61		
P10C	424887	609412	-0.17	-0.14	0.09	-0.04	-0.08	0.27			1.18	-0.20			1.26	-0.47			0.09	0.42		
P11	424967	609098	0.15	-0.17	0.01	-0.01	-0.04	0.09	-0.23	-0.08	1.02	0.28	-0.30	0.20	1.06	0.19	-0.07	0.28	-0.19	0.24	-0.23	-0.07
P11A	425152	608338	0.18	-0.11	-0.07	-0.02	-0.20	-0.05			0.97	0.12			1.17	0.17			-0.38	0.04		
P12	425376	607304	0.35	-0.22	0.32	0.17	0.59	0.09	-0.47	-0.03	0.31	-0.49	0.32	0.05	-0.28	-0.57	0.78	0.09	0.24	0.29	-0.77	-0.20
P12A	425655	606701	0.49	-0.26	0.22	0.15	0.23	0.36			0.07	1.01			-0.16	0.64			-0.27	0.62		
P13	425860	606034	0.89	-0.13	-0.02	0.17	0.11	0.23	0.09	0.14	0.67	-0.68	-0.42	-0.25	0.56	-0.92	-0.51	-0.39	-0.78	0.37	0.10	-0.02
P13A	426215	605717	-0.06	-0.07	2.90	1.33	1.35	-0.06			0.03	-0.42			-1.32	-0.35			1.41	-0.01		
P14	426469	605264	0.11	-0.04	0.40	0.21	-0.13	0.00	1.54	0.63	0.04	0.17	0.61	0.33	0.17	0.17	-0.89	-0.29	-0.24	0.03	1.07	0.43

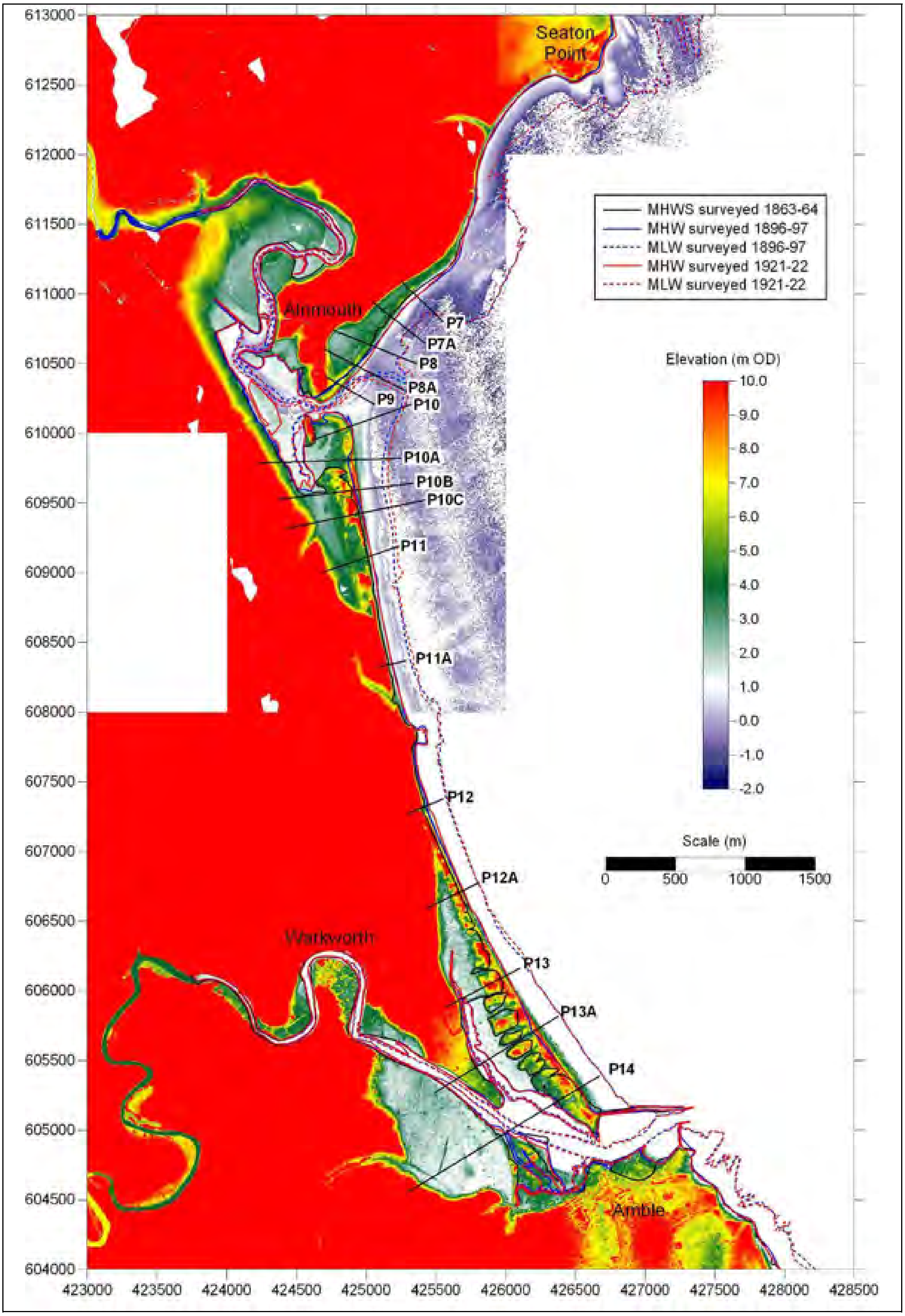


Figure 8.1 Digital terrain model of Alnmouth Bay (generated from LiDAR data flown February 2000 north of 508000 and SAR data south of 608000), locations of beach profiles, and historical shoreline positions digitised from Ordnance Survey maps.

Table 8.4 Predictions of position of 'back of beach': (a) in 2002 (based on the trend 1896-1952); and (b) in 2025, 2055 and 2105 (based on the trend 1952-2002).

Positions are relative to a point 500 metres landward of the profile marker.

(a) Predictions for 2002

Profile	Position in 1896 (m)	Position in 1952 (m)	Trend for 1896-1952 (m/year)	Prediction for 2002 (m)	Observed position in 2002 (m)	Difference between observation and prediction (m)
P7	527	525	-0.03	523	509	-15
P7A	513	508	-0.09	502	507	5
P8	507	490	-0.30	471	512	40
P8A	486	495	0.16	505	514	9
P9	485	500	0.26	516	521	5
P10	519	525	0.11	532	527	-5
P10A	338	444	1.89	563	516	-47
P10B	481	513	0.56	548	539	-9
P10C	561	552	-0.15	543	557	14
P11	546	545	-0.02	544	546	2
P11A	505	507	0.03	508	503	-5
P12	522	524	0.04	527	540	13
P12A	511	516	0.09	521	527	5
P13	626	645	0.34	666	644	-22
P13A	373	369	-0.07	365	514	149
P14	549	550	0.03	553	570	18

(b) Predictions for 2025, 2055 and 2105

Profile	Position in 1952 (m)	Position in 2002 (m)	Trend for 1952-2002 (m/year)	Prediction for 2025 (m)	Prediction for 2055 (m)	Prediction for 2105 (m)
P7	525	509	-0.33	501	491	475
P7A	508	507	-0.02	507	506	505
P8	490	512	0.43	521	534	555
P8A	495	514	0.39	523	535	554
P9	500	521	0.42	530	543	564
P10	525	527	0.03	527	528	530
P10A	444	516	1.44	549	592	664
P10B	513	539	0.52	551	567	593
P10C	552	557	0.09	559	562	566
P11	545	546	0.01	546	546	547
P11A	507	503	-0.07	501	499	495
P12	524	540	0.32	548	557	573
P12A	516	527	0.22	532	538	549
P13	645	644	-0.02	644	643	642
P13A	369	514	2.90	581	668	813
P14	550	570	0.40	579	591	611

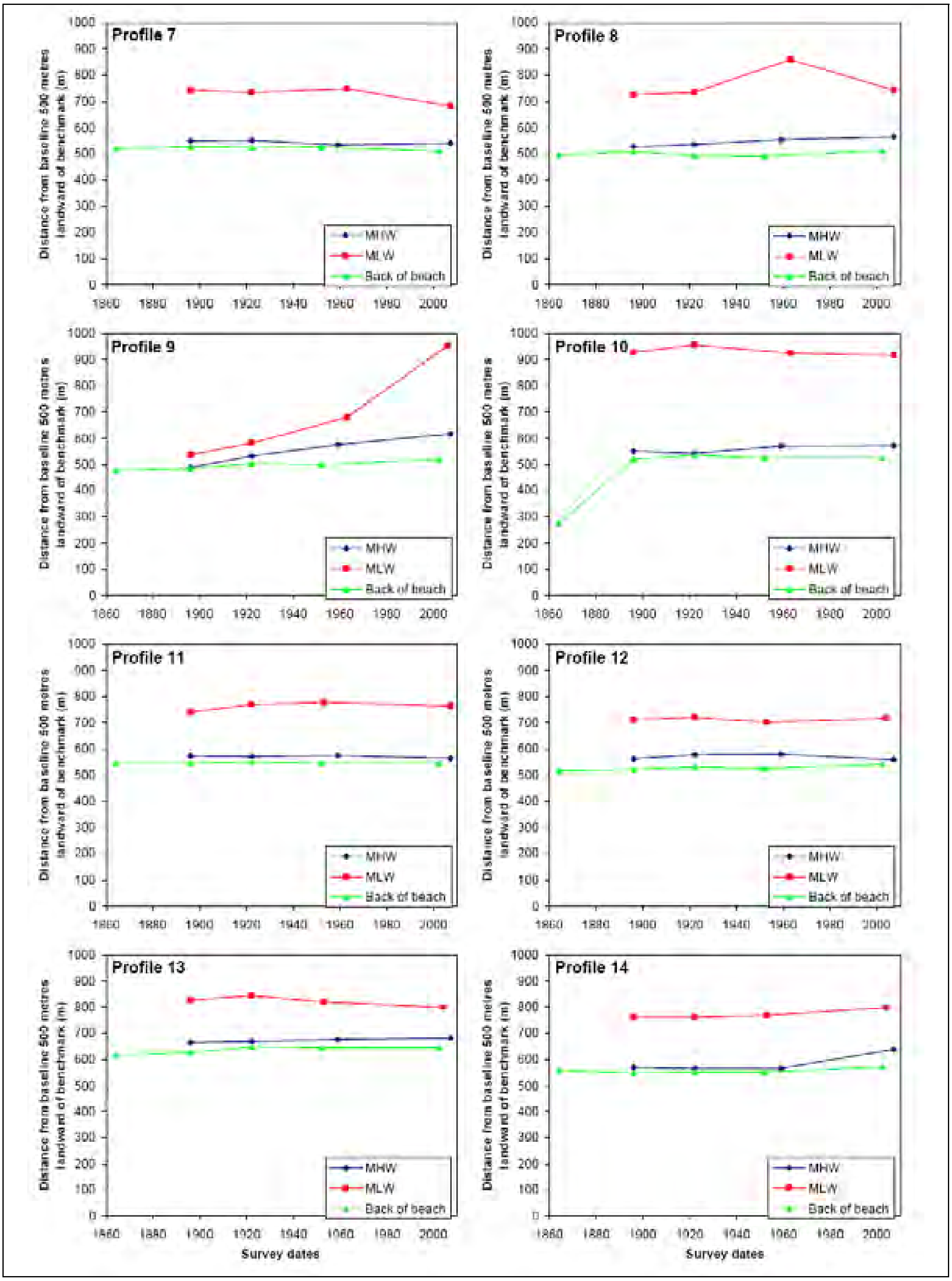


Figure 8.2 Landward and seaward movement of the positions of MHW, MLW and the back of beach in Alnmouth Bay, taken from historical Ordnance Survey maps.

8.3. The Bruun Rule and related models

Bruun (1954) proposed that the shoreface tends to maintain the same slope for a given water depth and wave exposure, and that there is a tendency for natural processes to establish an equilibrium beach and nearshore profile which provides a balance between the tendency of wave action to move sediment on shore and the tendency of gravity and currents to move sediment offshore. This concept was further developed (Bruun, 1962) to predict the response of an erodible soft sediment shore to a rise in sea level. According to this concept, as sea level rises the upper shoreface is eroded and sediment is deposited on the lower shoreface in order to maintain an equilibrium profile. The model was developed for a simple two-dimensional situation with no alongshore sediment transport. It was also assumed that all sediment eroded from the upper shoreface was transported in a seawards direction. The basic relationship between sea level rise (S) and the associated distance of shoreline retreat (R) is expressed by:

$$R = S(L/H)$$

where L = length of the active profile, defined as the horizontal distance between the shoreface (at the height of mean sea level) and the depth of closure (the limit of onshore-offshore transport)

H = height of the active profile defined as the height difference between mean sea level and the depth of closure.

Bruun (1962) justified his formulation using approximate calculations of shoreline retreat rate on several parts of the Florida coast. General support for the model was subsequently provided by a number of laboratory and field studies (Schwartz, 1965, 1967; Dubois, 1975, 1976, 1977; Rosen, 1978).

A number of modifications were also proposed (Weggel, 1979; Hands, 1983), including the incorporation of the height of the berm (B) as an addition to the closure depth to give the total effective height of the active profile:

$$R = S(L/(B + H))$$

The SCOR Working Group *et al*. (1991) pointed out that the basic Bruun Rule equation can also be expressed as:

$$R = S(1/\tan\theta)$$

where $\tan \theta$ = is the average slope of the nearshore across the cross shore width, L, given by (B+ H)/L.

Since many sandy nearshore profiles have average slopes of 0.1 to 0.2, this equation predicts a landward movement of the shoreline in the range 50S to 100S (Komar *et al*., 1991).

The term B has also been used to represent the height of dunes and cliffs behind the beach, although R is likely to be smaller than expected using the Bruun Rule where B is large relative to H, that is, where large amounts of sediment are added to the nearshore zone as a result of high dune or cliff erosion.

Hands (1983) recognized that the composition of back-beach sediments can have a significant effect on the response of the nearshore profile to sea level rise. For example, in situations where the back-beach area contains fine grained sediments (such as soft cliffs composed of glacial till, or saltmarsh or mudflat deposits beneath a sand beach veneer), a significant proportion of the eroded material may be transported outside the area in suspension. This factor can be taken into account using the following modified formula:

$$R = S[L/P(B+H)]$$

where P = proportion of sediment eroded which is sufficiently coarse to remain within the equilibrium shore profile (such as percentage of sand and gravel)

An alternative approach is to assume that historical erosion rates take into account the effects of longshore variations in sediment budget. If it is also assumed that future changes in sediment budget will be small in the face of sea level rise; a further modified equation can be used to predict future recession rates (Dean 1991):

$$R_2 = R_1 + (S_2 - S_1).\ L/P(B+H)$$

where R_1 = historical recession rate
R_2 = future recession rate
S^1 = historical rate of sea level rise
S_2 = estimated future rate of sea level rise

However, the assumption of little or no change in sediment budget may not be valid, for example if there is an increase in cliff erosion rates at the updrift end of a sediment cell as a result of the rise in sea level.

Dean and Maurmeyer (1983) proposed a modified version of the rule for use on barrier island and lagoon coastlines where sediment may be transported landwards by washover, as well as seawards:

$$R = \frac{S(L + W + L_{lg})}{(B_o + h_{bo}) - (B_L + h_{bl})}$$

where

W = width of barrier island, which is assumed to remain constant in time but accrete upwards with sea level rise;

L_{lg} = length of active profile of back-barrier lagoon;

Bo = berm elevation on ocean side;

h_{bo} = breaker depth on ocean side;

B_L = berm elevation on lagoon side; and

h_{bl} = breaker depth on lagoon side.

This reduces to Bruun's equation for the case of no deposition on the barrier or in the lagoon (for W, L_{lg}, B_L and h_{bl} = 0).

Bruun (1983, 1988) recognized that the Bruun Rule faces a number of difficulties which limit its application, notably the specification of representative values of L and H, and the existence of sediment inputs and outs in the alongshore dimension. Komar *et al*. (1991) maintained that a full consideration of total sediment budget within any coastal cell or sub-cell is required to accurately predict changes at any point. However, detailed sediment transport and sediment budget information is not available in many situations. Stive (2004) and Stive *et al.* (2008) used the sediment-transport balance equation for a fixed spatial volume, including cross-shore and alongshore sediment transports, sinks and sources to derive the following equation for rate of shoreline change:

$$R.H = -S.L - (q_{x,sea} - q_{x,dune}) - \frac{\partial Q_y}{\partial y} - s$$

where:

$q_{x,sea}$ = cross-shore sediment transport rate between beach and sea;

$q_{x,dune}$ = cross-shore sediment transport rate between beach and dune;

Q_y = longshore transport rate integrated over L;

y = longshore coordinate;

s = sinks and sources.

This expression is similar to the Dean and Maurmeyer (1983) equation. It determines shoreline change rate from the balance between the accommodation space generated by sea level rise (the first term on the right hand side of the equation) and the sediment availability (the last three terms on the right hand side of the equation). Stive (2004) contends that when rates of sea level rise are low (near stillstand conditions) as today, the Bruun effect is operational but is often overwhelmed by cross-shore and longshore gradients, sources and sinks.

Pilkey *et al*. (1993) argued that there is no scientific basis for the concepts of equilibrium nearshore profile, closure depth, conservation of sediment and consequently for the Bruun Rule. As emphasised by Stive (2004), coastal response to sea level rise is a complex issue involving multiple feedback mechanisms which are not accounted for by the simple profile translation model. Cooper and Pilkey (2004) have gone so far as to propose that, despite continuing claims regarding the validity of the Bruun Rule (see Leatherman *et al*., 2000; Zhang *et al*., 2004), it should now be abandoned.

Stive (2004) and Stive *et al.* (2008) have, however, shown how to include the Bruun Rule (for the cross-shore preservation of sediment) into an overall sediment balance model. In its simplest case this would be the combination of the Bruun Rule with a one-line model (see Section 8.5). On balance it no longer seems appropriate to use the original version of the Bruun Rule without proper consideration of the total sediment budget.

The modified Bruun Rule could be incorporated into a large-scale long-term system model that used coastal system mapping (Chapter 6) to define the relevant sediment exchanges. This would be an advance on the modelling tools presently available. At its simplest level this would amount to incorporating the Bruun approach for the preservation of sediment in the cross-shore, with a one-line modelling approach for the conservation of sediment in the longshore. Additional modules for other gains and losses could be added later, as appropriate. Stive *et al.* (2008), Cowell *et al.* (2003a, b) demonstrate how such an approach could be applied conceptually to a coastal tract.

Davidson-Arnott (2005) described a modified version of the Bruun model for use on dune coasts, where aeolian processes are important in bringing about landward transfer of sand eroded from the shoreface (analogous to Dean and Maurmeyer's 1983 adaptation of the Bruun Rule for the barrier island/lagoon coasts). If sufficient sand is blown landward by the wind during shoreline retreat, the frontal dune may maintain an equilibrium profile as it moves landwards and upwards (Davidson-Arnott, 2005). Whether or not this occurs will depend on the balance of beach and frontal dune sediment budgets, as discussed by Psuty (1988). Davidson-Arnott did not attempt to mathematically formalise or test this conceptual model.

A number of similar conceptual models of beach-dune system response to rising sea level have been discussed by Pye *et al*., (2007). Depending of the rate of sea level rise, the incidence of storms which cause wave erosion of the beach and frontal dunes, the sand size and the available wind energy, aeolian processes may be able to transport sufficient sand landwards to maintain a constant frontal dune profile, as postulated by Davidson-Arnott (2005; this was termed the 'equilibrium rollover model' by Pye *et al*. (2007). However, in situations of low wind energy or coarse sand, dune volume may diminish as sea level rises and the shore moves landwards ('dissipation rollover'), leading eventually to washover or breaching of the dunes ('washover rollover'). In areas of very high wind energy, and where the shore is backed by a considerable width of sandy sediments, a large proportion of sediment eroded from the beach may be transported landwards and the dunes may increase their sediment volume over time ('snowball rollover'). Equilibrium and snowball rollover are likely to be associated with rapid rates of shoreline recession, since insufficient sediment is moved seawards to maintain an equilibrium nearshore profile.

Despite the obvious assumptions and limitations of the Bruun Rule, its relative simplicity and capacity for quantitative prediction make it attractive and the method can provide a useful yardstick against which to compare projections made using other methods. Bray and Hooke (1997) found the modified Bruun model, including P and B terms, to be useful in predicting soft cliff erosion rates in southern England, although they pointed out that there is likely to be a lagged response to rapid changes in sea level and that spatial variations in response should be expected due to local factors which influence cliff sensitivity. The uncertainties and limitations associated with any projections made using the Bruun model should always be borne in mind. In is rarely sufficient to make projections of future shoreline positions in plan based on cross-sectional for one shoreline position. Calculations should be made for a series of profile positions, the number and spacing of points being dependent on the length and type of shore under consideration.

8.3.1. Example applications

8.3.1.1. Cardigan Bay

Pye and Saye (2005) and Saye *et al*. (2007) used the simple version of the Bruun Rule alongside HTA-FCE and EGA to predict likely future loss of dune habitats at 13 SAC and SSSI localities in Wales, including the Ynyslas, Aberdyfi, Morfa Dyffryn and Morfa Harlech dune systems in Cardigan Bay (Figure 8.3). At each locality, the length of the active shore profile was defined at approximately one-km intervals as the distance between MHWS tide level and the -10m Chart Datum (CD) depth contour shown on the most recent Admiralty chart. However, in some bays and estuary mouth areas this was not possible, either because the shore-normal profiles did not cross the -10 m isobath, or because complex series of banks and channel were present. In these situations the -5 m or -2 m isobaths were used instead. The vertical distance between MHWS and the assumed closure depth was used to define the depth of the active shore profile. For the purposes of the calculations, a sea level rise of 0.41 m by 2100 was considered (based on an average of the UKCIP02 low emissions and high emissions scenarios, corrected for land movements in West Wales (Hulme *et al*., 2002). The simple Bruun model was found to give sensible estimates of future shoreline recession in most areas, although anomalous predictions were made in some locations (for example where the predicted shoreline position lay landward of a hard rock cliff line).

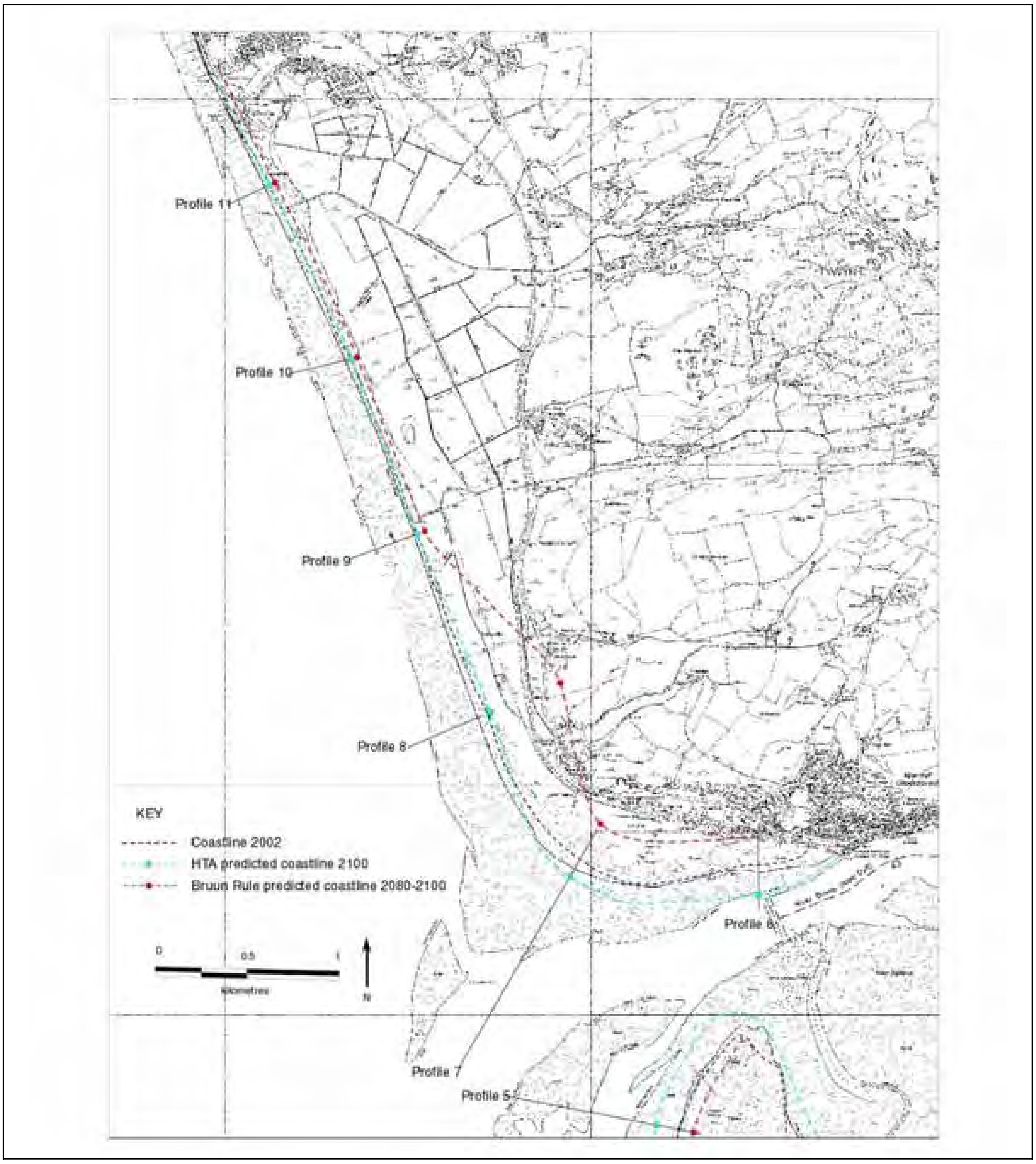


Figure 8.3 Predicted coastline positions by 2080-2100 at Aberdovey based on (a) extrapolation of historical trend analysis (HTA) and (b) the Bruun Rule using 0.41 m sea level rise. The location of the shore normal profiles used to calculate width changes are also shown. After Pye and Saye (2005).

8.3.1.2. Alnmouth Bay

Pye and Blott (2008b) used five different methods to estimate future shoreline change in Almouth Bay, including the simple version of the Bruun model used by Pye and Saye (2005), the modified Bruun Rule proposed by Hands (1983), and the combined Bruun Rule-recession model described by Komar *et al.*. (1991). The length of the active profile was defined as the distance between MHWS and the 10 m CD depth contour as shown on Admiralty Chart 156 (Hydrographer of the Navy, 2002) and the depth of the active profile defined as the height difference between MHW and the -10m CD isobath (H = 15m). Values for the height of the frontal dunes behind the beach at 16 profile locations were obtained from 2007 field survey data and from LiDAR and SAR data flown in 2000. A value of one was assumed for the P parameter since the back-beach sediments at the profiles under consideration consist entirely of dune sand (although hard rock outcrops occur behind the dunes in some places and at Birling Carrs).

Estimates of historical sea level change (S1) were derived from the North Shields Class A tide gauge for the period 1896-2007 (yielding a linear trend of 1.90 mm/year). Model runs were carried out using three estimates of future sea level rise, 3 mm/year, 6 mm/year and 9 mm/year. The results are shown in Table 8.5. The simple Bruun model indicated retreat at all profile locations with an overall range of retreat rates of 38 m/year to 1.53 m/year. The modified Bruun model also indicated retreat at all sites but with lower average rates (0.23 to 1.22 m/year). The combined Bruun Rule-historical recession model (Komar *et al*., 1991) predicted a more varied picture, with shoreline recession along the Alnmouth Golf Club frontage and along the northern Birling Links frontage, but some further accretion at the mouth of the Aln estuary and immediately to the north of Warkworth Harbour. The model also predicted more widespread and more rapid shoreline recession with higher rates of sea level rise.

Table 8.5 Predictions of future shoreline change in Alnmouth Bay, using three versions of the Bruun model.

(a) Simple Bruun Rule (Bruun, 1962) [R = S(L/H)]								
Profile	L	H	S	$R_{(3.0)}$	S	$R_{(6.0)}$	S	$R_{(9.0)}$
	(m)	(m)	(mm/yr)	(m/yr)	(mm/yr)	(m/yr)	(mm/yr)	(m/yr)
P7	2100	15.0	3.0	-0.42	6.0	-0.84	9.0	-1.26
P7A	2100	15.0	3.0	-0.42	6.0	-0.84	9.0	-1.26
P8	2250	15.0	3.0	-0.45	6.0	-0.90	9.0	-1.35
P8A	2400	15.0	3.0	-0.48	6.0	-0.96	9.0	-1.44
P9	2550	15.0	3.0	-0.51	6.0	-1.02	9.0	-1.53
P10	2250	15.0	3.0	-0.45	6.0	-0.90	9.0	-1.35
P10A	2175	15.0	3.0	-0.44	6.0	-0.87	9.0	-1.31
P10B	2100	15.0	3.0	-0.42	6.0	-0.84	9.0	-1.26
P10C	2100	15.0	3.0	-0.42	6.0	-0.84	9.0	-1.26
P11	2100	15.0	3.0	-0.42	6.0	-0.84	9.0	-1.26
P11A	2025	15.0	3.0	-0.41	6.0	-0.81	9.0	-1.22
P12	1950	15.0	3.0	-0.39	6.0	-0.78	9.0	-1.17
P12A	1950	15.0	3.0	-0.39	6.0	-0.78	9.0	-1.17
P13	1875	15.0	3.0	-0.38	6.0	-0.75	9.0	-1.13
P13A	1875	15.0	3.0	-0.38	6.0	-0.75	9.0	-1.13
P14	1875	15.0	3.0	-0.38	6.0	-0.75	9.0	-1.13

(b) Modified Bruun Rule (Hands, 1983) [R = S(L/(B+H)]									
Profile	L	B	H	S	$R_{(3.0)}$	S	$R_{(6.0)}$	S	$R_{(9.0)}$
	(m)	(m)	(m)	(mm/yr)	(m/yr)	(mm/yr)	(m/yr)	(mm/yr)	(m/yr)
P7	2100	3.6	15.0	3.0	-0.34	6.0	-0.68	9.0	-1.02
P7A	2100	2.5	15.0	3.0	-0.36	6.0	-0.72	9.0	-1.08
P8	2250	3.0	15.0	3.0	-0.38	6.0	-0.75	9.0	-1.13
P8A	2400	3.4	15.0	3.0	-0.39	6.0	-0.78	9.0	-1.17
P9	2550	5.0	15.0	3.0	-0.38	6.0	-0.77	9.0	-1.15
P10	2250	6.2	15.0	3.0	-0.32	6.0	-0.64	9.0	-0.96
P10A	2175	4.5	15.0	3.0	-0.33	6.0	-0.67	9.0	-1.00
P10B	2100	8.6	15.0	3.0	-0.27	6.0	-0.53	9.0	-0.80
P10C	2100	12.8	15.0	3.0	-0.23	6.0	-0.45	9.0	-0.68
P11	2100	6.9	15.0	3.0	-0.29	6.0	-0.58	9.0	-0.86
P11A	2025	0.0	15.0	3.0	-0.41	6.0	-0.81	9.0	-1.22
P12	1950	7.0	15.0	3.0	-0.27	6.0	-0.53	9.0	-0.80
P12A	1950	9.7	15.0	3.0	-0.24	6.0	-0.47	9.0	-0.71
P13	1875	9.1	15.0	3.0	-0.23	6.0	-0.47	9.0	-0.70
P13A	1875	8.3	15.0	3.0	-0.24	6.0	-0.48	9.0	-0.72
P14	1875	7.1	15.0	3.0	-0.25	6.0	-0.51	9.0	-0.76

(c) Combined Brunn-Historical Recession Model (Komar *et al.*. 1991) [$R_2 = (R_1 + (S_2\text{-}S_1).L/P(B+H)$]												
Profile	L	B	H	P	$R_{1\ (1896\text{-}2002)}$	$S_{1\ (1896\text{-}2007)}$	S_2	$R_{2\ (3.0)}$	S_2	$R_{2\ (6.0)}$	S_2	$R_{2\ (9.0)}$
	(m)	(m)	(m)		(m/yr)	(mm/yr)	(mm/yr)	(m/yr)	(mm/yr)	(m/yr)	(mm/yr)	(m/yr)
P7	2100	3.6	15.0	1.0	-0.18	1.90	3.00	-0.30	6.00	-0.64	9.00	-0.98
P7A	2100	2.5	15.0	1.0	-0.06	1.90	3.00	-0.19	6.00	-0.55	9.00	-0.91
P8	2250	3.0	15.0	1.0	0.04	1.90	3.00	-0.09	6.00	-0.47	9.00	-0.84
P8A	2400	3.4	15.0	1.0	0.28	1.90	3.00	0.14	6.00	-0.25	9.00	-0.65
P9	2550	5.0	15.0	1.0	0.32	1.90	3.00	0.18	6.00	-0.21	9.00	-0.59
P10	2250	6.2	15.0	1.0	0.07	1.90	3.00	-0.04	6.00	-0.36	9.00	-0.68
P10A	2175	4.5	15.0	1.0	1.75	1.90	3.00	1.62	6.00	1.29	9.00	0.95
P10B	2100	8.6	15.0	1.0	0.56	1.90	3.00	0.47	6.00	0.20	9.00	-0.07
P10C	2100	12.8	15.0	1.0	-0.04	1.90	3.00	-0.12	6.00	-0.35	9.00	-0.58
P11	2100	6.9	15.0	1.0	-0.01	1.90	3.00	-0.11	6.00	-0.40	9.00	-0.69
P11A	2025	0.0	15.0	1.0	-0.02	1.90	3.00	-0.17	6.00	-0.58	9.00	-0.98
P12	1950	7.0	15.0	1.0	0.18	1.90	3.00	0.08	6.00	-0.18	9.00	-0.45
P12A	1950	9.7	15.0	1.0	0.16	1.90	3.00	0.07	6.00	-0.17	9.00	-0.40
P13	1875	9.1	15.0	1.0	0.18	1.90	3.00	0.09	6.00	-0.14	9.00	-0.37
P13A	1875	8.3	15.0	1.0	1.39	1.90	3.00	1.30	6.00	1.06	9.00	0.81
P14	1875	7.1	15.0	1.0	0.21	1.90	3.00	0.12	6.00	-0.13	9.00	-0.39

8.4. Equilibrium bay shape

Rocky coasts with headland-bay beaches represent about 50 per cent of the world's coastline (Short and Masselink, 1999). The term headland-bay beach has been used to define a sandy shoreline bounded by rocky outcrops or headlands, either natural or man-made, where the shoreline assumes some form of curvature. These beaches have received various names in the past, such as: zeta curved bays (Halligan, 1904), half-heart shaped bays (Silvester, 1960), logarithmic spiral beaches (Yasso, 1965), crenulate shaped bays (Silvester and Ho, 1972; Gonzalez and Medina, 2001), curved or hooked beaches (Rea and Komar, 1975), pocket beaches, (Silvester *et al*., 1980) and embayed beaches (Short and Masselink, 1999). These headland-bay beaches are common features of shorelines that experience incident waves from a predominant direction with the presence of at least one natural or artificial fixed point, leading to diffraction of incoming waves. It is widely known that the plan form of a beach is governed mainly by the wave-induced currents; with headland-bay beaches the waves are diffracted in such a way as to break simultaneously around the periphery of the bay once an equilibrium planform shape has been established. Wave heights and periods are not included in expressions of equilibrium bay shape, although they were once investigated but found to be insignificant for bayed beaches in static equilibrium (Hsu and Evans, 1989).

Parameters affecting the planform of bayed beaches include dimensions of headland, beach orientation, bathymetric configuration, presence of offshore obstacles (rocky outcrops, small islands), coastal structures and sediment supply. In most cases, bayed beaches with a single headland have asymmetric shapes characterised by a curved shadow zone, a gently curved transitional zone and a relatively straight tangential zone at the “downcoast end” (Figure 8.4), as stated in Silvester and Hsu (1997) and Short and Masselink (1999). Bayed beaches bounded by two headlands have a distinctive double curvature with the “downcoast end” in the middle of its periphery, while bays with offshore obstacles or bathymetric discontinuities have semi-predictable discontinuities in their planform (Hsu *et al*., 2004).

Several empirical bay shape equations have been derived to fit curves to the shoreline planform of headland-bay beaches. Most of these equations have tended to define geometry of the (often large scale) bay without the input of wave direction and the headland position. The static form of an equilibrium bay can be predicted by the application of empirical relationships based on logarithmic, parabolic and hyperbolic formulae. However only the parabolic shape equation (PBSE) of Hsu and Evans (1989) directly links the change of shoreline to the point of diffraction, which is a fixed point that physically exists (either a natural headland or a coastal structure). Because the physical location of the wave diffraction point is used as the centre of the co-ordinate system for the parabolic bay shape equation, the effect of its relocation, by various engineering means, can be easily assessed using the new diffraction point. PBSE is currently the most widely adopted method for the assessment of headland-bay beach stability and the effects of coastal structures on headland-bay beaches.

The PBSE is a second order polynomial equation developed by Hsu and Evans (1989) from fitting the planform of 27 mixed cases of prototype and model bays believed to be in *static equilibrium* (with no nett littoral drift).

$$\frac{R}{R_\beta} = C_0 + C_1\left(\frac{\beta}{\theta}\right) + C_2\left(\frac{\beta}{\theta}\right)^2$$

Where:

R_β = Control line length

R = Radius to a point along the curve at an angle θ

β = Wave obliquity

C = Constants generated by regression analysis to fit the peripheries of the 27 prototype and model bays

θ = Angle between wave crest and radius to any point on the bay periphery in static equilibrium

The two basic parameters are the reference wave obliquity *β* and *control line* length R_β (Figure 8.4). The variable *β* is a reference angle of wave obliquity or the angle between the incident wave crest (assumed linear) and the *control line*, joining the upcoast diffraction point to a point on the near straight beach called the downcoast diffraction point. The radius R to any point on the bay periphery in static equilibrium is angled θ from the same wave crest line radiating from the point of upcoast wave diffraction point. The three C constants, generated by regression analysis to fit the peripheries of the 27 prototype and model bays, differ with reference angle β (Hsu and Evans, 1989).

8.4.1. Example applications

Figure 8.4 (Kemp and Bast, 2008) shows an equilibrium bay predicted using the parabolic shape PDSE equation quoted above. Figure 8.4 shows the upcoast (red) and downcoast (blue) diffraction points selected by the user, who has also input the dominant wave crest direction (straight line extending 105° from the upcoast point). The model has plotted the (straight) control line and the resulting parabolic equilibrium bay shape that links the updrift and downdrift control points.

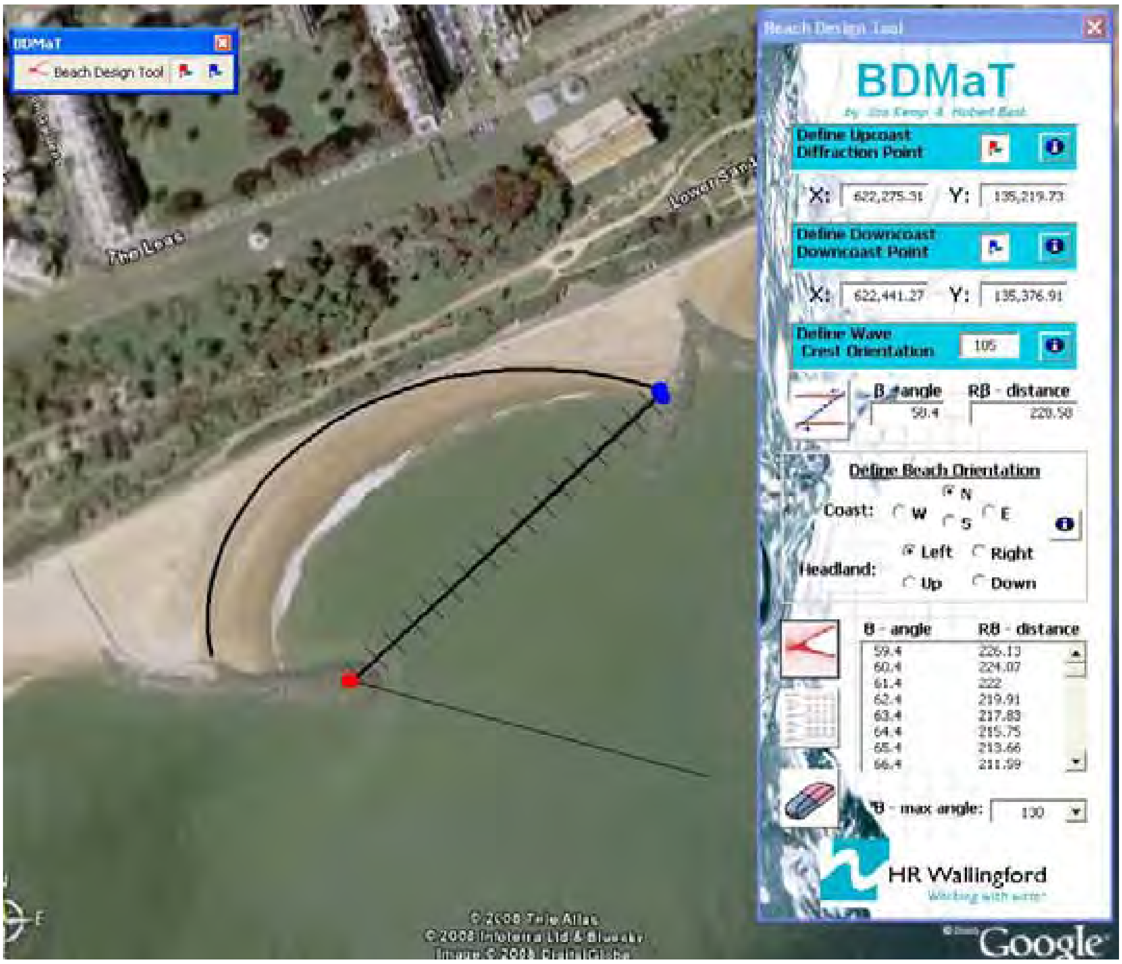


Figure 8.4 Equilibrium bay prediction using parabolic shape equation.

8.5. One-line models

One-line models predict changes to beaches caused by wave action over longshore distances of kilometres and timescales of years to decades. The cross-shore beach profile is usually assumed to be constant, unchanging with time, so that changes in the beach morphology can be described uniquely in terms of the shoreline position – hence the name 'one-line model'.

One-line numerical models originated from analytical solutions to the diffusion equation for the small amplitude departures from a rectilinear coastline (Pelnard-Considère, 1956, Bakker, Klein Breteler and Roos, 1970, Falqués, 2003). There has been revived academic interest in the use of analytical solutions in recent years (Falqués, 2003, Murray and Ashton, 2003, Reeve, 2006) but most one-line modelling for coastal management is likely to be performed using numerical models (see Hanson and Kraus, 1989, Ozasa and Brampton, 1980) due to their flexibility in modelling realistic, non-idealised coastlines.

The initial beach is defined by digitising the representative contour at the required start time. This information is usually taken from a survey of the site, or simply from an appropriate nautical chart or map. Starting from the initial shoreline, the model evaluates successive shoreline positions, at discrete time intervals, at locations along the shore separated by discrete distances alongshore (**Error! Reference source not found.**.5). Each length of coast ∂x is referred to as a beach section or compartment. At the start of the modelling process, various other parameters describing the beach also need to be defined, for example the beach slope at each section. Although these beach parameters can vary along the beach, in order to model the prototype conditions realistically, once they are set up, they are assumed to remain constant with time.

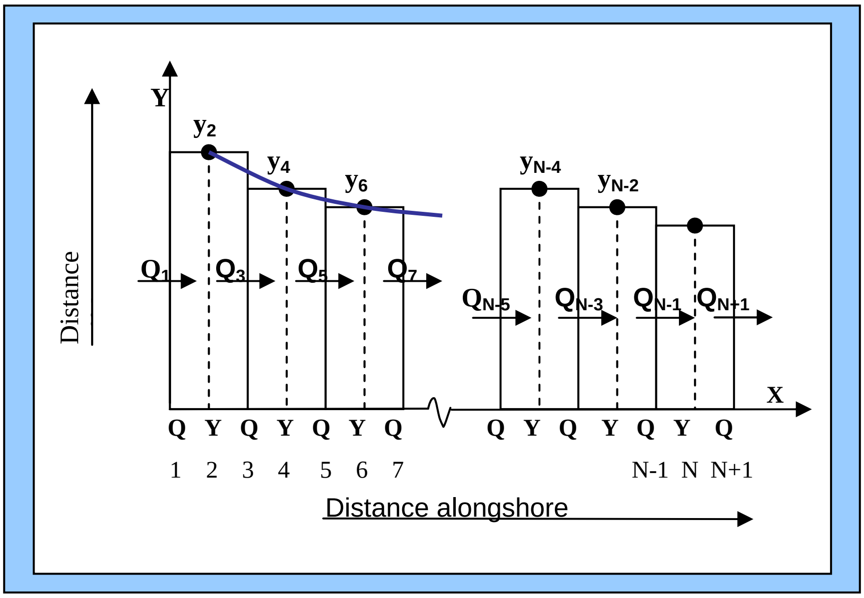


Figure 8.5 Generic one-line model set-up.

Wave input to the model is defined by specifying wave conditions at an offshore point in a known water depth. Waves are transformed to each beach compartment where the longshore sediment transport, Q_n, is calculated. Commonly this calculation is performed using a bulk longshore drift equation, such as the CERC equation, which may be modified to take into account longshore variations in wave height. Alternatively the longshore transport may be calculated using a cross-shore profile model.

Numerical one-line models can include the effects of structures by empirical representations of their effects. For example, wave transmission through structures, bypassing of groynes and breakwaters and effects of detached offshore breakwaters and seawalls on sediment transport have all been included in one-line models.

The model also takes into account any user-defined renourishment or removal (to represent beach recycling for example). A sediment budget algorithm is then used along the beach to ensure continuity of material and shoreline positions are moved to reflect the new volume of sediment in each beach compartment. The process is repeated until the run time specified by the user elapses. Although one-line models can be used in comparative applications to evaluate the performance of different schemes, model calibration and validation with historic shoreline positions is required to demonstrate the quality of predictions.

Sometimes the one-line model is extended to model a number of different contours. These models are known as N-line models, but they are relatively uncommon compared to one-line models.

8.5.1. Example application

Numerical modelling of beach plan shape changes has been undertaken to select a set of beach control structures for construction between Sandbanks and Branksome Dene Chine in Poole. The study frontage is shown in **Error! Reference source not found.**.6, which highlights a rock groyne (dark red) and existing wooden groynes (brown) as well as the proposed new groynes (black). The beaches along this part of the shoreline of Poole Bay have recently been improved by a recharge scheme. The main purpose of these improvements is to boost the standard of coastal defence, although the strategy will also help maintain and enhance the amenity, tourism and recreational values of Poole Borough's coastline.

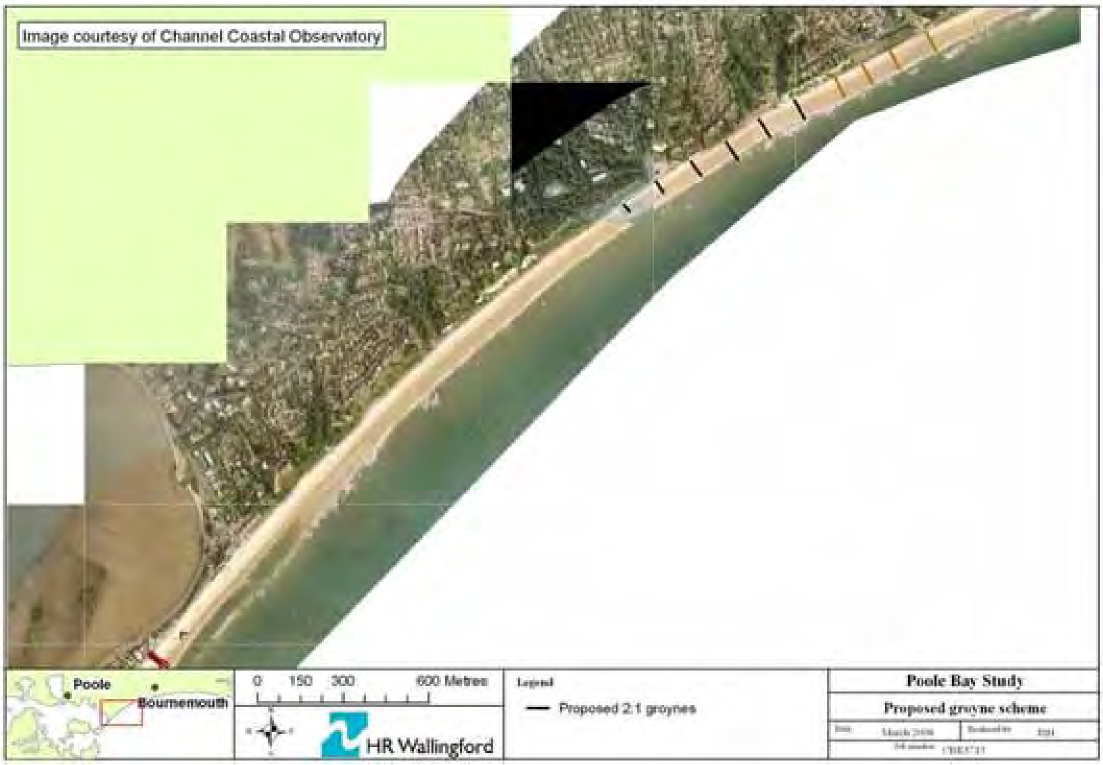


Figure 8.6 Location of proposed groynes at Poole.

The one-line model Beachplan was run to model the baseline case (without new structures) and a number of options. The minimum, mean and maximum shoreline positions from Year 4 of the model run with new groynes are presented in **Error! Reference source not found.**.7. In Year 4, the minimum, mean and maximum beach positions are all close together west of the structures (chainage greater than 4,300 m) generally with less than 10 m range in beach width, indicating that there is little variability throughout the year. These positions diverge more within the groyne bays, as would be expected, although the minimum beach positions stay seaward of the seawall over the whole Poole frontage. Though the net drift is strongly eastward, areas within the groyne bays where the minimum beach positions are worst are just at the western side of the groyne, indicating that erosion still takes place during episodes of reverse drift. Beach positions have remained close to the initial shoreline throughout, apart from where some smoothing of irregularities in the original shoreline has occurred.

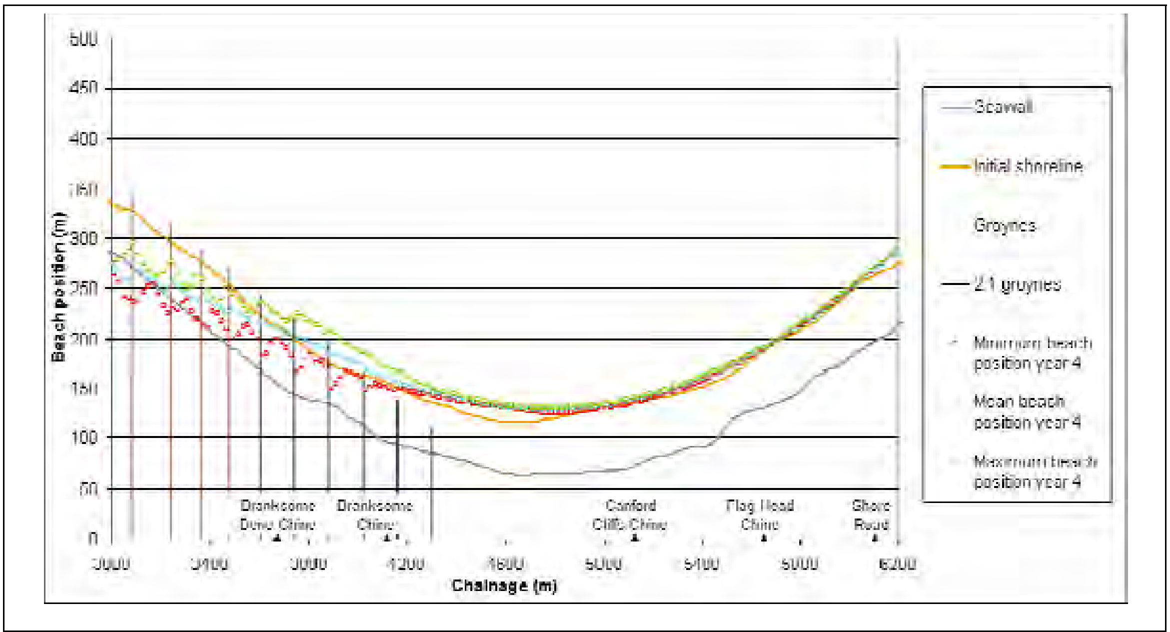


Figure 8.7 **Predicted ranges of beach position using Beachpla.**

Points showing the minimum beach width are not joined to form a continuous line so as to emphasise the fact that these positions do not occur concurrently. This form of presentation is also used for the mean and maximum beach widths and is considered to be better representations of beach positions than predicted shorelines at any given time, as these merely represent snapshots of a constantly changing beach position.

8.6. Coastal Profile Models

Coastal profile models of the numerical type – coupled hydrodynamic and sediment transport profile models – simplify the coast to a 2D longshore uniform system (with processes in the vertical and cross-shore directions being modelled). These models commonly include wave shoaling, wave breaking due to depth and bottom friction, cross-shore undertow and sediment transport. Coastal profile models were designed to model beach profile response to storms, and the cross-shore distribution of longshore drift (but not both together). Coastal profile models tend to be poor at re-building beaches between storms (they are poor at modelling nett onshore transport) so are restricted to relatively short simulations of cross-shore transport, but can be used for much longer simulations of longshore transport.

Van Rijn *et al*. (2003) compared the results from coastal profile models with hydrodynamic and morphodynamic data on the timescale of storms and seasons, as summarised below. Profile models were shown to predict the cross-shore variation in significant wave height to within 10 per cent if properly calibrated. They were also shown to predict offshore and longshore current speeds in the laboratory and in the field within 40 per cent. Profile models can reasonably represent the movement of outer and inner sand bars on the timescale of storms. They cannot simulate the beach recovery process on the post-storm scale, as the 3D processes involved are not sufficiently well understood to be parameterised. Profile models cannot be used to simulate the behaviour of sand bars or the beach on a seasonal scale unless they have been tuned using beach profile data.

Potential roles for coastal profile models in studies of long-term large-scale geomorphological change include:

- Give the cross-shore distribution of longshore transport in a one-line model (as LITPACK does) to assist in determining sediment bypassing (of a groyne or at an inlet) or the development of an n-line model.
- Determine the erosion of dunes or shingle barriers during storm as the basis for determining a fragility curve or a minimum cross-sectional area for safety (van Rijn, 2009).

8.6.1. Example application

HR Wallingford's coastal profile model COSMOS (Southgate and Nairn, 1993, Nairn and Southgate, 1993) was used to predict the cross-shore evolution of the barred beach at Egmond-aan-Zee (NL) during a storm from 24 to 31 October 1998 (Brady and Sutherland, 2001). The root-mean-square wave height measured in about 16 m water depth during this week is shown in **Error! Reference source not found.**.8. The average root-mean-square wave height was 2.1 m with an average peak wave period of 8.5 seconds. **Error! Reference source not found.**.9 shows the mean ± one standard deviation of the measured cross-shore profiles on 24 and 31 October, with the modelled profile on 31 October. During the storm the outer and inner bars moved offshore and their crests were raised or remained the same height. The model correctly predicted offshore movement of the bar crests, but lowered the crest elevation slightly. There was little movement of the swash bar in the measurements or the model.

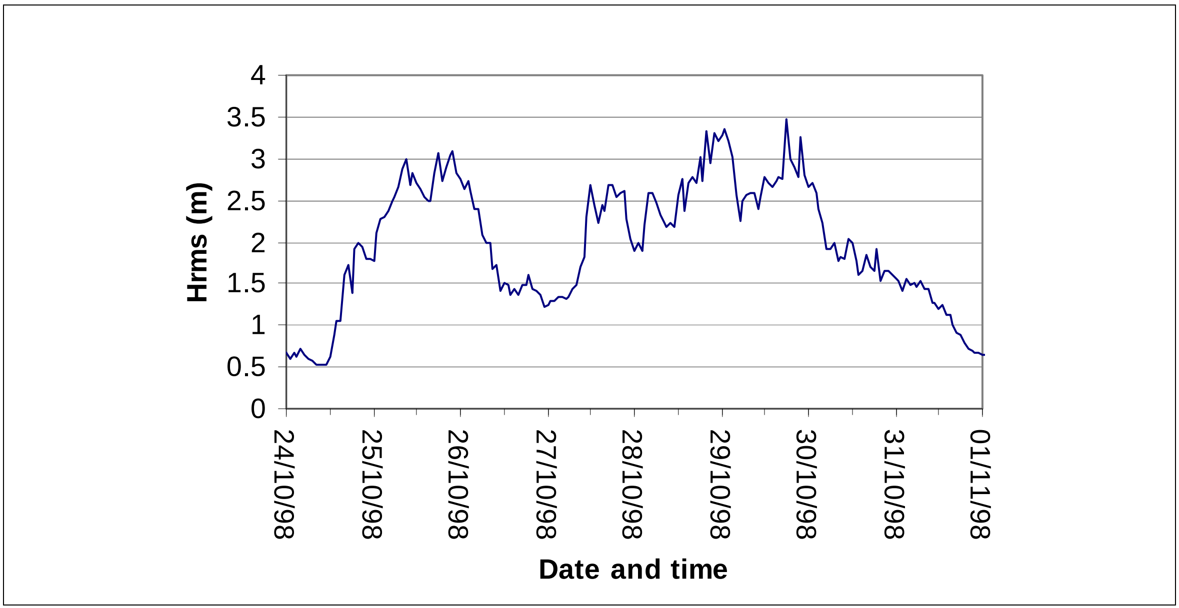


Figure 8.8 Root-mean-square wave heights at Egmond-ann-Zee.

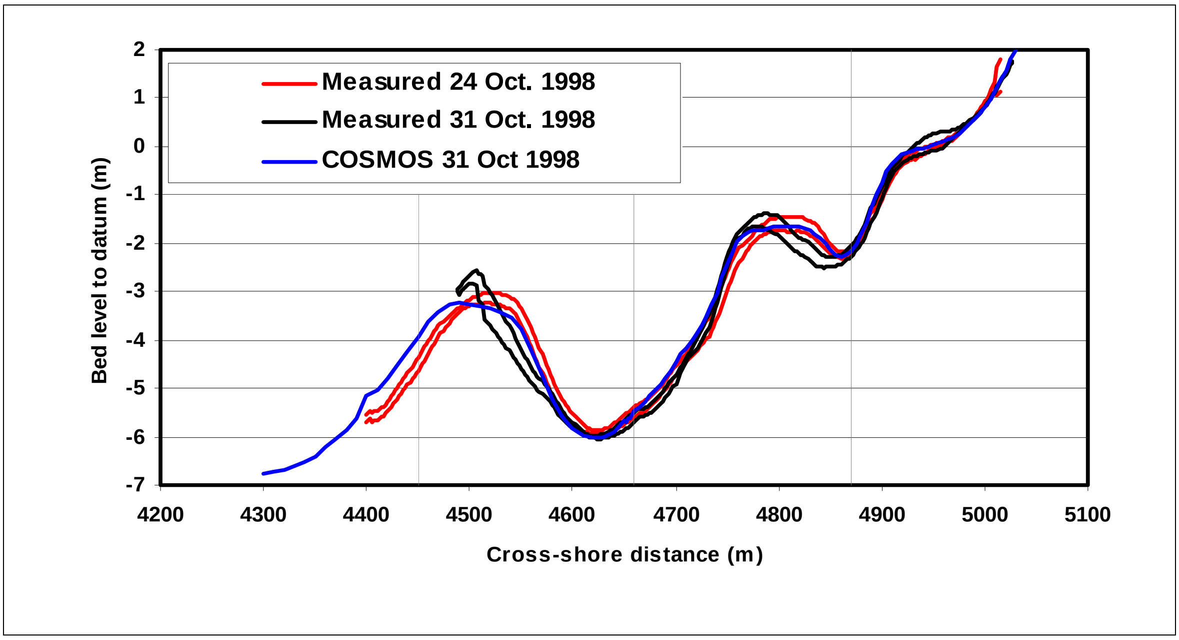


Figure 8.9 Cross-shore profile evolution during storm at Egmond-aan-Zee.

8.7. Coastal area models

Process-based coastal area models have been used for years to study short-term (generally depth-averaged) hydrodynamic and sediment transport problems, and given their ability to simulate fields that are both identifiable and (potentially) verifiable, there is appeal in the potential to apply such models to longer term problems. However, the issues associated with application of process-based models are long-established (see for example, de Vriend *et al*., 1993), and include problems associated with the requirement to model large areas with relatively fine meshes (in order to resolve the relevant processes) and the need to simulate relatively long timescales. There are also the associated problems of supplying the model with the correct set of input conditions (and sometimes the sequence of these conditions) that will determine the morphology.

In order to drive the model for long-term simulations, it is necessary to perform simplifying or filtering techniques. These are of two main types:

- Input filtering involves selecting a number of representative cases, rather than running a full time series.
- Process filtering involves reducing the number of computations by, for example, reducing the number of calls to the flow model and using continuity, for example, to adjust flow speeds between full runs of the flow model.

One of the limitations of coastal area models for considering beach evolution in front of coastal structures is that surf-zone processes, such as undertow, are not represented in the model. Wave reflection and diffraction are only rarely included in coastal area models.

8.7.1. Single representative wave

The aim of input filtering is to reduce the number of input conditions to run a model whilst maintaining the overall effect of the processes simulated. One method of input filtering is the single representative wave method (Chesher and Miles, 1992) described below.

A wave climate consists of many different components in terms of wave height, wave period and direction. To determine the sediment transport, all these components need to be taken into account. The single representative wave method schematises results from repeated applications of a wave module (Chesher and Miles, 1992). The starting point is a wave climate as given by an annual wave height exceedence table (a double-entry table where the probability of occurrence of each condition is given by a pair of wave height range and wave direction range). Once the main directions are chosen, rather than running every single condition in each of these directions, a representative wave height per direction θ is chosen, $H_{rep,\theta}$. This is calculated by calculating a weighted average according to:

$$H_{rep,\theta} = \left[\frac{\sum_{m=1}^{m=conds} \left(f\,H \right)^n}{\sum_{m=1}^{m=conds} \left(f \right)} \right]^{1/n}$$

where n is given by the process to be represented. This filtering procedure is based on the assumption that: *Process* $\propto (H)^n$.

In the classical approach (no filtering), having generated the input wave fields for the tidal current and transport models, each wave directional case H_θ would be run and the sediment transport patterns combined using as weighting factors the relative frequencies shown in the annual wave height exceedence table. In comparison, in the single representative wave height method the waves are first combined in one wave field $H_{rep,\theta}$ by averaging over the directional space with suitable weighting factors. The sediment transport model is run only once for each direction, as shown in **Error! Reference source not found.**.10.

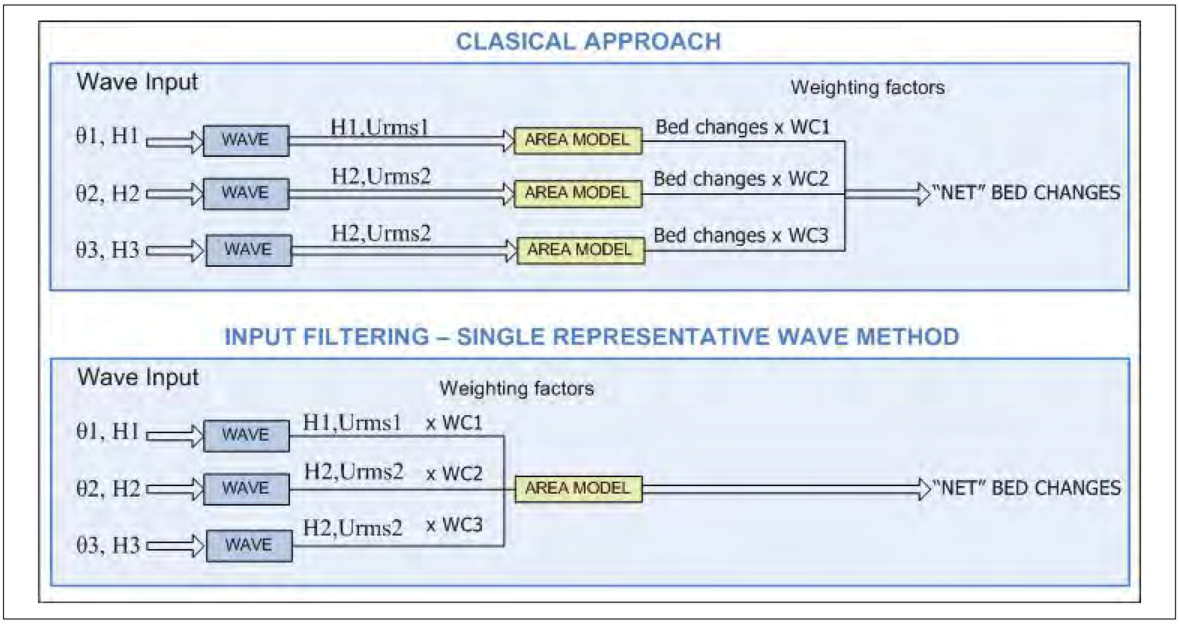


Figure 8.10 Flow diagrams for classical and single representative wave methods.

8.8. Breaching of shingle barrier beaches

Shingle (or gravel) and mixed sand/shingle beaches are widespread in many parts of the UK and Europe. These beaches are highly efficient and practical forms of coastal protection with high ecological, amenity and aesthetic value. In some instances these beaches are natural, but there are also many examples of engineered (recharged) beaches, which have suffered from erosion and subsequent landward retreat of the shoreline, whether from increased sea level, increased frequency of storms or a reduction in sediment volume (Stripling *et al.*, 2008). Consequently over a period of time a beach which was originally of satisfactory dimensions may be reduced to such an extent that it no longer constitutes an acceptable 'line of defence' with an increased risk of overwashing or breaching under extreme events at many sites. Anticipating this state is clearly important if shingle beaches are to be managed effectively, and landward structures are not to be damaged by flooding.

Whilst the breaching of a shingle (or gravel) barrier beach is dictated by storm conditions, such an event can have large-scale and long-term implications on coastal geomorphological behaviour, particularly if the breaching leads to the formation of a permanent or semi-permanent tidal inlet

Predictive methods are required to provide coastal managers with robust management tools, to assess the probability of occurrence of breaching, to identify and quantify drivers and responses and to engineer management solutions. An extended review of processes, models, management interventions and case studies of UK shingle barrier beaches is provided by Stripling *et al.* (2008).

Varying definitions of breaching have been used in connection with shingle barrier beaches within the geomorphological and engineering communities. The definition commonly used within an engineering context, and within the current investigation, describes breaching as the short-term lowering of the barrier crest, resulting from wave-induced overwashing (Bradbury, 2000); this condition is likely to result in short-term flooding of land in the immediate area. Breaching events are generally confined to extreme conditions and cannot be examined systematically in the field, because of their low temporal frequency of occurrence.

The classical dynamic equilibrium shingle beach profile (Powell, 1990) develops whilst conditions are sufficiently benign that wave run-up cannot exceed the crest; this provides a distinct berm, breaker-step and toe at the seaward limit. The dynamic equilibrium profile can be predicted reliably using the SHINGLE model (Section 8.8.1) for given combinations of wave, water level and sediment size under such conditions. Clearly defined ephemeral berms form beneath the crest, in response to the dynamics of the wave and water-level conditions. As the combination of wave period and water level conditions become more severe, however, wave-run up may exceed the crest and at this point the predictive profile model fails to function (Bradbury, 2000). Nevertheless, the SHINGLE model was used to produce the first fragility curve for shingle barriers. This fragility curve has recently been updated using the barrier inertia threshold curve (Obhrai *et al.*, 2008).

8.8.1. SHINGLE parametric model

Powell (1990) has provided a series of formulae to describe the shape of a shingle beach; these were derived by curve fitting to data from an extensive series of random wave tests, undertaken in a two-dimensional random wave flume. Powell (1990) describes the shingle beach profile by three hyperbolic curves: from beach crest to the static water level shoreline; static water level to the top edge of the step; and the top edge of the step to the lower limit of profile deformation, as shown in **Error! Reference source not found.**.11.

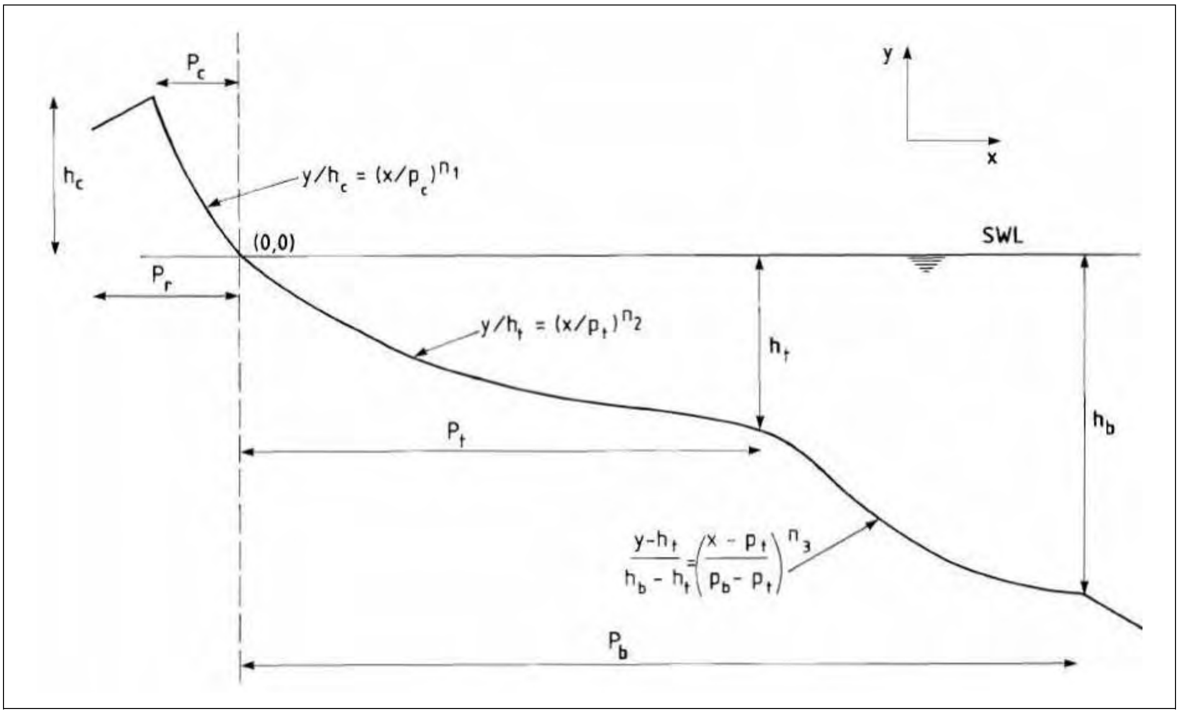


Figure 8.11 Shingle model representation of beach profile.

The following variables were considered in development of the model

- Significant wave height H_s
- Mean wave period T_m
- Grain size D_{50}
- Offshore wave length L_m
- Water level at storm peak SWL
- Approach slope
- Depth of sediment.

Functional relationships were produced for the profile descriptors and, on the basis of dimensional analysis, three dimensionless parameter groupings were derived:

a. H_s / D_{50}, ratio of wave height to sediment size;

b. H_s / L_m, wave steepness;

c. $H_s T_m g^{1/2} / D_{50}^{3/2}$, ratio of wave power to sediment size.

A suite of empirical equations were derived and coded as the SHINGLE parametric model of wave run-up and beach profile response due to onshore/offshore sediment transport. Profile equations for the upper segment of the profile are summarised in Table 8.6 where:

p_r = schematised run-up limit relative to shoreline;

p_c = schematised beach crest position relative to shoreline;

h_c = schematised beach crest elevation relative to still water level.

Table 8.6 Summary of functional relationships for use as beach profile descriptors (Powell, 1990).

Functional Relationship	Limit of Applicability
$p_r / H_s = 6.38 + 3.25 \ln(H_s / L_m)$	$0.01 < H_s / L_m < 0.06$
$p_c D_{50} / H_s L_m = -0.23 \left(H_s T_m g^{1/2} / D_{50}^{3/2} \right)^{-0.588}$	$0.01 < H_s / L_m < 0.06$
$h_c / H_s = 2.86 - 62.69 (H_s / L_m) + 443.29 (H_s / L_m)^2$	$0.01 < H_s / L_m < 0.06$

The model provides an estimate of the dynamic equilibrium beach profile that will form for any given combination of conditions, within the range of validity. The model was developed for clearly defined combinations of conditions and ranges of validity and confidence limits are stated for each. Importantly, the model is not intended to describe the upper part of a barrier profile under overtopping conditions.

The model is designed to run on a beach profile of defined geometry. It is assumed that there is no net loss of material from the profile. Calculations are made of the profile descriptors relative to static water level at the storm peak.

8.8.2. SHINGLE example application

Obhrai *et al.* (2008) performed physical model tests to assess the method of Powell to predict the failure of shingle barrier beaches. Powell's (1990) SHINGLE model performed well under the storm wave conditions, particularly for the finer sediment. **Error! Reference source not found.**.12 shows an example (scaled from physical model scale to full scale) of the measured profile, with the initial profile input to the model, equilibrium profile for H_s of two metres and observed failed profile for the finer sediment (D_{50} = 16 mm, full scale). The position of the crest for the failed H_s is close to the rear of the crest which suggests that SHINGLE would have predicted failure at the correct threshold H_s in this case.

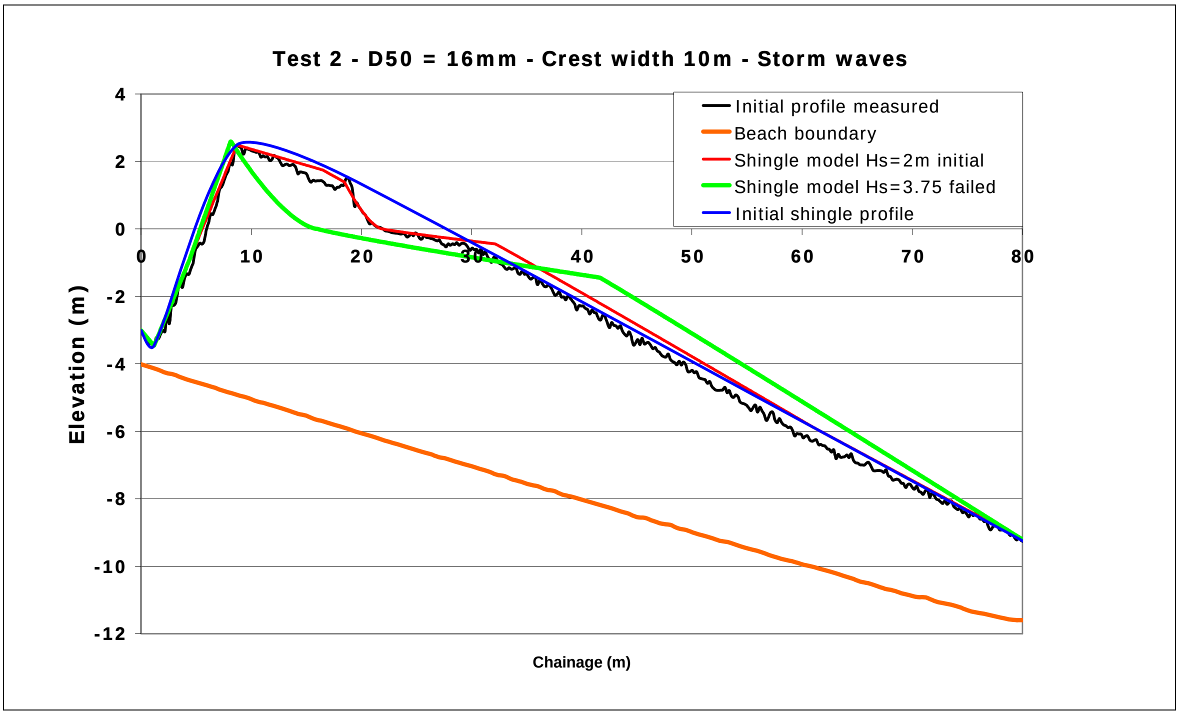


Figure 8.12 Predictions of post-storm cross-shore profile from SHINGLE.

8.8.3. Barrier inertia

Extensive three-dimensional physical model investigations and limited fieldwork by Bradbury (1998, 2000) provided an empirical predictive framework and a preliminary estimate of the risk of breaching of shingle barriers of defined cross-section. The conceptual approaches outlined by Bradbury (2005) were developed to examine the short-term profile response, by reference to the wave climate, storm peak static water level datum, barrier freeboard R_c and the barrier cross-section area above this datum, B_a. The dimensionless barrier inertia parameter, B_i, is described by:

$$B_i = R_c B_a / H_s^3$$

Where R_c (m) is the barrier freeboard, B_a(m^2) is the cross-sectional area of the beach above storm peak water level and H_s (m) is the significant wave height.

The predictive framework considers the morphodynamic response of shingle barrier beaches of varying geometry to a range of hydrodynamic variables and provides a preliminary estimate of the overwashing threshold under extreme conditions. The barrier inertia parameter is plotted against a dimensionless wave steepness parameter, which provides a measure of the combined wave height and period; H_s/L_m where; wavelength $L_m = gT_m^2/2\pi$, and T_m is the mean wave period.

This empirical model only includes the effects of wave steepness and barrier cross-sectional area. Results from recent physical model tests (Obhrai *et al*., 2008) indicate that the sediment size and barrier geometry also have a significant effect on the threshold for failure. Obhrai *et al*. (2008) combined their physical model data with that of Bradbury (2005) and modified the Bradbury empirical model. A simple linear fit provided the best description of the upper limit for the threshold for breaching and can be described as follows:

$$\frac{R_C B_A}{H_S^3} < -153.1\frac{H_S}{L_M} + 10.9$$

Valid for the range 0.01 < H_s/L_m < *0.06*

This data is plotted in **Error! Reference source not found.**.13, which includes data from Dunwich discussed in Section 7.6.1 that was not included in the Obhrai *et al.* (2008) analysis. Being below the curve implies that breaching is likely to occur.

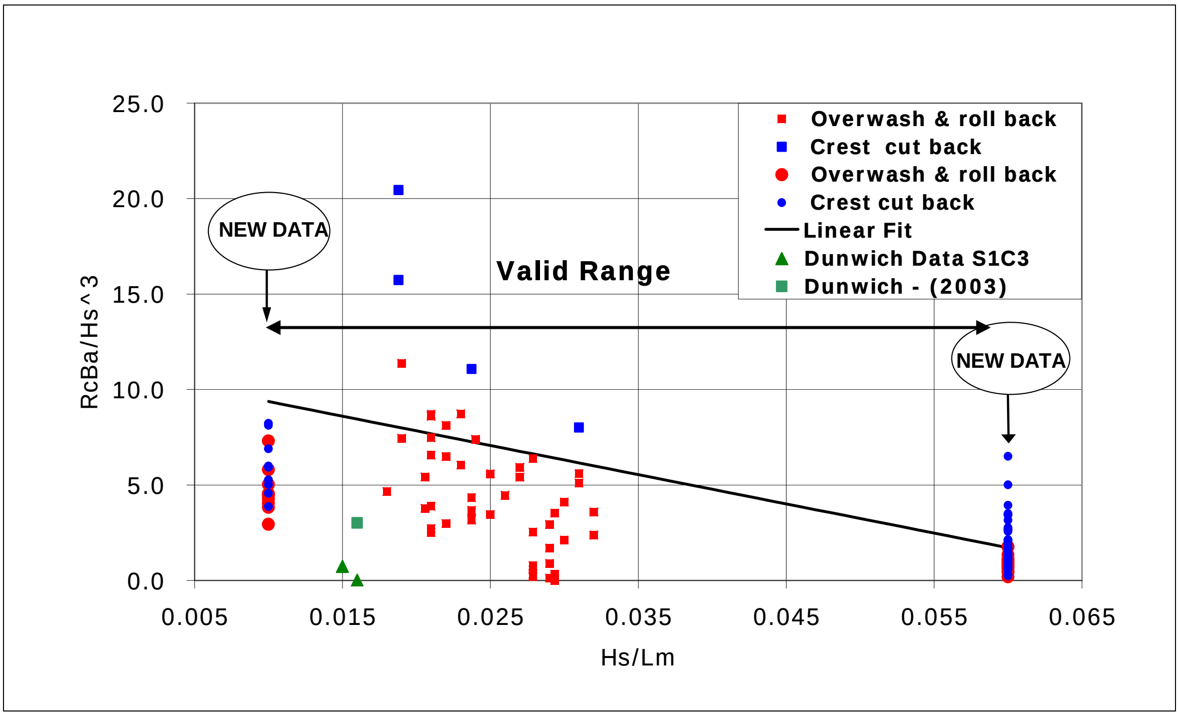


Figure 8.13 Empirical curve for threshold of breaching with data from the two storm events at Dunwich for profile S1C3.

8.8.4. Barrier Inertia example application: Dunwich

The linear fit equation was assessed using field data obtained from Dunwich Bay at a time when the managed shingle ridge was breached by washover events (Pye and Blott, 2009). Two storm events were identified where the shingle barrier in Dunwich bay was known to have been overtopped. The first event occurred on 1 November 2006 and second on 9 November 2007. Wave and water level data were obtained from a WAVENET data buoy located inshore in Dunwich bay (52° 17.190' N 001° 38.570' E, OSGB: TM 648541mE 271629 mN), as shown in **Error! Reference source not found.**.14. Summer 2006 beach profiles were obtained from the Environment Agency at the location of S1C4 and S1C4 as shown in **Error! Reference source not found.**.15. A summary of input water and wave conditions to the empirical model and results value of the Barrier inertia parameter are given in Table 8.7. The results for profile S1C3 predicted breaching in both storm events. At the position of S1C4 the barrier appeared more resilient and the model does not predict breaching in this case.

Table 8.7 Input conditions to the empirical model for the 2006 and 2007 storm events for the two profile locations.

Date	Profile	H_s (m)	T_m (s)	Surge level (mODN)	B_i
01/11/06	S1C3	1.75	8.29	2.40	0.01
01/11/06	S1C4	1.75	8.29	2.40	29.11
09/11/07	S1C3	1.29	7.4	2.54	0.73
09/11/07	S1C4	1.29	7.4	2.54	73

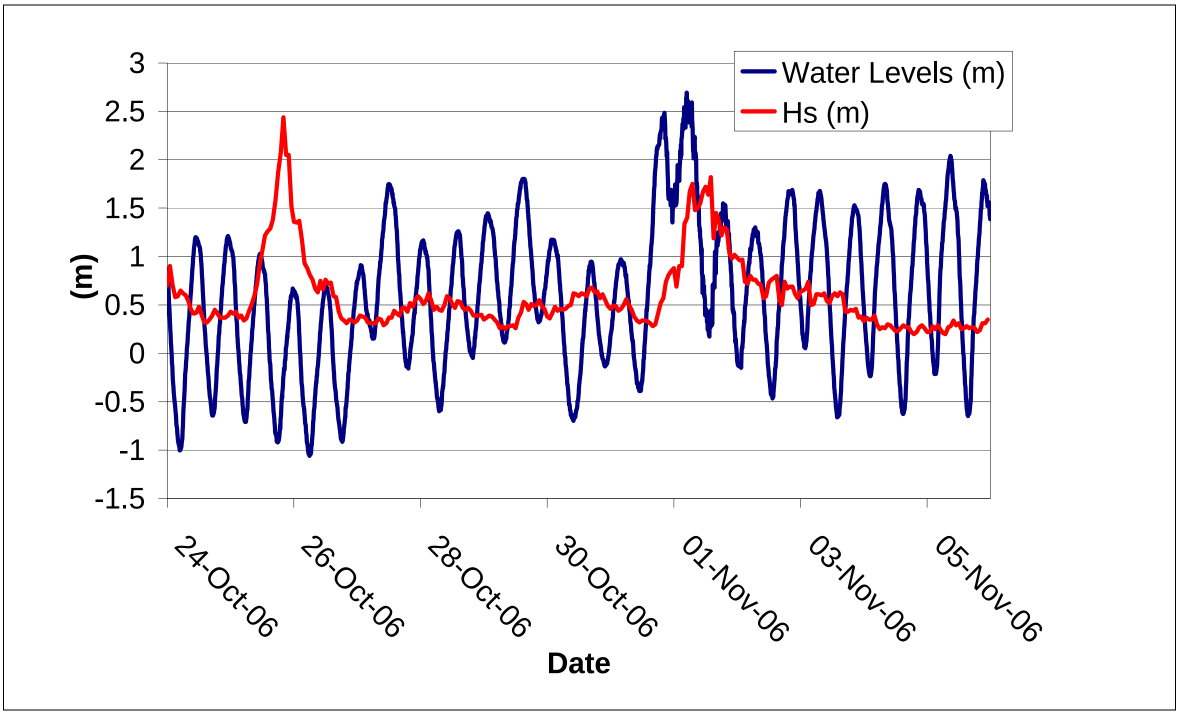


Figure 8.14 Wave and water level data from the 2006 storm event.

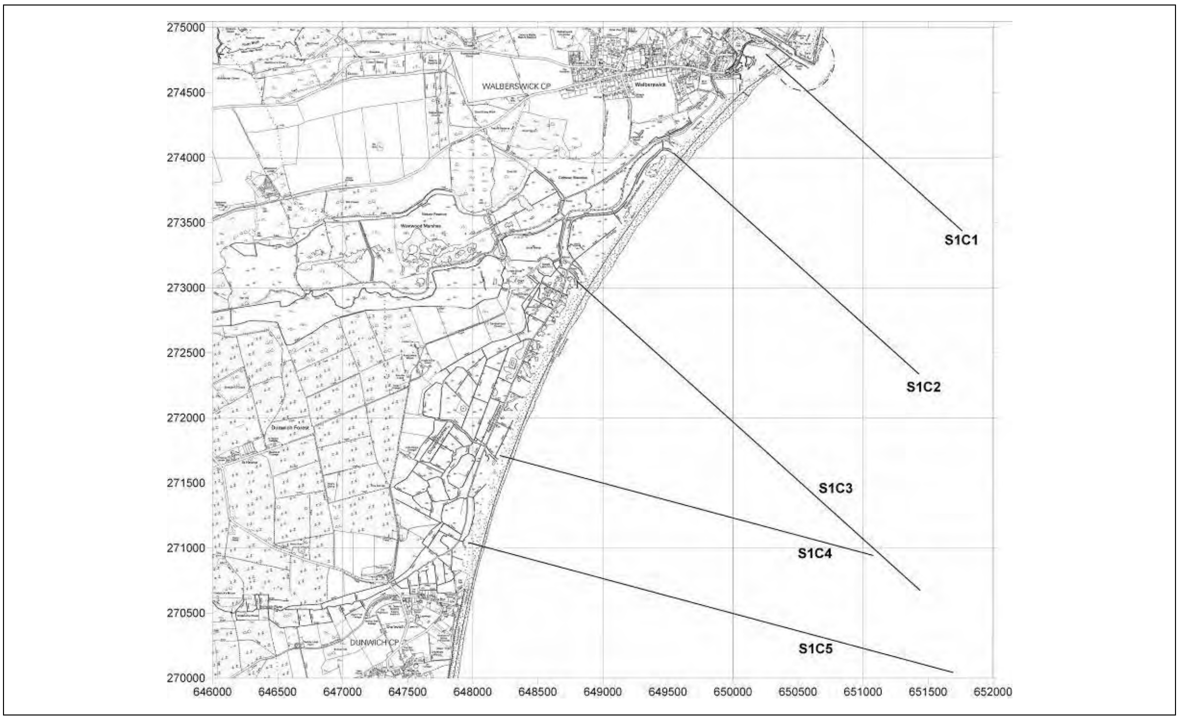


Figure 8.15 Map showing the location of beach profiles at Dunwich.

8.9. Tidal inlet stability

8.9.1. Background

Much literature is available on inlet stability and the range of semi-empirical techniques developed, mainly in the USA, and subsequently modified to provide an insight into different aspects of stability.

Stability is primarily determined by the balance between the rate of sediment supply to the inlet and tidal flows/river discharges through the mouth. Hence, inlet stability can be assessed in relation to:

- mouth cross-sectional area;
- sediment flushing ability.

A stable inlet will occur when the mouth cross-sectional area fluctuates but returns to an equilibrium condition following some perturbation to the system. An unstable inlet will occur when the mouth cross-section area does not return to equilibrium.

An important correlation exists between tidal prism[1] and mouth cross-sectional area and this has important implications for inlet stability. Sediment supply and deposition in the inlet mouth can reduce the cross-sectional area, which could have a knock-on effect on the tidal prism and scouring ability of flows at the mouth.

8.9.2. Review of available inlet stability assessment techniques

Nine main semi-empirical tools are available for assessing inlet stability. Some key characteristics are discussed below.

8.9.2.1. Technique 1: Cross-sectional area versus tidal prism

O'Brien (1931) developed the following linear relationship between cross-sectional area (A) and tidal prism (P):

$$A = cP^n$$

where c and n are constants empirically derived from regression equations.

This approach can be used to determine the equilibrium cross-sectional area of an inlet. Effects of parameters such as littoral drift rates and tidal conditions are implicitly defined by the choice of constants c and n, based on regression analysis of local/ regional trends in a large number of inlets with similar characteristics (Townend, 2005).

This equation is best suited for determining a new (long-term average) equilibrium cross-sectional area given some perturbation to the tidal prism (for example, caused by land claim or managed realignment). The approach was recently applied by Hartley and Pontee (2008) to a coastal gravel barrier at Slaughden in Suffolk in order to assess potential mouth dimensions should a breach occur.

[1] Volume of water that enters and leaves an inlet within the timeframe of a tidal cycle.

8.9.2.2. Technique 2: Brown method/Escoffier curves

Escoffier (1940) further developed a method originated by Brown (1928) for calculating the mean tidal velocity at the time of peak tidal discharge through an inlet, when the mouth dimensions, inlet dimensions and tidal range are known. This mean tidal velocity at time of peak tidal discharge is then compared against a critical velocity for sediment mobilisation to determine whether or not sediment infilling will occur within the inlet channel. The approach uses 'Escoffier curves' showing inlet cross-sectional area plotted against mean velocity through the inlet (**Error! Reference source not found.**.16).

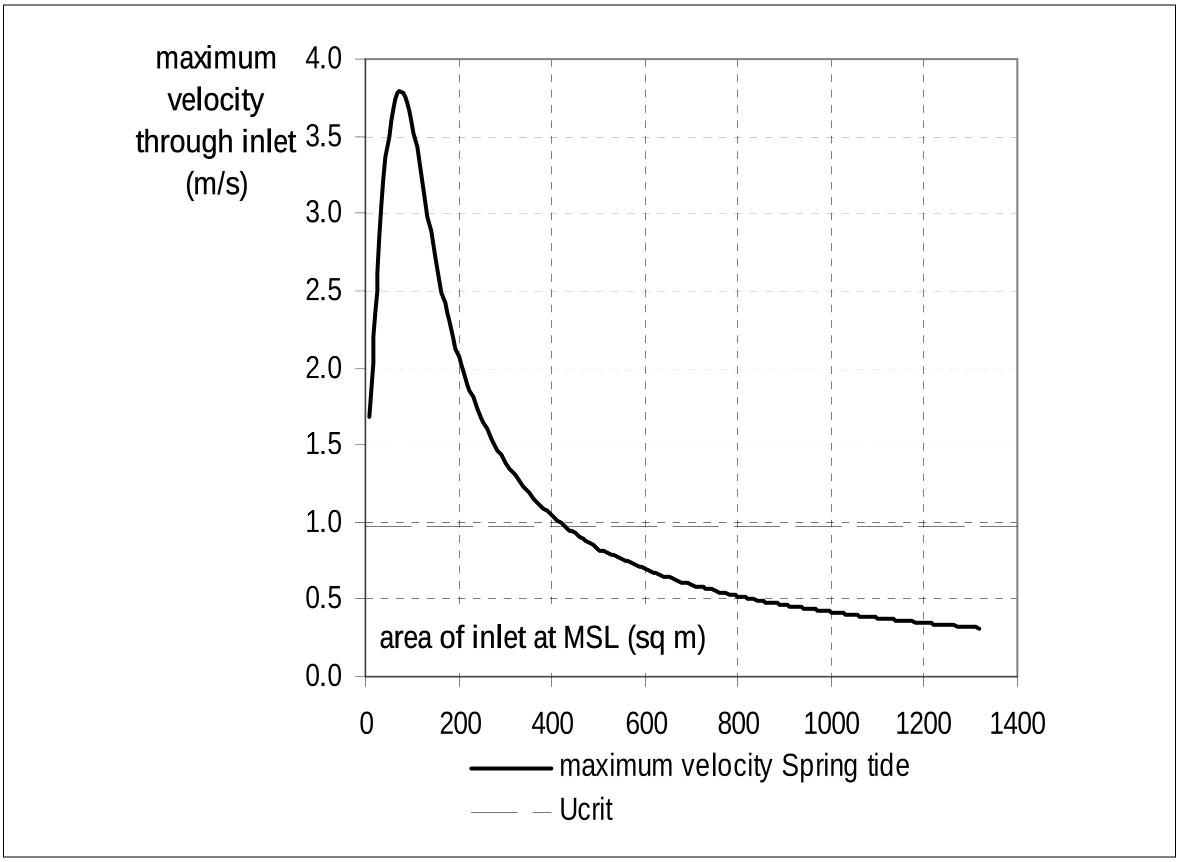


Figure 8.16 A typical 'Escoffier curve'.

Typically, as the cross-sectional area increases, so the velocity increases until a point is reached where tidal characteristics impose a constraint and further increases in cross-sectional area result in decreases in velocity.

The approach has also been used at Cuckmere Haven (River Cuckmere estuary – ABPmer, 2005) and Littlehampton (River Arun estuary – Royal Haskoning, 2007) to assess the implications of various Environment Agency activities, such as managed realignment of estuary defences, on flushing ability at the estuary mouth.

8.9.2.3. Technique 3: Maximum velocity criteria

Peak velocity through an inlet (U_{max}) can also be related to a threshold velocity required to mobilise sediments (U_{crit}) in a more simplistic way, where:

$U_{max} > U_{crit}$ = stable inlet (mouth is swept clear of sediments)

$U_{max} < U_{crit}$ = unstable inlet (sediments are deposited in mouth)

8.9.2.4. Technique 4: Inlet closure parameter

O'Brien (1971) derived an inlet closure parameter (Cw) whereby wave energy, tidal period and amplitude were considered in the form:

$$Cw = \frac{E_s \; T_p \; b}{\Omega \, (2 \, a_o) \, \gamma}$$

Where:

E_s = wave energy (N-m s^{-1} per m width of beach)

T_p = tidal period (s)

b = inlet width (m)

a_o = tidal amplitude (m)

γ = unit weight of water (N/m³)

8.9.2.5. Technique 5: Wave power versus tidal prism

Johnson (1973) modified the above approach by correlating deep water wave power with tidal prism.

8.9.2.6. Technique 6: 'r' factor

This dimensionless parameter, the 'r' factor, was developed by Bruun and Gerritsen (1960) to consider sediment bypassing of tidal inlets.

8.9.2.7. Technique 7: Ω/M_{TOT} ratio

Bruun and Gerittsen (1960) also derived an empirical ratio between tidal prism (Ω) and total sediment transport into the inlet by longshire drift (M_{TOT}).

$$\frac{\Omega}{M_{TOT}}$$

A large ratio indicates a dominance of tidal flows over sediment supply, and hence a more stable inlet.

The approach was recently applied by Hartley and Pontee (2008) to a coastal gravel barrier at Slaughden in Suffolk to assess the likelihood of inlet stability should a breach occur. It has also been used at the Blyth Estuary in Suffolk to show improved stability of the inlet following natural breaching of extensive reclaimed areas in the 1940s (French, 2008). The approach has been used at Cuckmere Haven (River Cuckmere estuary – ABPmer, 2005), Littlehampton (River Arun estuary – Royal Haskoning, 2007) and Medmerry (West Sussex) to assess the implications of various Environment Agency activities, such as managed realignment of estuary defences, removal of a training wall that intercepts longshore drift, and consequences from inlet creation of breaching through a gravel barrier following cessation of maintenance (Cope, 2004).

8.9.2.8. Technique 8: "K_c criterion"

Gao and Collins (1994) refined the Bruun and Gerittsen approach to include freshwater flows and tidal characteristics and provide a coefficient of inlet stability (K_c).

8.9.2.9. Technique 9: Sedimentological/morphological interpretation

Fitzgerald *et al*. (2000) proposed a series of nine qualitative conceptual models, illustrating the different potential mechanisms through which sediment can be transferred to, or past, inlet mouths. The models provide a useful framework with which to understand inlet characteristics. Burningham and French (2007) adopted a sedimentological/morphological approach to understanding the behaviour of inlet shoals, such as the ebb-tide delta, through use of digital elevation models using data from recent historic time periods and application of empirical relationships between tidal prism and ebb-tidal delta volume (Hicks and Hume, 1996).

8.9.3. Case study application to the Blyth Estuary (Suffolk)

Coastal sub-cell 3c was described in Section 6.2.1. Along this frontage the Blyth Estuary has been defined as a specific feature within the coastal system. Some of the above techniques have been applied to the case study of the Blyth Estuary to show their usefulness in understanding the behaviour of specific aspects of the system.

8.9.3.1. Blyth Estuary

The Blyth Estuary is a barrier-enclosed meso-tidal estuary. Wave-driven littoral sediment transport is predominantly from north to south. Historically, the inlet was prone to blockage during winter storms (French, Burningham and Benson, 2008), a situation exacerbated by reclamation of most of the inter-tidal area by the early nineteenth century (Simper, 1994). This necessitated frequent dredging and successive harbour improvements that culminated in the jetties at Southwold Harbour that presently maintain a narrow inlet channel.

Following failure of some flood defences in the 1920s and 1940s, tidal action was restored to a large portion of the middle estuary. This increase in tidal prism has subsequently helped to maintain the inlet.

Present-day parameters of relevance to inlet stability analysis are shown in Table 8.8.

Table 8.8 Blyth Estuary Parameters.

Parameter	Value	Source
Spring Tidal Range	2.0 m	Admiralty Tide Tables
Neap Tidal Range	1.1 m	Admiralty Tide Tables
Spring Tidal Prism	3.15×10^6 m^3/s	LiDAR-based DGM
Neap Tidal Prism	1.49×10^6 m^3/s	LiDAR-based DGM
Planar area at MHWS	4.3×10^6 m^2	LiDAR-based DGM
Planar area at MHWN	3.3×10^6 m^2	LiDAR-based DGM
Width of inlet at MWL	65 m	LiDAR-based DGM

Mean river flow	0.4 m^3/s	French, 2008
Longshore drift	18 x 10^6 m^3/year	HR Wallingford, 2002

8.9.4. Application of Brown/Escoffier method

This inlet stability solution is that originated by Brown (1928) and subsequently expanded upon and more widely disseminated by Escoffier (1940). **Error! Reference source not found.**.17 shows the underlying physical assumptions of the method.

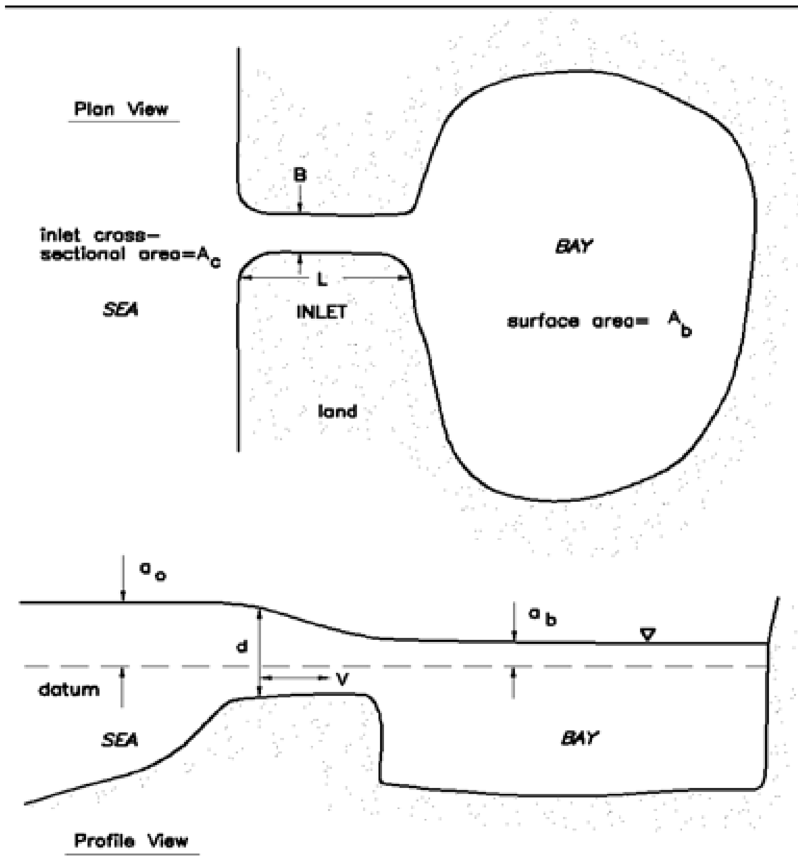


Figure 8.17 Schematic layout of assumptions underlying the Brown/Escoffier model of tidal inlet behaviour.

The system is assumed to consist of a bay, of approximately uniform depth, connected to the sea by a tidal inlet. The hydraulic characteristics of the inlet and volume of the basin determine the behaviour of the system overall. There is a difference in water level between the basin and the sea outside the inlet, by virtue of the inlet constriction, which causes a time lag, and due to the bed roughness losses along the inlet channel. The bed roughness losses, which cause backwatering along the inlet channel, are a function of the length and cross-sectional dimensions of the channel itself and upon the roughness characteristics of the bed.

The Brown solution for v_{max}, the mean tidally-generated current speed at time of peak tidal discharge within the inlet channel, is given by:

$$v_{max} = C\sqrt{\frac{A_c}{2pL}}\left(H^2 - h^2\right)^{1/4}$$

Where:

A_b	plan area of free surface of bay (m^2)
A_c	cross-sectional area of inlet channel flow section (m^2)
B_o	width of tidal inlet (m)
C	Chézy roughness coefficient of inlet channel bed ($m^{3/2}/s$)
H	tidal range in sea outside inlet (m)
h	tidal range in basin (m)
L	length of inlet channel (m)
p	wetted perimeter of flow cross-sectional area in inlet (m)
T_p	duration of tidal period (s)
v_{max}	mean velocity of flow at time of peak tidal discharge within inlet channel (m/s)

The value of *h*, the tidal range in the basin, is given by:

$$h = \sqrt{[B_o(2H^2 + b)]^{0.5}} - B_o$$

$$B_o = 0.5\left(\frac{0.27CT_p}{A_b}\right)^4 \frac{A_c^{\ 6}}{(pL)^2}$$

The procedure then is to compare the value of v_{max} estimated by the Brown method with the tidal current speed at the threshold of motion for the inlet material. The aim is to establish the degree to which the inlet is able to maintain an open condition under the prevailing tidal regime.

The threshold of motion solution proposed by Soulsby (1997) has been used here.

$$U_{crit} = 7\left(\frac{h}{D_{50}}\right)^{1/7} \sqrt{g(s-1)D_{50}f(D^*)}$$

$$f(D^*) = \frac{0.30}{1.0 + 1.2D^*} + 0.055\{1.0 - \exp(-0.02D^*)\}$$

$$D^* = \left[\frac{g(s-1)}{\nu^2}\right]^{1/3} \cdot D_{50}$$

Where:

D_{50}	median sediment diameter (m)
g	acceleration due to gravity (m/s^2)
h	water depth at the location under consideration (m)
s	relative density of the granular material (2.65 or similar)
v	kinematic viscosity of water (m^2/s)

To understand more about how the system presently functions, the Brown/Escoffier method was applied to the existing, base case, situation. If we assume that the estuary can be replicated in the Brown/Escoffier approach as an inlet channel of 1.5 km, a maximum tidal velocity through the inlet mouth on a neap and spring tide can be calculated for different mouth areas. The resulting Brown/Escoffier curves are shown in **Error! Reference source not found.**.18 assuming ebb and flood durations are roughly similar (although in reality there is an asymmetry in the Blyth). The critical threshold velocity (U_{crit}) for the mobilisation of one mm diameter grain sizes is shown on the plots as a dashed horizontal line indicating a U_{crit} value of 0.42 m/s for this sediment grain size.

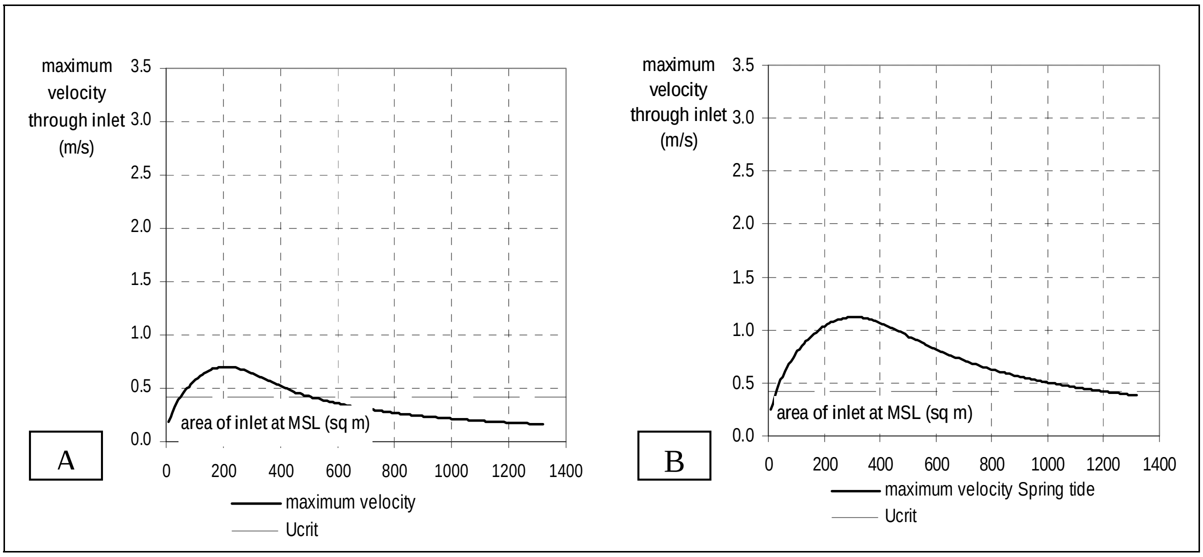


Figure 8.18 Tidal velocities through inlet mouth area for a neap tide (A) and spring tide (B).

At time of MWL, the mouth cross-sectional area below the water line is 144 m^2 and at time of MHWS it is 200 m^2. This shows that at present, the flow velocities through the mouth are reasonably competent at mobilising fine and medium-sized sediment from the mouth. If, however, coarser sediment such as coarse sand or shingle were to be deposited in the mouth, the velocities would be insufficient to re-mobilise the coarser fractions.

8.9.5. Application of Gao and Collins method

The stability criterion developed by Gao and Collins (1994) is presented by the following equation:

$$K_c = \frac{P + 0.5T_p Q_f}{M}$$

Where:

K_c	stability factor
M	longshore sediment transport (m^3/year)
P	volume of tidal prism (m^3)
Q_f	freshwater flow component (m^3/s)
T_p	duration of the tidal period (s)

Gao and Collins categorised stability according to the K_c ranges and stability classes presented in Table 8.9.

Table 8.9 Gao and Collins' K_c values and stability classes.

Kc range	Stability Class		Stability
150 < Kc	Good conditions, good flushing. Minor bar	Extremely high stability	↑
100 < Kc < 150	Bar usually more offshore	High stability	
50 < Kc < 100	Large bar by entrance, but usually a channel through bar	Moderate stability	
20 < Kc < 50	Typical bar-bypasser – storm events provide flushing	Low stability	
Kc < 20	Very unstable inlets, mainly just outflow channels	Highly unstable	

Assuming a longshore drift rate of 18,000 m^3/year, the Gao and Collins method reveals a K_c value of 83 on neap tides and 175 on springs. This means that on spring tide conditions the inlet is stable, but that during neaps the stability reduces to moderate levels. If a storm were to coincide with neap tides, it is possible that during high tide marine sands and shingles could be swept into the estuary mouth and not cleared until the subsequent spring tide.

8.9.6. Scenario testing

Having characterised the behaviour of the Blyth Estuary system using both the Brown/Escoffier and Gao and Collins methods, it is now possible to use the tools to test the sensitivity of the system to changes in management regime. In this case study, two examples have been tested:

1. The effect of removal of the North Jetty at Southwold Harbour.
2. The effect of abandonment of all tidal flood defences within the estuary combined with the effect of sea level rise over 100 years.

8.9.6.1. Removal of the North Jetty at Southwold Harbour

If we assume that removal of the jetty at Southwold Harbour would result in a ten-fold increase in littoral drift across the mouth of the Blyth Estuary, application of the Gao and Collins method suggests that the inlet would become very unstable on both neap and spring tides, probably just with outflow channels across a shingle bar. To maintain stability at moderate or better levels, longshore drift should not exceed around 50,000 m^3/year.

8.9.6.2. Abandonment of all tidal flood defences

If all existing tidal defences within the estuary were abandoned (hypothetically), there would be significant increases in both the tidal prism (on spring and neap tides) and planimetric flooded area (on spring and neap tides); see Table 8.10.

Table 8.10 Blyth Estuary parameters assuming abandonment of all tidal flood defences.

Parameter	Value	Source
Spring Tidal Prism	6.4×10^6 m^3/s	LiDAR-based DGM
Neap Tidal Prism	3.4×10^6 m^3/s	LiDAR-based DGM
Planar area at MHWS	7.7×10^6 m^2	LiDAR-based DGM
Planar area at MHWN	6.2×10^6 m^2	LiDAR-based DGM

The resulting increase in tidal flow relative to an assumed constant littoral drift of 18,000 m^3/year would result in very stable inlets (in terms of avoidance of closure) according to the Gao and Collins method.

The significantly increased tidal prism would, however, also result in increased velocities at the mouth.

The resulting Brown/Escoffier curves for this scenario are shown in Figure 8.19 assuming ebb and flood durations are roughly similar (although in reality there is an asymmetry in the Blyth).

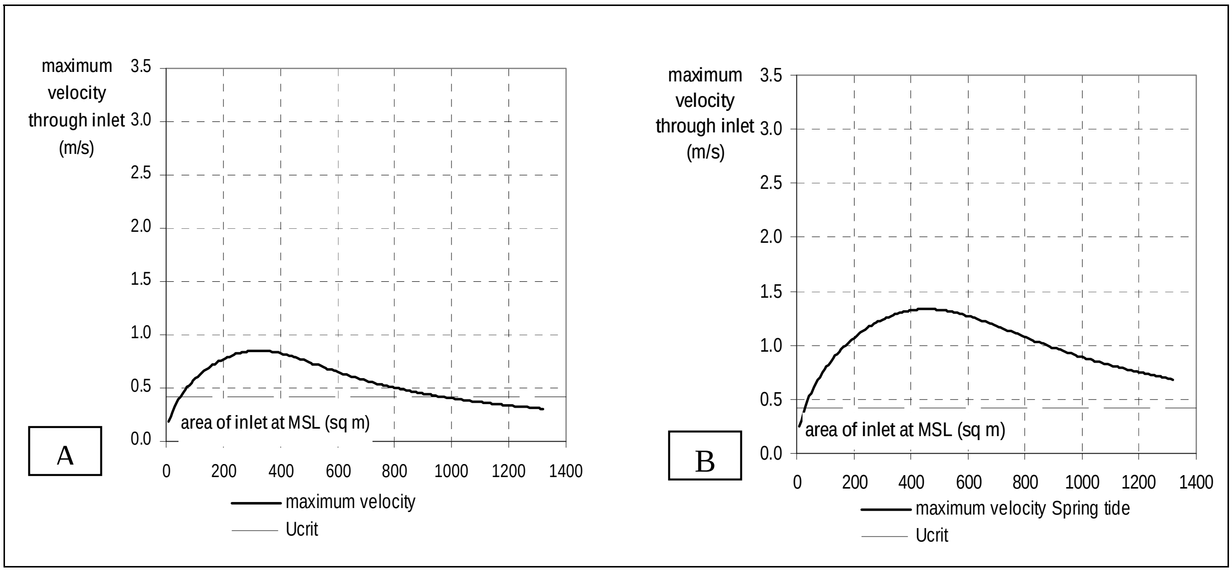


Figure 8.19 Tidal velocities through inlet mouth area for a neap tide (A) and spring tide (B) following abandonment of all tidal flood defences.

This reveals a greater possible erosional tendency on the mouth, which would seek to widen and/or deepen to accommodate the increased flows.

If the jetty at Southwold Harbour was removed and this resulted in a corresponding ten-fold increase in littoral drift across the mouth of the Blyth Estuary, application of the Gao and Collins method suggests that the inlet would become a typical bar-bypasser, with storm events providing flushing. Hence, abandonment of all tidal flood defences in the estuary would improve the stability by a whole category of Gao and Collins' stability classes.

8.9.7. Summary

Empirical and conceptual inlet stability tools provide a useful basis for understanding the relative dominance of different processes of influence at inlet mouths and sensitivity of systems to natural perturbations, such as increased tidal prisms in rising sea levels.

In addition, they form useful tools for assessing the relative impacts of different management techniques, such as changes in littoral drift caused by the presence or absence of groynes and changes in tidal prism due to estuary reclamation or abandonment of defences.

8.10. Reduced complexity modelling

Reduced complexity numerical models were used in the project and the results are summarised in Chapter 7 of this report and in Walkden and Rossington (2009). The two models used were:

- SCAPE – Soft Cliff and Platform Erosion
- ASMITA – Aggregated Scale Morphological Interaction between Tidal basin and the Adjacent coast

The results showed that quantification of the links between coasts and estuaries was able to be modelled in a manner useful for coastal management decision-making.

8.11. Conclusions

Each of the methods described in this section considers a particular aspect of coastal behaviour, such as cross-shore profile response to sea level rise, equilibrium embayment formation, stability of a tidal inlet, breaching of a gravel barrier and so on.

To provide a comprehensive picture of large-scale and long-term coastal geomorphological behaviour, it is necessary to synthesise the findings from assessments of aspects of the system within an overall conceptual understanding. This process is referred to as expert geomorphological assessment (EGA) and it integrates information from various sources, including historical trend analysis, the results of both short-term and long-term modelling, application of empirical tools, and conceptual understanding based on field and laboratory studies carried out elsewhere. It takes account of the geological and geomorphological framework, the nature of present, past and possible future environmental conditions and processes (wind, waves, tides, currents, sea level, sediment supply) (Pye and van der Wal, 2000).

As yet there are no protocols for this type of analysis, although guidance on scope and general methods is contained in the Estuaries Analysis and Modelling Guide (ABPmer, 2004) and HR Wallingford *et al.* (2006). EGA can be applied to many different spatial and temporal scales but is heavily dependent on the amount and quality of data available and on the expertise of those undertaking the assessment.

A number of stages can be defined in a typical EGA study which aims to address the possible consequences of a particular system intervention of management interest. These include: (1) scoping - definition of study objectives, study area and timescale, including identification and appraisal of available data, (2) synthesis of available data and development of conceptual model, (3) prediction of changes, (4) synthesis of changes, (5) initial conclusions, (6) discussions with partners and interested groups, (7) final conclusions and presentation of findings.

EGA, therefore, is the means by which assessments of long-term, large-scale coastal geomorphological behaviours can be made within a suitable framework as described in Section 3.3 of this report. Further information on EGA with examples is presented in Chapter 9.

9. Expert geomorphological assessment

9.1. The nature of EGA

Expert Geomorphological Assessment (EGA) integrates information from several sources, including analysis of modern and historical maps, aerial photographs, LiDAR data and satellite imagery, field surveys, laboratory sediment analysis and results generated by other tools including those described earlier in this report. The assessment process takes account of the geological and geomorphological framework, the nature of present, past and possible future environmental conditions and processes (wind, waves, tides, currents, sea level, sediment supply), and often involves manipulation of the data within a GIS framework (Pye and van der Wal, 2000). General guidance relating to the approach and methods which can be employed as part of EGA is provided in the Estuaries Analysis and Modelling Guide (ABPmer, 2004 and www.estuary-guide.net), and HR Wallingford *et al.* (2006) to which additional reference should be made. The purpose of this chapter is to illustrate the application of the approach to open coast and estuary-coast interaction situations.

A number of distinct stages can be defined in a typical EGA exercise. The presentation here is an extension of the study process presented in Section 3.3. The stages are:

1. Problem definition, including identification of the study objectives, limits of the study area and timescales of interest.
2. Collation and evaluation of existing data.
3. Development of a preliminary conceptual model of the area, which helps identify important gaps in our knowledge.
4. Collection and analysis of additional data.
5. Data synthesis and refinement of the conceptual model.
6. Explanation of past changes and current trends, together with prediction of future trends where required.
7. Recommendations for further work and/or the development of policy (Figure 9.1).

1. **Problem Definition**
    - **Study objectives**
    - **Limits of study area**
    - **Timescale**
2. **Collation and Analysis of Existing Background Data**
    - **Desk study**
    - **Site visit**
3. **Development of Preliminary Conceptual Model**
    - **Identify gaps in knowledge**
4. **Additional Data Collection**
    - **Remote sensing**
    - **Field surveys**
    - **Sediment sampling and analysis**
    - **Computer modelling**
5. **Data synthesis and Refinement of Conceptual Model**
6. **Explanation/Prediction**
7. **Recommendations**

Figure 9.1 Summary of the stages in expert geomorphological assessment.

Definition of the study area and aims is closely linked to the nature of the problem which requires investigation. The types and quantity of data which need to be collated and reviewed also depends on the nature and scale of the problem. Following a review of published literature, unpublished reports, maps, charts and aerial photographs, a reconnaissance visit to the study area should normally be undertaken to make observations and interpretations based on the initial desk study. A system mapping exercise, of the type described earlier in this report, can usefully be undertaken at this stage and may be of considerable assistance in developing the preliminary conceptual model of the area, and in identifying gaps in knowledge and requirements for further data collection. These may include topographic and bathymetric surveys, acquisition of LiDAR or aerial photographs for photogrammetry, collection of sediment samples for laboratory analysis, and field measurements to calibrate and/or validate hydrodynamic models. If an assessment of historical changes has not previously been undertaken it may be necessary to digitize historical maps, charts and aerial photographs in order to identify historical trends on different timescales. Time series datasets obtained from coastal and offshore monitoring may require analysis using a variety of graphical and statistical procedures in order to identify temporal and spatial trends in properties such as beach width, cross-shore and alongshore sediment volume, mudflat and saltmarsh surface level, or changes in environmental forcing factors such as mean sea level, tidal levels, wave energy and storm surges. Longer term morphodynamic modelling may also be employed, using the historical datasets and models such as SCAPE and ASMITA, as described earlier in this report (Chapter 7).

In the data synthesis stage, information obtained from previous exercises is brought together and used to refine the original conceptual model of the geomorphological behaviour of the study area. The model should be able to explain the historical evolution of the area and provide a basis for assessment of future evolution under different scenarios (such as different rates of sea level rise or different management regimes). A number of further modelling exercises may be undertaken at this stage to establish the sensitivity of different parts of the system to changes in controlling variables, such as sea level rise, wave energy and direction, and different management interventions. The uncertainties associated with any projections relating to future morphological change should be identified and quantified wherever possible.

9.2. Example of EGA approach on Suffolk coast

The Suffolk coast (Figure 9.2) is characterised by lengths of 'soft' cliff separated by narrow estuaries and small bays, the entrances to which are blocked to varying degrees by sand and shingle barriers. The coast of East Anglia as a whole has experienced net erosion over the last few thousand years, although the pattern and rate of erosion have varied in time and space. Locally, sediment has accumulated in front of sections of cliff, leading to the formation of beach-ridge plains and nesses. However, these features are inherently dynamic, exhibiting short-term fluctuations between erosion and accretion on timescales of a few years to decades and centuries.

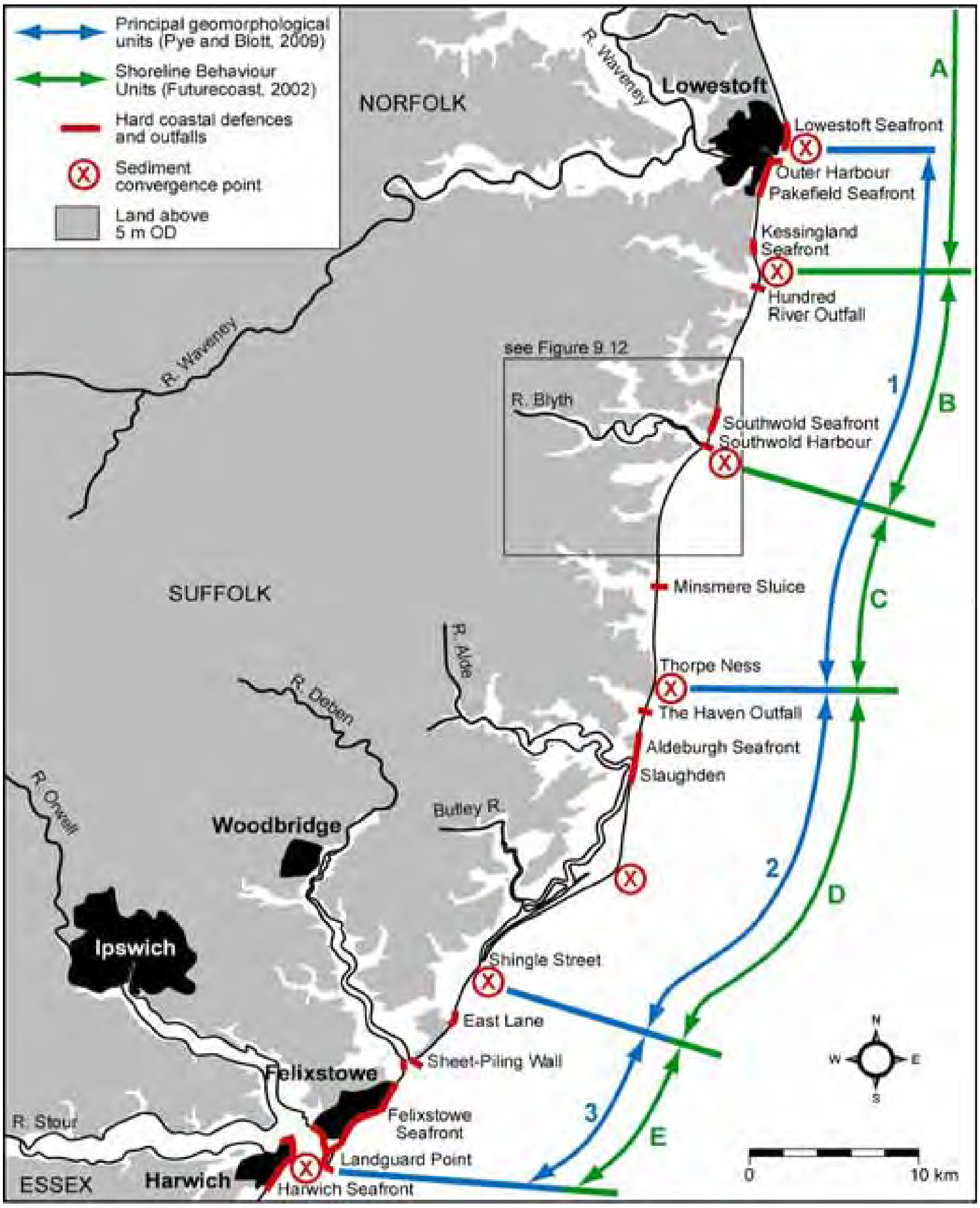


Figure 9.2 Location map showing artificial hard points and principal coastal geomorphological units in Suffolk.

(1) Lowestoft to Thorpe Ness; (2) Thorpe Ness to Shingle Street; (3) Shingle Street to Landguard Point. Shoreline Behaviour Units identified in the Futurecoast study are also shown for comparison: (A) Winterton to Benacre Ness; (B) Benacre Ness to Blyth Estuary; (C) Blyth Estuary to Thorpe Ness; (D) Thorpe Ness to Shingle Street; (E) Shingle Street to Landguard Point (after Pye and Blott, 2009a).

The natural variability of coastal features, combined with the long-term trend for erosion along much of the open coast, creates a range of problems for coastal erosion and flood risk management, and for habitat conservation. In areas of active erosion and beach lowering there is a direct threat to property, in terms of flood risk and structural collapse. Erosion also leads to loss of habitat area, with important consequences for nature conservation. Sediment accretion, on the other hand, may pose difficulties for navigation and may also have negative impacts on habitats and biotopes.

Significant sections of the Suffolk coast are now protected by hard defences, notably around Lowestoft, Southwold, Aldeburgh and Felixstowe, but most of the coast is still undefended and retains much of its natural character. A large part of the Suffolk coast is designated as Heritage Coast and an Area of Outstanding Natural Beauty. Benacre Ness and Orford Ness are designated in the Geological Conservation Review for their international geomorphological and geological interest (May, 2003a; 2003b), but there are localities which contain 'classic' landforms and stratigraphic 'type' sections.

A number of man-made structures act as hard points which have exerted a strong influence on the pattern of shoreline evolution in the past 200 years (such as the entrance to Lowestoft harbour, piers at the entrance to Blyth Estuary, Benacre Flume at the outlet of the Hundred River, Minsmere Sluice, and groynes at the mouth of the Deben estuary and at Languard Point; Figure 9.2). The effect of such structures has been to stop or slow landward movement of the shoreline immediately behind and adjacent , and they have often had an effect on the intervening sections of unprotected shore by altering patterns of littoral drift, reducing inputs of sediment to the coastal zone, and changing the pattern of wave refraction and reflection.

The East Anglian estuaries have acted as sediment sinks throughout the Holocene (McCave, 1987; Brew *et al*., 1992), leading to the development of extensive areas of saltmarsh and tidal flats. Much of the former saltmarsh area was embanked and reclaimed between the eleventh and nineteenth centuries, leading to major reductions in tidal capacity and changes in the morphology around the estuary mouths. Some of the smaller estuaries, such as those of the Hundred River and the Minsmere River, have been entirely blocked off from the sea.

Recent years have seen increasing concern about the long-term costs and technical feasibility of controlling coastal erosion, and maintaining both open coast and estuarine flood defences, in the face of climate change and sea level rise. Strong arguments have also been presented on the environmental benefits which might be gained by allowing the coast to evolve in tune with natural processes, and by encouraging the recreation of former inter-tidal environments in areas of embanked marshland. Increasingly, coastal erosion and flood risk management policy has been moving away from 'hold the line' towards 'no active intervention' and managed realignment'. Against this background, in Suffolk, as elsewhere, there is a pressing requirement to develop better tools to help assess the likely impacts of changes in climate, sea level and coastal management policy on timescales ranging from short (up to 20 years), medium (20-50 years) to long (50-100 years or more). Since the mid-1990s a number of studies have been undertaken to improve our understanding of coastal processes and morphological change in the area, to provide a sound scientific basis for future coastal management. These studies have been undertaken at the regional scale (see Halcrow, 1998; 2001; HR Wallingford *et al*., 2002; Royal Haskoning, 2002), and at the more local scale, related to individual coastal and estuary strategies, schemes, and sites of special scientific interest (see Rees, 2005; Halcrow, 2006; Pye and Blott, 2006a; Black and Veatch, 2007). Several research projects have also been carried out on process-form interactions and longer term-response of the open coast and estuaries to sea level rise (such as Pontee *et al*., 2004).

9.2.1. The Southwold-Dunwich-Blyth Estuary area

The coastal frontage between Easton Bavents cliffs and the Blyth Estuary is presently defended by concrete walls, groynes and a programme of beach nourishment. The Southwold defences have recently been upgraded (Halcrow, 2004), but continuing erosion of the soft cliffs at Easton Bavents creates a risk that the northern limit of the defence will be circumvented unless further action is taken (the possibility of a large rock groyne or similar structure at the southern end of the cliffs has been suggested in the Shoreline Management Plan Review, currently in progress; Royal Haskoning, 2009b).

The entrance to the Blyth Estuary is fixed by concrete and timber piers, reinforced by rock armour. The north pier effectively acts as a terminal groyne which plays an important role in holding the beach to the north and prevents blocking of the Blyth entrance during periods of strong southward sediment drift.

The coast between the south entrance pier and Dunwich Cliffs is mostly without hard defences, although there is a low concrete and sheet piling wall beneath dunes which front the village of Walberswick. An extensive sand and gravel barrier system extends between Walberswick and Dunwich Cliffs, behind which lies an extensive area of reedbeds and saline lagoons (Halcrow, 2006). Until 2005 the position and height of the barrier were maintained by bulldozing, but this practice was abandoned following a series of severe storms which beached and flattened the barrier in the period 2004-2007 (Pye and Blott, 2006a, b, 2009b). The morphology of the barrier has since been substantially modified by natural processes, including periodic over-washing, and lobes of sand and gravel have transgressed into the Dunwich River. During the storm events ebb-scour channels have been cut through the barrier, although none has yet developed into a permanent tidal inlet.

The cliffs south of Dunwich are predominantly composed of sandy Crag deposits and have little inherent resistance to erosion. Historically, there have been periods of rapid coastal erosion in the area, interspersed with periods of much slower erosion and stability. During the later nineteenth and early twentieth centuries the cliffs retreated at a rate of several metres per year, but over the last 80 years the average rate of erosion has been less than one metre/year (Pye and Blott, 2006). The cliffs at Dunwich itself experienced some erosion during the later 1980s and early 1990s, but since 1993 beach levels have been high and the cliff face has been fairly stable.

The Blyth Estuary represents a drowned river valley which has been incised into soft Tertiary and Quaternary sedimentary formations. The outer and central parts were flooded in the early Holocene by postglacial rising sea level, leading to the deposition of estuarine silts. The stratigraphy determined from boreholes suggests there may have been slight fluctuations in relative sea level in the period after 6500 years BP, leading to the accumulation of alternating peat, saltmarsh and tidal flat deposits (Brew *et al*., 1992). During the Middle Ages the Blyth entrance was deflected southwards by a spit which extended down the coast from Southwold. However, during the fifteenth to early seventeenth centuries a series of new cuts to the sea were dug across the barrier close to Walberswick. The present form of Southwold Harbour was created by excavations around 1630. Since that time there have been further structural changes to improve navigation, including extension, realignment and reinforcement of the entrance piers.

Significant areas of saltmarsh and higher mudflat were embanked and claimed for agriculture during the second half of the eighteenth century and early nineteenth century, and part of the Blyth was diverted into an artificial cut as part of a scheme to create a navigable waterway to Haleswsorth. By 1890 the estuary had effectively been reduced to a tidal canal. However, following the cessation of maintenance of the embankments in the mid-estuary during the period 1925-1968, significant areas of

Bulcamp Marshes, Angel Marshes and Sandpit Covert Marshes have reverted to mudflat with peripheral areas of saltmarsh (French, 2001; Pye and Blott, 2009b). Significant lengths of the remaining embankments are nearing the end of their design lives, and there have been a number of breaches during recent storm surge events.

With the prospect of accelerated sea level rise and possible increased storminess over the next century, there is concern that the estuarine flood defences may become unsustainable. Consequently, we need to assess the likely impacts of different policy options on short, medium and long timescales, within the estuary and on the adjoining coast. The reliability of such assessments strongly depends on adequate conceptual models of the long-term, broad-scale geomorphological behaviour of the area.

9.2.2. Factors controlling coastal evolution

Changes in the Southwold-Dunwich area reflect the balance of the local beach and nearshore sediment budgets, which in turn reflect the nature of sediment inputs, outputs and sediment transport pathways within the wider regional area. Historically, the principal sources of coastal sediments in this area have been the neighbouring coastal cliffs which are composed mainly of late Tertiary and Quaternary sediments and soft sedimentary rocks. The main sediment sinks have been (a) the estuaries, (b) local areas of net sediment accretion on the open coast and (c) offshore banks (Figure 9.3). The volumes of gravel, sand and mud supplied by erosion of different cliff sources have been estimated by analysis of historical maps and using information of cliff sediment composition supplied by BGS (Pye and Blott, 2009a; Figure 9.4). The rates of cliff erosion, and volumes of sediment input to the coastal zone, have varied significantly in time and space over the last 125 years. For example, erosion of Dunwich Cliffs provided an important source of sediment in the late nineteenth century and early twentieth, but since the mid-twentieth century the importance of this source has declined significantly. Erosion of the cliffs at Covehithe and Easton Bavents has provided an important sediment source throughout the period. By contrast, there has been no significant sediment input from the cliffs at Aldeburgh, Sizewell and Felixstowe over this period.

The coastal waters adjacent to the northern and central parts of the Suffolk coast are relatively shallow, with several well-developed banks. Figure 9.5 shows a bathymetric digital elevation model of the Walberswick-Sizewell area based on recent Admiralty surveys. The Sizewell-Dunwich Bank, which extends northwards sub-parallel to the shore between Thorpeness and Walberswick, exerts important influences on coastal processes along the shoreline. This, and other banks in the area, has acted as important long-term sediment sinks.

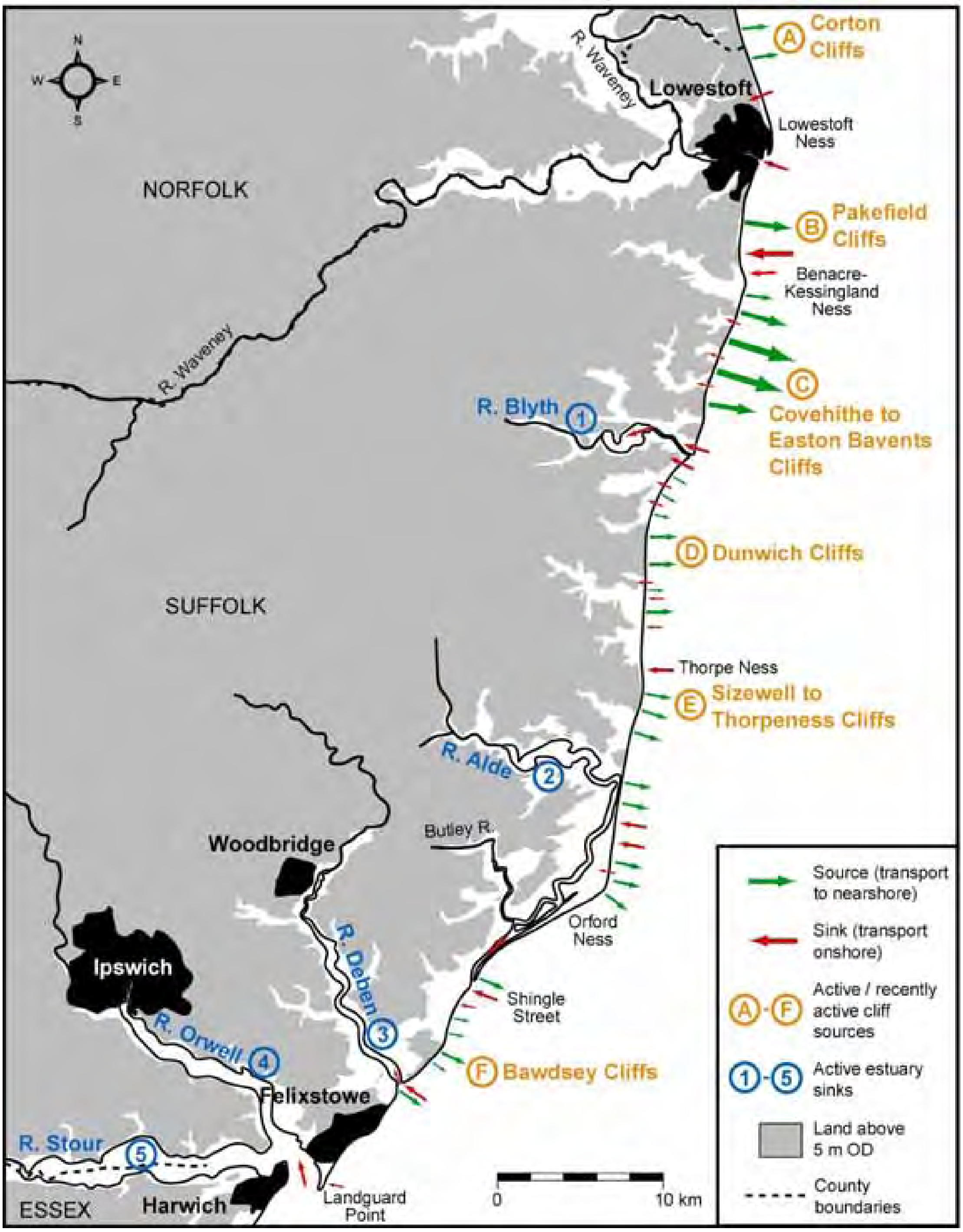


Figure 9.3 Schematic representation of the main net sediment sources and sinks along the Suffolk coast (after Pye and Blott, 2009a).

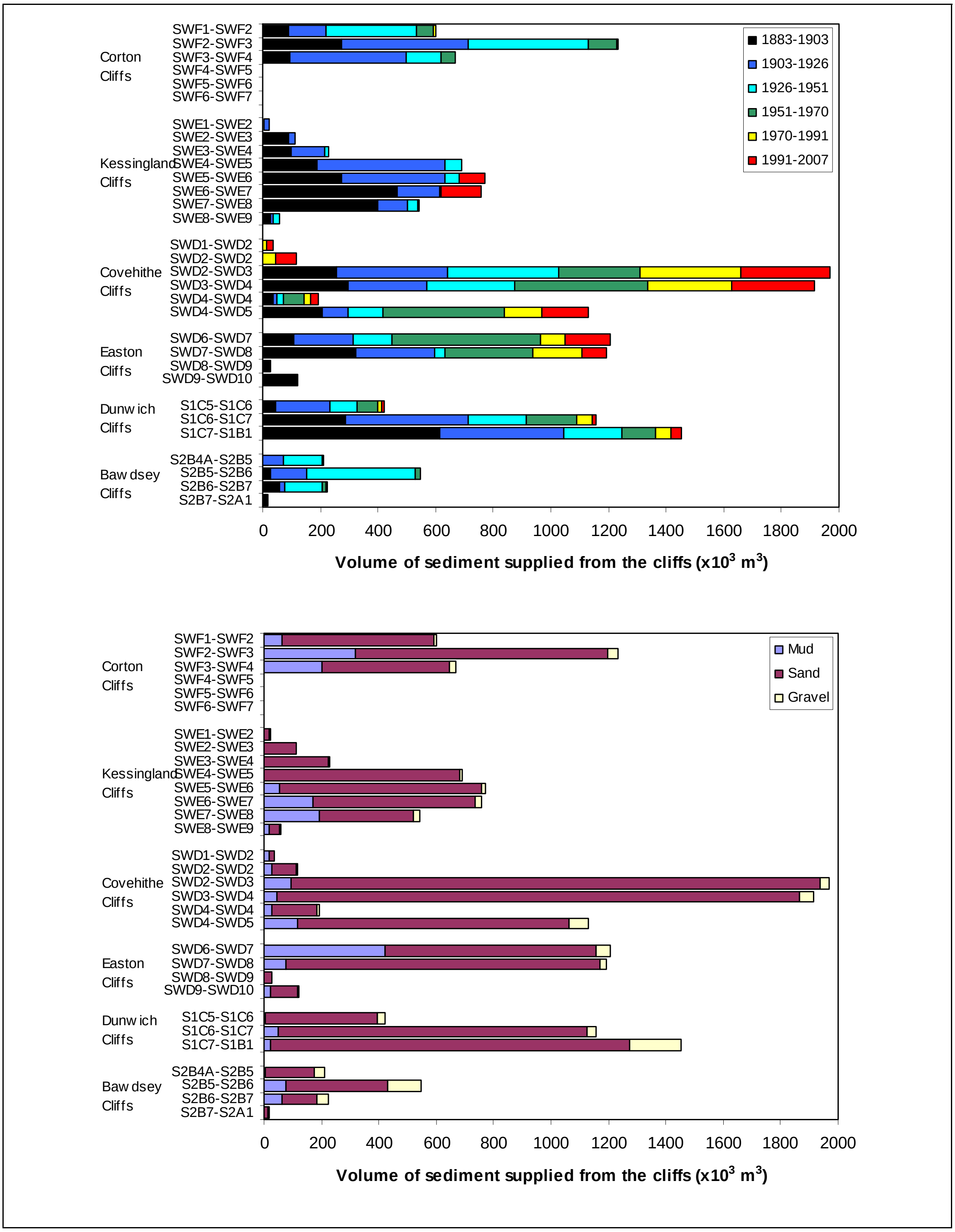


Figure 9.4 Volumes of sediment supplied to the coast from cliff erosion, calculated at Environment Agency monitoring locations from Ordnance Survey six-inch County Series maps surveyed 1883-1971, and beach profiles surveyed in 2007.

(Top) volumes of sediment supplied in each survey period; (Bottom) total volumes of gravel, sand and mud supplied in the period 1883-2007. Note that cliffs are also present at Sizewell, Aldeburgh and Felixstowe, but these exhibited no significant erosion in the period 1883-2007. From Pye and Blott (2009a).

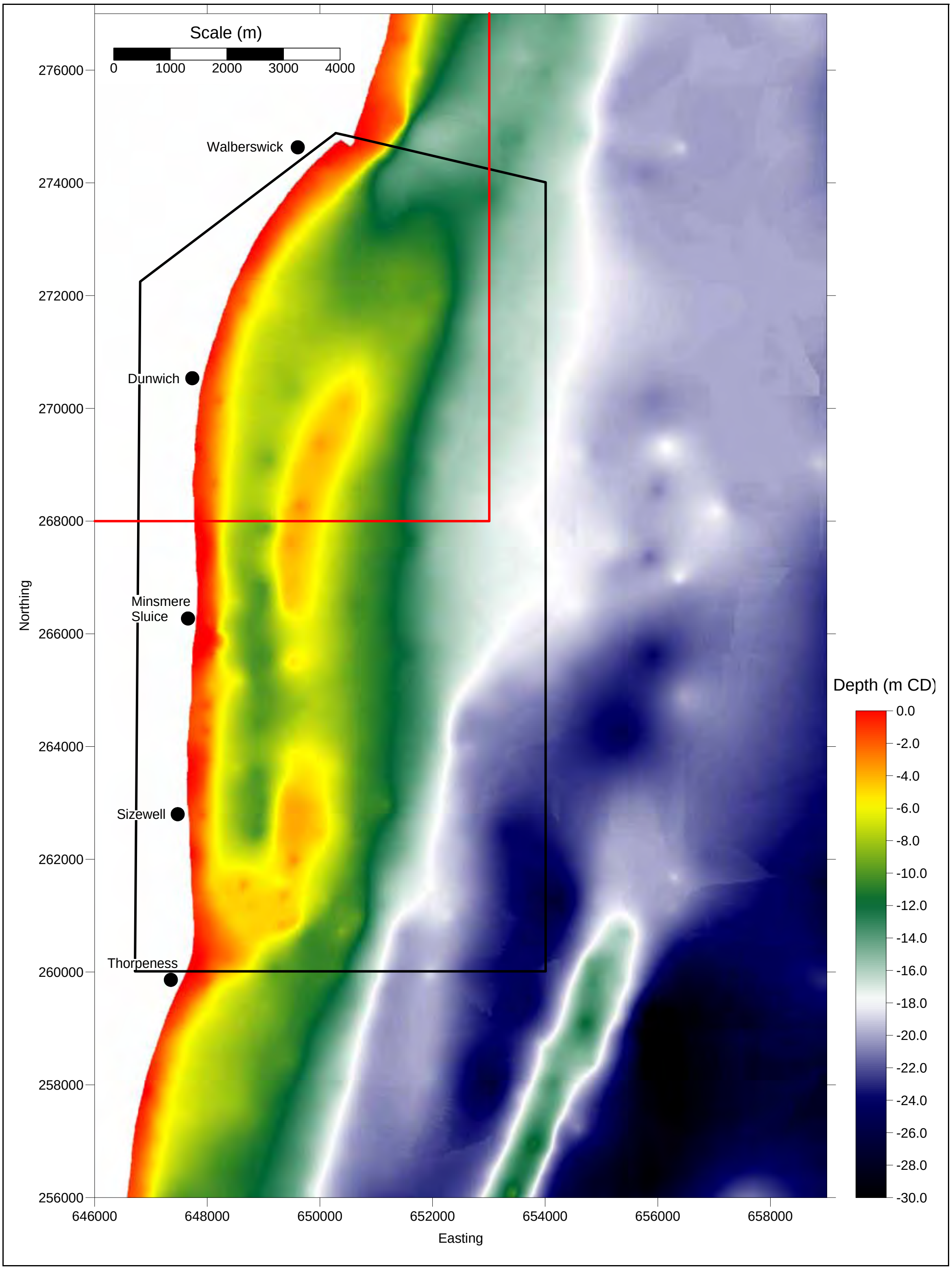


Figure 9.5 Digital elevation model of the nearshore and offshore zones between Southwold and Thorpeness, including Sizewell-Dunwich Banks, based on historical Admiralty Charts.

The black line indicates the limits of area for which sediment volume calculations were made, illustrated in Figure 9.7. The red line indicates the area shown in Figure 9.12. After Pye and Blott (2009a).

A detailed system map of the entire Suffolk coast, showing the links between different features and elements, was described earlier in this report (Section 6.2.1). A simpler conceptual representation of the main features and their sediment exchange interactions, referred to by Pye and Blott (2009a) as a system component diagram, SCD, is shown in Figure 9.6 for the more limited coastal area between Minsmere Sluice and Kessingland Cliffs.

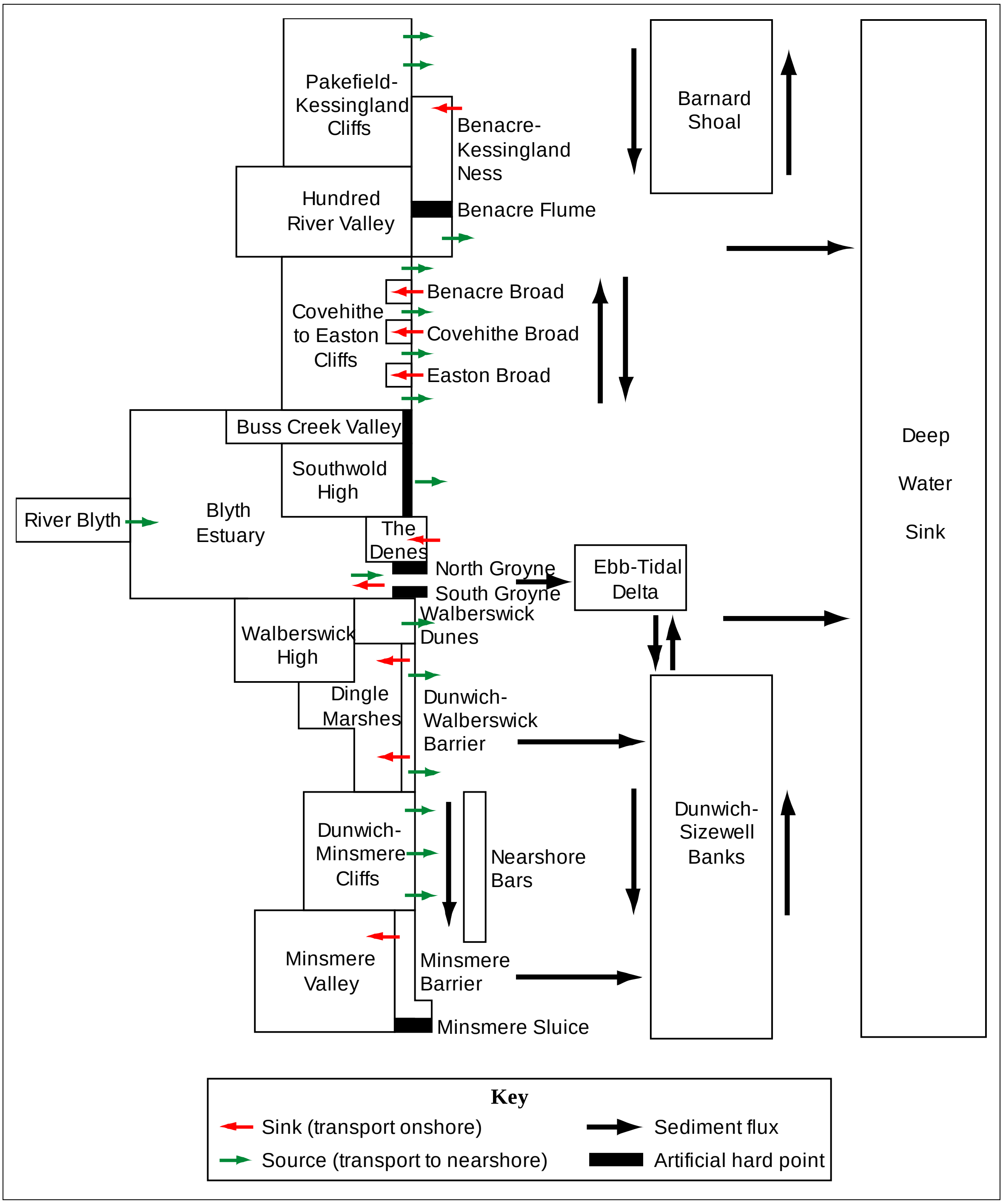


Figure 9.6 System component diagram (SCD) showing the main geomorphological features on the central Suffolk coast and their spatial relationships (after Pye and Blott, 2009a).

Changes in bathymetry and stored sediment volume within this area have been quantified by analysis of historical charts (Pye and Blott, 2006a,b, 2009a). Figure 9.7

shows a summary of sediment volume changes in the area between Southwold and Thorpeness, including the Sizewell-Dunwich Banks, above the -10 m Chart Datum level between 1824 and 1984. Even when allowance is made for errors associated with the surveys, charting methods and digitization process, there appears to have been a significant increase in the sediment volume between the 1867 and 1958 surveys (especially 1867-1921), but an apparent decrease between the 1965 and 1984 ones. The apparent increase during the earlier period corresponds with a period of rapid cliff erosion, while the apparent reduction in the later twentieth century corresponds with a period of generally lower rates of cliff erosion.

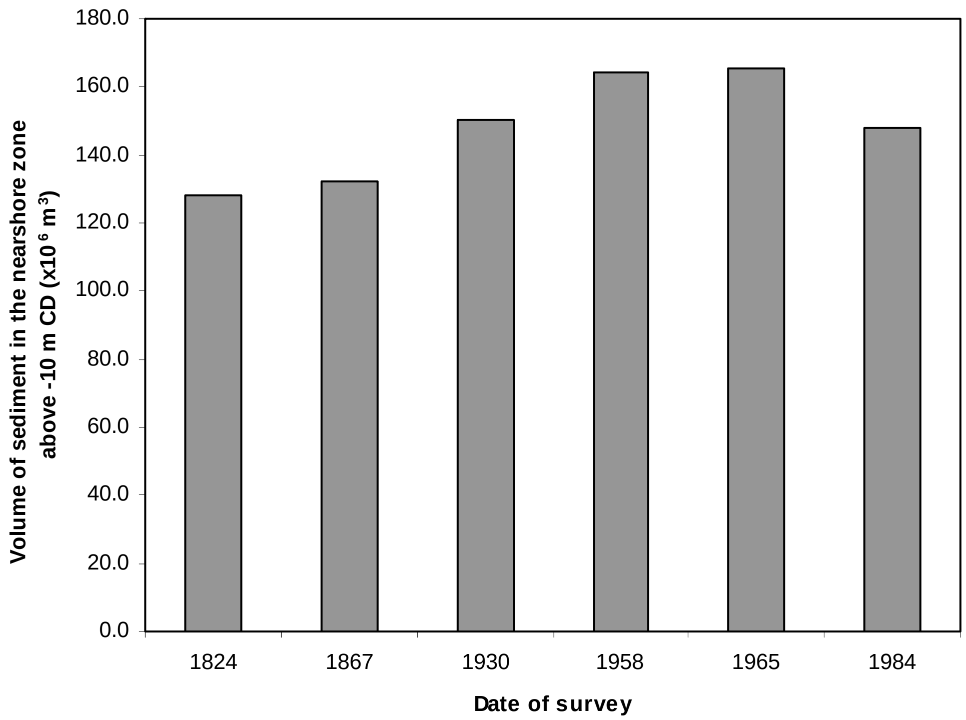


Figure 9.7 Volumes of sediment above -10 m CD in the nearshore and offshore zones between Southwold and Thorpeness, including Sizewell-Dunwich Banks.

Calculated from digital elevation models generated from historical Admiralty Charts (see Figure 9.5). The reduction after 1965 was primarily due to a decrease in the volume of the crestal areas of the Sizewell-Dunwich Banks.

The main potential drivers of cliff erosion are storm waves and rising sea level. Short-term cliff erosion rates are closely linked to the volume of sediment in the fronting beach, which acts to protect the cliff toe from wave attack. Beach widths and volumes are strongly influenced in the short term by sediment supply and wave energy conditions; the latter depend partly on meteorological forcing factors and partly on changes in offshore and nearshore bank behaviour (see Dolphin *et al*., 2007).

Wave regime along the Suffolk coast is bi-directional, with periods dominated by waves from the north east alternating with periods of waves from the southeast (Figure 9.8). Net drift directions show reversals on several different timescales, varying from a few days to decades. Although total potential transport rates are fairly high, net transport rates in most areas are low because northerly and southerly movement largely cancel themselves out. However, areas of net sediment transport divergence and convergence can be identified, based on the results of computer modelling (see Halcrow, 2001; HR Wallingford *et al*., 2002; Black and Veatch, 2005) and geomorphological assessment (Pye and Blott, 2009a, b). Some of the areas of net sediment convergence are reflected by the formation of nesses (such as Benacre-Kessingland Ness), while areas of sediment transport divergence are associated with beach volume loss and shoreline retreat (such as the central part of the Dunwich-Walberswick barrier).

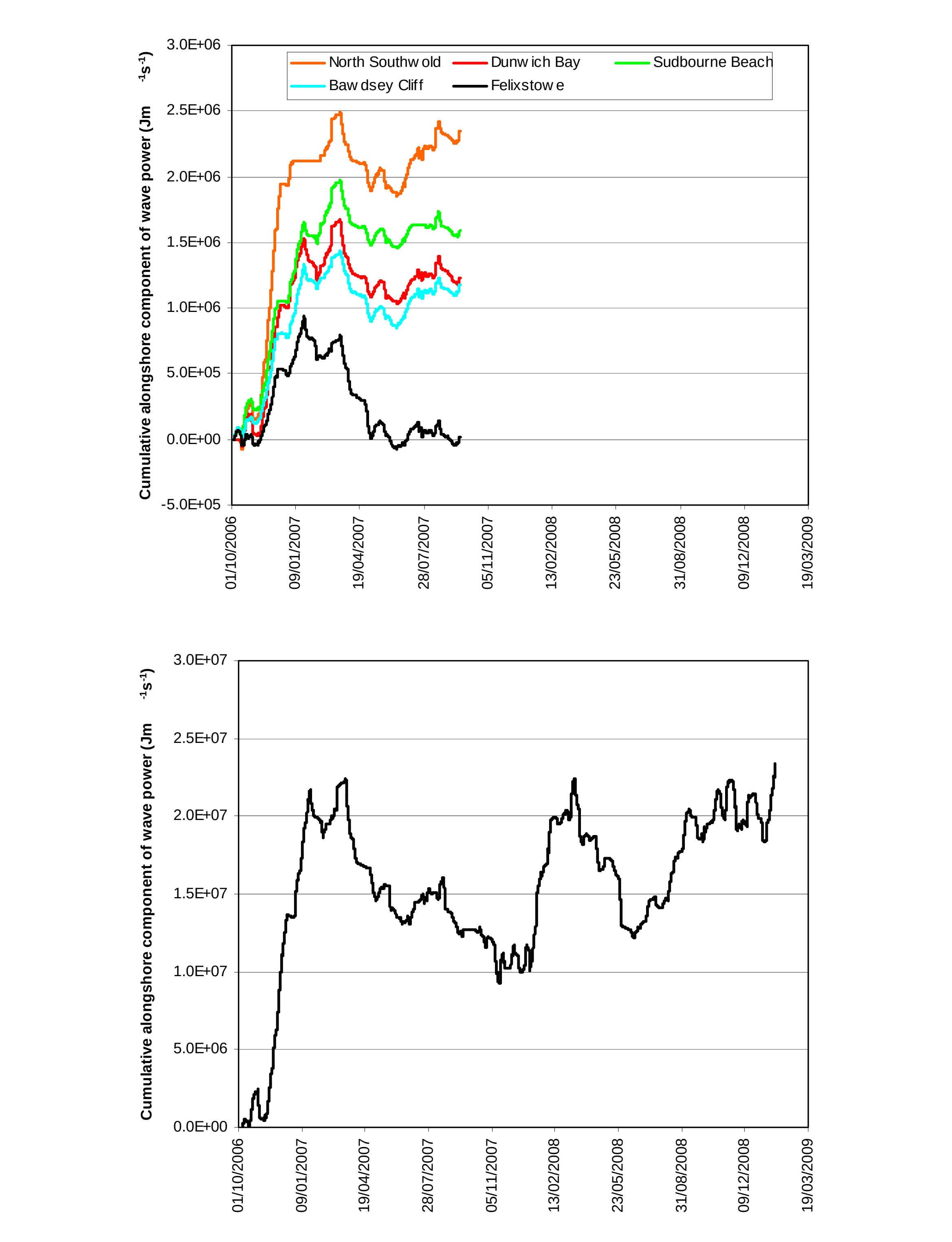


Figure 9.8 Potential alongshore transport rates inferred from the cumulative alongshore component of wave power measured at wave recorders near the Suffolk coast.

(Top) five inshore AWAC recorders at North Southwold, Dunwich Bay, Sudbourne Beach, Bawdsey Cliff and Felixstowe, positioned approximately 300 m from the coast, between October 2006 and September 2007; (Bottom) offshore waverider buoy at Southwold Approach, positioned approximately 7 km from the coast, between October 2006 and January 2009. Positive values indicate a northward component of wave power along the adjoining coastline. Seasonal and shorter-term reversals in potential transport direction are clearly evident (after Pye and Blott, 2009a).

Geological and archaeological evidence suggests that sea level has been rising at 1-2 mm/year in East Anglia for much of the last 1,000 to 2,000 years, and tide gauge records indicate an average rate of mean sea level rise of 2.8 mm/year since 1964 (Figure 9.9). However, the total sea level rise over this period (around 0.12 m) is small compared with the magnitude of storm surges which can raise predicted high water levels by more than one metre. There is no convincing evidence that rising sea level has had any major effect on cliff erosion rates in Suffolk (Pye and Blott, 2008, 2009a).

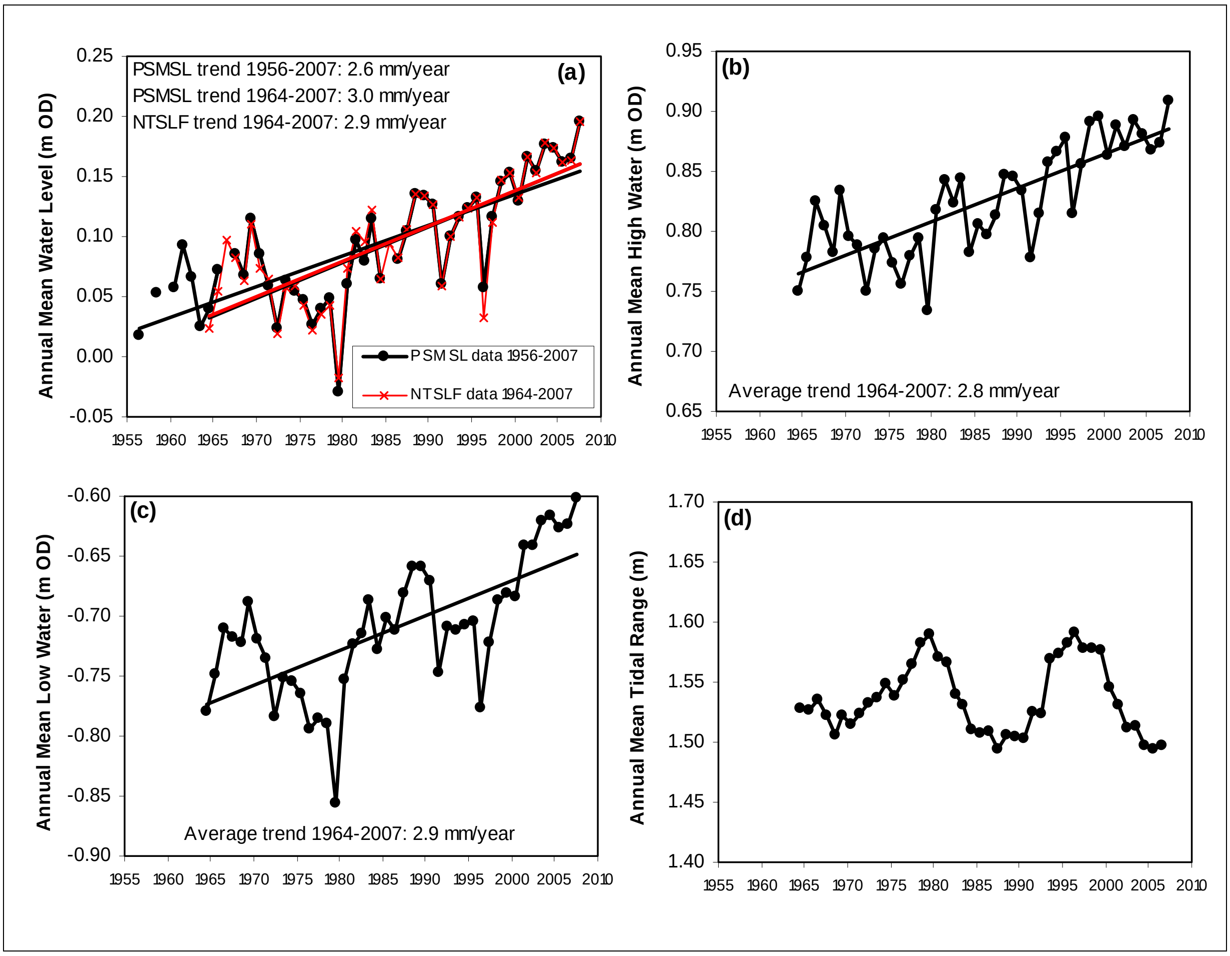


Figure 9.9 Trends in sea levels recorded at the Class A gauge at Lowestoft, 1956-2007: (a) annual mean sea level; (b) annual mean high waters; (c) annual mean low waters; and (d) annual mean tidal range. Data sources: PSMSL and NTSLF. From Pye and Blott (2009c).

Analysis of beach and nearshore profile data obtained as part of the Environment Agency Anglian Region coastal monitoring programme has revealed significant spatial variations. Figure 9.10 shows changes in shoreline position, defined in terms of MHWS level, and beach sediment volume above LAT, between 1992 and 2003 at 81 profile positions between Corton Cliffs and Landguard Point. The data show marked landward movement of the shoreline and loss of sediment volume along the cliffed coast north of Southwold and near the Orford Ness lighthouse. Significant seaward movement of the shoreline, associated with increases in beach sediment volume, occurred at Kessingland, Pakefield, and Shingle Street. In the former case, shoreline progradation was associated with the northward movement of Benacre Ness.

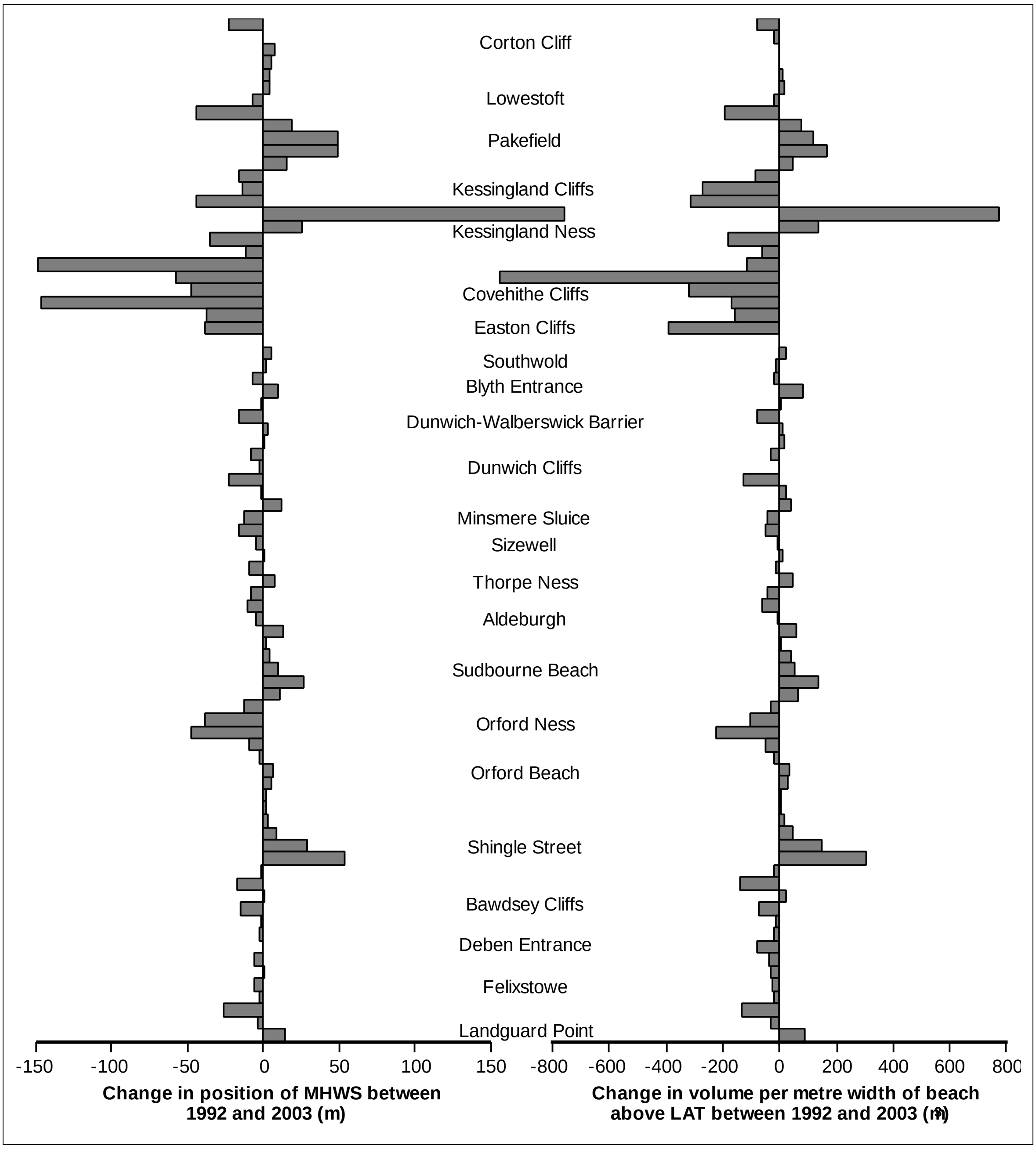


Figure 9.10 Bar charts showing changes between 1992 and 2003 on 81 Environment Agency beach and bathymetric profile lines between Corton and Landguard Point*.

*(Left) changes in the position of MHWS; (Right) changes in beach volume per metre width above LAT (after Pye and Blott, 2009a).

9.2.3. Coastal changes on different timescales

Historical maps and archival data sources indicate that the coastal morphology in the Southwold-Dunwich area has changed considerably over the last few hundred years. During the Middle Ages there was a large promontory to the north of Southwold, known as Easton Ness, which at that time was reportedly the most easterly point in England. Relatively high ground continued southwards from Easton towards Southwold, creating a natural barrier at the eastern end of Easton Marshes. The high ground on which Southwold now lies extended further east, creating a bay (Sole Bay) between it and Easton Ness. A significant spit feature (King's Holm) extended south from Southwold almost as far as Dunwich. Another promontory existed to the east of Dunwich, creating an area (Eastwood) on which a large part of Dunwich town was built. Dunwich was an important port at this time, with ships able to anchor in Dunwich Bay, to the north of Eastwood, and in the estuary of the Dunwich and Blyth rivers, which entered the sea near Dunwich (Pye and Blott, 2006b).

The Little Ice Age (thirteenth to mid-nineteenth centuries) was generally a stormy period which led to rapid erosion along much of the north and central Suffolk coast, although there were interludes of less stormy conditions. Easton Ness and the Eastwood promontory were completely eroded away, and the Southwold frontage also experienced recession. Most of the sediment released was removed from the near-shore system and either became fixed in offshore banks or moved south under the influence of dominant southerly drift. Dunwich harbour entrance was blocked several times during severe storms, and eventually a new artificial cut was made near Walberswick, diverting the outflow of the Blyth and Dunwich rivers to a point close to the present outlet.

After 1850 average climatic conditions began to improve (become warmer and less stormy), with increasing frequency of westerly conditions compared with easterly and northeasterly conditions (Lamb, 1972). The consequence on the Suffolk coast is likely to have been an increased frequency of waves from the southeast relative to northeast and east, resulting in a reduction in the rate of net southerly sediment transport. By analogy with events over the last 20 years for which both meteorological and coastal monitoring data are available, this is likely to have favoured higher beach levels and lower rates of coastal cliff erosion in many areas, although there would have been shorter-term variations superimposed on the longer-term trend (Pye and Blott, 2009d). If this conceptual model is correct, a trend towards further warming over the next 100 years may produce increased frequency of westerly and southwesterly winds, southeasterly waves and northerly sediment drift conditions on many parts of the Suffolk coast.

The evidence from historical Ordnance Survey maps has shown that rates of cliff erosion in most parts of Suffolk have declined since the late nineteenth century (Pye and Blott, 2009a). Some sections of cliff have become entirely protected by the development of wide beaches (such as between Sizewell and Thorpeness, at Kessingland, and at Pakefield). At Dunwich the average rate of cliff recession has remained low since the early twentieth century, and only at Covehithe has the rate of recession remained relatively consistent at 3.5 to 4.0 m/year over the last 30 years.

A second major cause of coastal change in Suffolk has been the increasing scale of human interventions. Embanking and land claim within some estuaries may have begun as early as Roman times, but it became significant in the medieval period and continued until the late twentieth century. The period 1750-1830 was particularly important in terms of the creation of artificial cuts, land drainage and embanking. Harbour works also have along history, notably at the major ports of Lowestoft and Felixstowe, but also at some of the smaller ports and havens. Following the growth of seaside tourism in Victorian times, there was considerable expansion of beach front developments at Lowestoft, Southwold, Aldeburgh and Felixstowe. The combined effects of these activities were four-fold: (1) tidal exchange capacities within the estuaries were greatly reduced, (2) estuarine channels became fixed, especially near the estuary mouths, (3) the natural dynamism of some lengths of open coast frontage was constrained, and (4) regional scale sediment transport pathways were broken into sub-cells defined by the hard defences. Secondary effects included a reduction in the size of tidal deltas at estuary mouths, build-up of sediment on the updrift sides of harbour walls, terminal groynes and sluices, beach depletion on the downdrift sides of such structures, and beach lowering due to wave reflection and scouring in front of some protected frontages. Where shoreline positions have been held artificially by management measures, the present cross-shore profiles are often out of equilibrium with current processes, and have required successive phases of management intervention in the form of rock armour, wooden revetments or beach nourishment to prevent undermining of the defences and flooding or collapse of property. Particular problems have arisen at the ends of defended frontages where recession has continued, in some cases threatening to circumvent the defence works (such as at the Easton Bavents end of the Southwold defences shown in Figure 19.13.a). An increase in nearshore water depths of the order of 25 cm over the past century, due to average sea level rise of around 2.5 mm/year, has contributed to the problem, albeit in a relatively minor way.

Even along the relatively short section of coast between Southwold and Dunwich, there have been significant spatial and temporal variations in beach width and volume since 1992 (Figure 9.10). Sediment accretion has continued on the north side of the North Pier of the Blyth because this structure traps sediment drifted from the north and prevents the erosion of trapped sediment during periods of south-easterly wave activity. There is limited space to allow further progradation of the shoreline, but the area will continue to act as a sediment store for windblown sand. South of the Blyth entrance, the shoreline position has fluctuated only by a few metres following the completion of a dune restoration scheme in the early 1990s. This area will also help to act as a sink for windblown sand. The central part of the Walberswick-Dunwich barrier has continued to lose sediment volume due to net drift of sediment both to the north and south, and the low level of the barrier means that sediment will continue to be pushed landwards by washover. This trend has been ongoing for the last 500 years and is likely to continue for the foreseeable future (Pye and Blott, 2006a, b, 2009b; Figure 9.11).

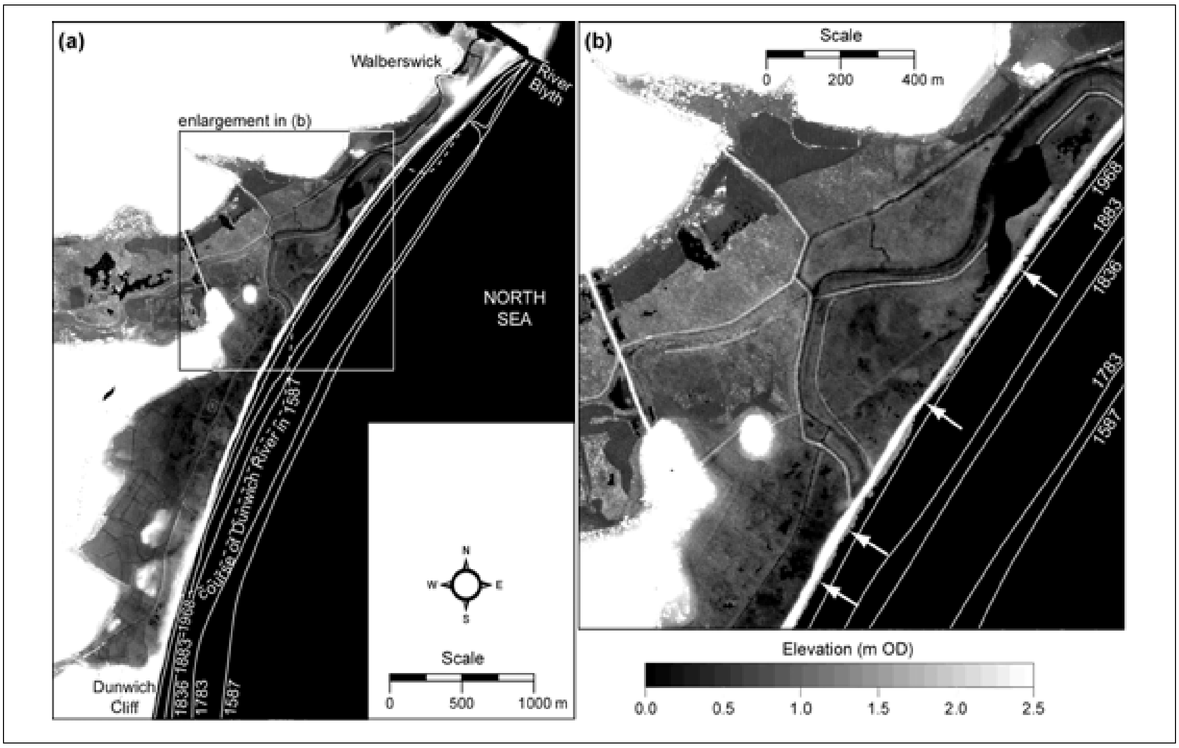


Figure 9.11 (a) LiDAR image of Walberswick to Dunwich area with superimposed historical shoreline positions digitised from historical maps; (b) enlargement showing central part of barrier and locations of four major breach channels formed during storm of 31 Oct to 1 Nov 2006. After Pye and Blott (2006b).

Until 2005 the position and height of the Walberswick barrier were maintained by bull-dozing of sediment, mainly, but not exclusively, from the seaward side. The effect was to slow the rate of shoreline recession for a number of years, but progressive loss of sediment volume from the central area and a series of major breakthroughs after 2004 made the policy unsustainable. Since abandonment of management the barrier has re-established a flatter, wider profile which is subject to partial washover several times each year (Pye and Blott, 2009b). Modification of the profile is progressing towards Dunwich and Walberswick. Modelling of the conditions under which the early failures of the flood bank occurred in 2006 and 2007 have indicated that surge levels were more important than wave energy (see Section 8.8 of this report). Analysis of digital surface models created using LiDAR data acquired in 1999, 2003 and 2008 has allowed quantification of the changes in the cross-section morphology and sediment volume along the barrier (Figures 9.12 and 9.13). Using a similar approach, calculations have been made of the volumes of water which are likely to flood the marshes behind the barrier during surge events of differing magnitude, from which estimations have been made of the associated tidal flow velocities through the breaches in the barrier (Pye and Blott, 2006a). This type of DEM-based process modelling and morphological response assessment provides a useful accompaniment to other tools, such as inlet stability analysis described in Section 8.9 of this report.

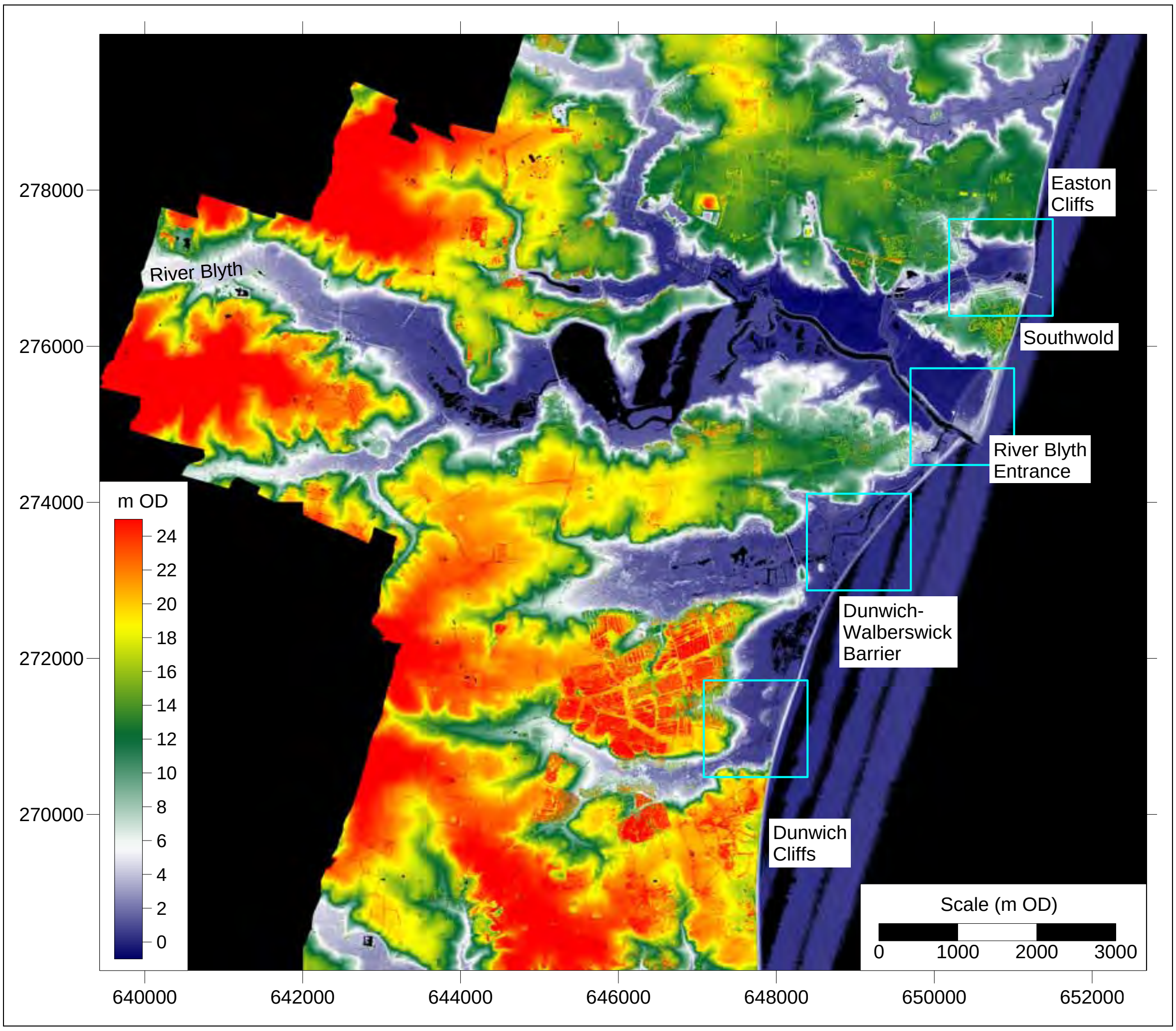


Figure 9.12 Digital surface model of Suffolk coastal area between Easton Cliffs and Dunwich Cliffs, generated from unfiltered Environment Agency LiDAR data flown 27 February 2008. Blue boxes indicate the areas covered in Figure 9.13.

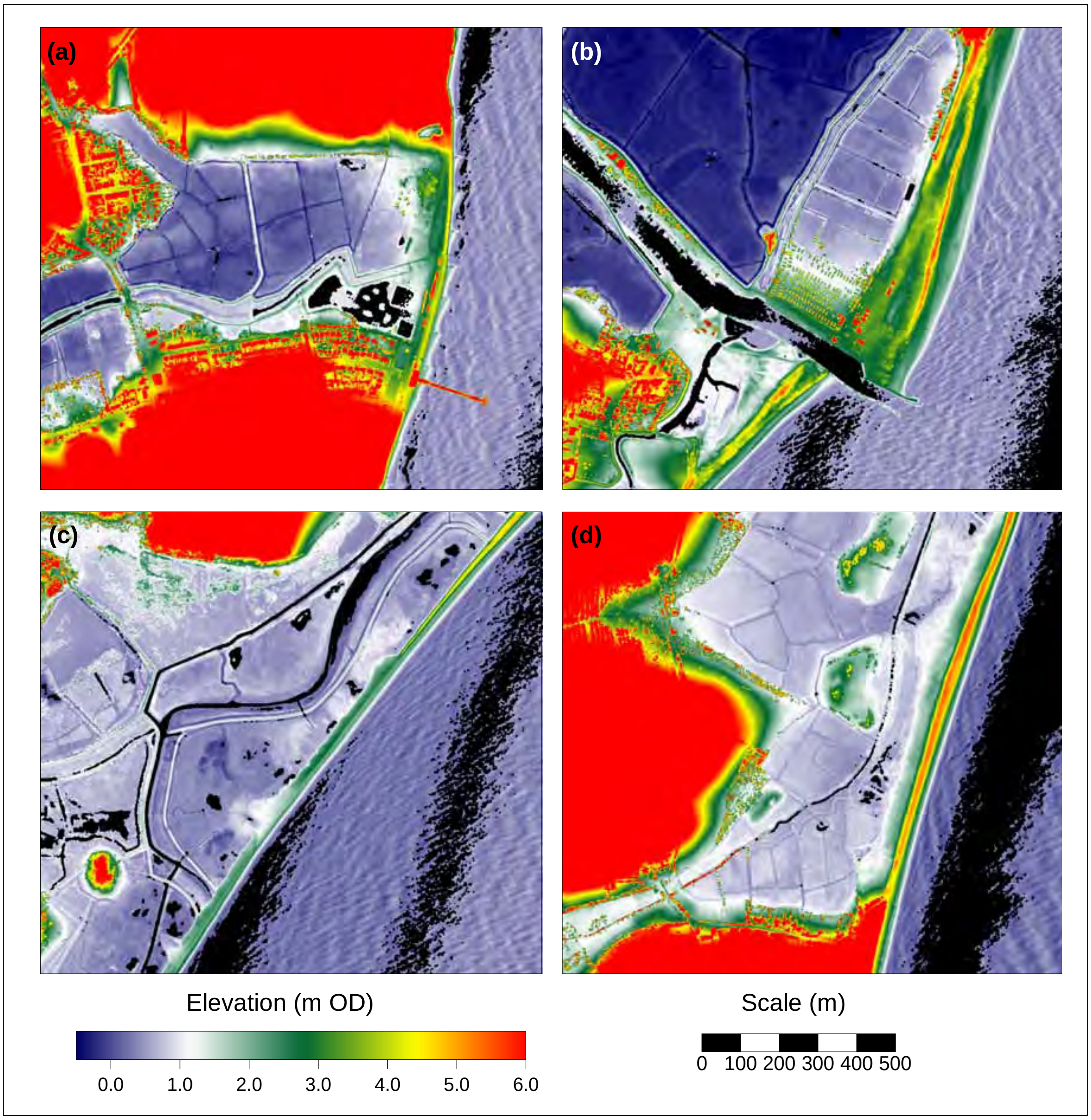


Figure 9.13 Digital surface models of key locations between Easton Cliffs and Dunwich Cliffs, generated from unfiltered Environment Agency LiDAR data flown 27 February 2008*.

*(a) Sea wall at eastern end of Easton Marshes, north of Southwold, which is in danger of being outflanked by soft cliff erosion at northern end; (b) Entrance to Blyth Estuary, showing sand dune barriers on north and south sides of piers; (c) Central part of the Dunwich-Walberswick barrier, showing very low crest elevations and recent washovers onto Corporation Marshes; (d) Wider and higher southern end of Dunwich-Walberswick barrier and northern end of Dunwich Ciffs.

9.2.4. Prediction of future coastal changes

Based on a synthesis of the results from previous studies, historical trend analysis, process monitoring and the application of other modelling tools, Pye and Blott (2006a, 2009b) predicted that by 2115 the central part of the barrier will have retreated almost to Great Dingle Hill, effectively separating the back-barrier area into two parts (Figure 9.14). By this time the Dunwich River is likely to have established a new outlet to the sea somewhere along the Reedland and Corporation Marshes frontage. The reed beds to the west and north of Great Dingle Hill will experience regular tidal influence unless surrounding embankments are raised significantly. Drainage from Westwood and Old Town marshes is likely to continue to enter the Blyth Estuary near Walberswick, but these areas are likely to become progressively more saline over the next 100 years.

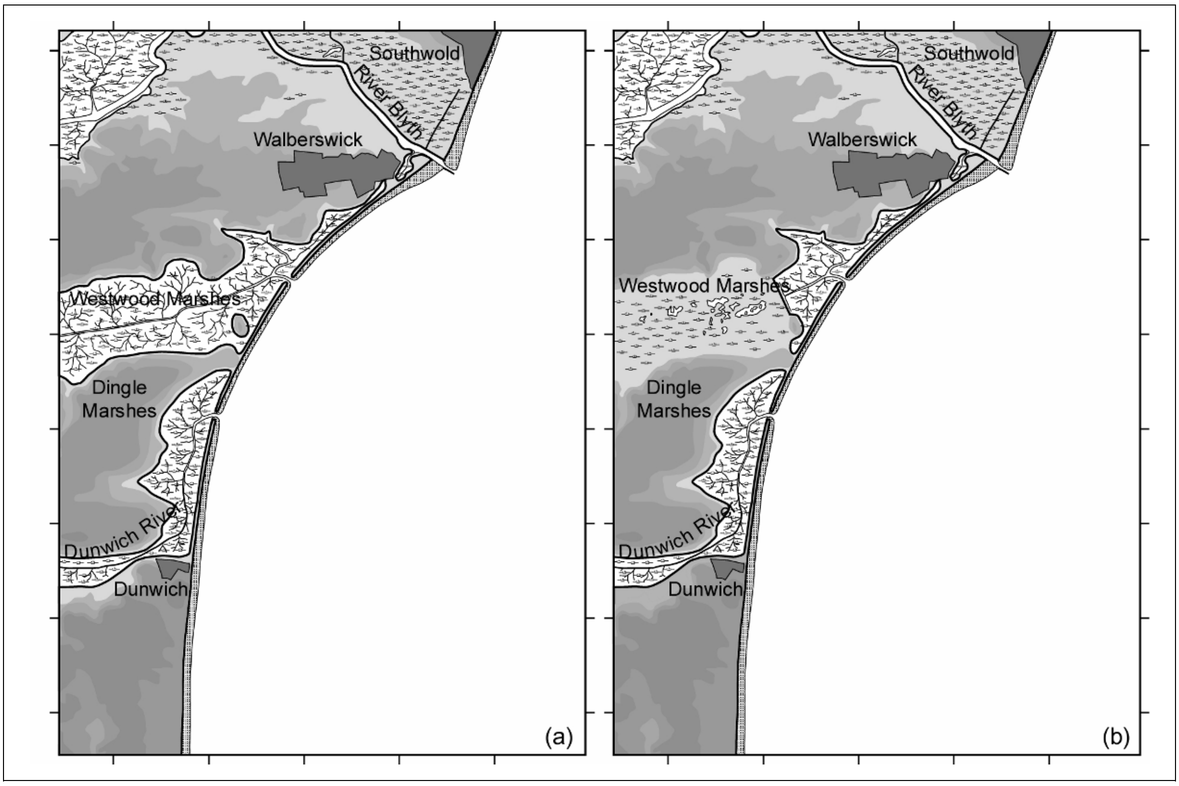


Figure 9.14 Indicative prediction of the coastal morphology between Southwold and Dunwich in the twenty-second century: (a) under a 'do nothing' scenario; and (b) with maintenance of the Westwood Marshes embankment to cope with rising sea level (after Pye and Blott, 2006b)*.

*It has been assumed that the engineering situation at the mouth of the Blyth, and the hard coastal defences at Southwold, will be maintained and improved as necessary.

There is uncertainty over future management of the Blyth Estuary entrance. The current recommended management policy for the Southwold frontage is to hold the line for the next 100 years; to achieve this, it will be necessary to maintain the North Pier which plays an important role in holding the beach to the north (Royal Haskoning, 2009). However, even if maintenance of the harbour mouth structures is discontinued, the remains of the North and South Piers, and the harbour behind, are likely to continue to exert a major influence on processes around the mouth of the estuary for at least the next 100 years.

A general policy of ‘no active intervention’ is currently proposed by the Environment Agency for flood defences within the Blyth Estuary, but it is uncertain whether some or all of the embankments will be maintained by private landowners and other interested parties. Embankments upstream of the A12 at Blythborough, and those surrounding Tinkers Marsh in the mid-estuary, were breached during storm surge events in 2006 and 2007, although breaches in the Tinkers Marsh wall have since been repaired. Earlier breaches in the walls around Angel, Sandpit Covert and Bulcamp Marshes, which occurred during the period 1927-1968, have not been repaired and these areas have reverted to mudflat. Short-term process studies in these areas have shown that short-term rates of sediment accretion are strongly dependent on degree of wind wave activity which controls the likelihood of mud re-suspension (French, 2001; French *et al*., 2006, 2008). However, a recent study of mud thickness above the former reclaimed land surfaces has shown an average net accretion of more than half a metre across the area since the time of breaching (Pye and Blott, 2009c; (Figure 9.15a and b)). Although the results of hydrodynamic modelling (French, 2001, Black and Veatch, 2006), and limited field monitoring (Gardline, 2003), suggest that significant parts of the estuary are ebb-dominated, the sedimentological evidence has shown that the estuary has accumulated a large volume of mud over the last 65 years, derived principally from North Sea sources (Pye and Blott, 2009c). Even if sea level rises by up to one metre over the next century, mudflat accretion will probably keep pace unless there is a significant reduction in the suspended sediment concentration of North Sea waters entering the estuary, or a significant increase in wave-induced mud re-suspension.

As noted above, the tidally-influenced area of the Blyth has varied considerably over the last 200 years, largely in response to embanking and reclamation (Figure 9.16). Consequently, the tidal prism and average tidal current velocities with the estuary have changed considerably (Figure 9.17 and 9.18). One of the most significant effects of embanking and reclamation has been to reduce the flood and ebb tidal velocities in the main channel of the estuary, leading to persistent problems for navigation at the harbour entrance. Breaching of walls around some of the former reclaimed marshes over the past 65 years has increased the tidal area, tidal prism and tidal current velocities at the estuary entrance. Further increases can be predicted if some or all of the remaining embanked areas are eventually abandoned, even without any significant further increase in sea level (French, 20001; Black and Veatch, 2006, 2007; Pye and Blott, 2009b). The effects of increases in flood and ebb tidal velocities are likely to include deepening and/or widening of the main channel in the lower estuary, placing greater pressure on the harbour structures and embankments around Robinson's Marsh and Southwold Town Marsh. In time, these could fail if maintenance is not carried out.

Another potential consequence of large scale realignment within the estuary could be the development of a larger tidal delta at the mouth of the estuary, with implications for the longshore transport of sediment across the mouth of the Blyth and wave action on the Southwold and Walberswick frontages. However, growth of the ebb tidal delta would require the availability of a suitable source of sand and gravel. Erosion of the Covehithe and Easton cliffs provides a potential source of suitable sandy sediment, but the evidence from monitoring suggests that little of the sediment released from this source in recent decades has found its way to the mouth of the Blyth, or on to the Walberswick-Dunwich frontage. In part, this may reflect a relatively high incidence of southerly wave energy, leading to northerly longshore drift over the period or offshore movement of sediment along the Southwold frontage into deeper water. Large-scale managed or unmanaged realignment within the Blyth may therefore have little or no beneficial effect on the adjoining coastal frontages. Further studies are required to investigate the inter-relationships between coast and estuary in more detail.

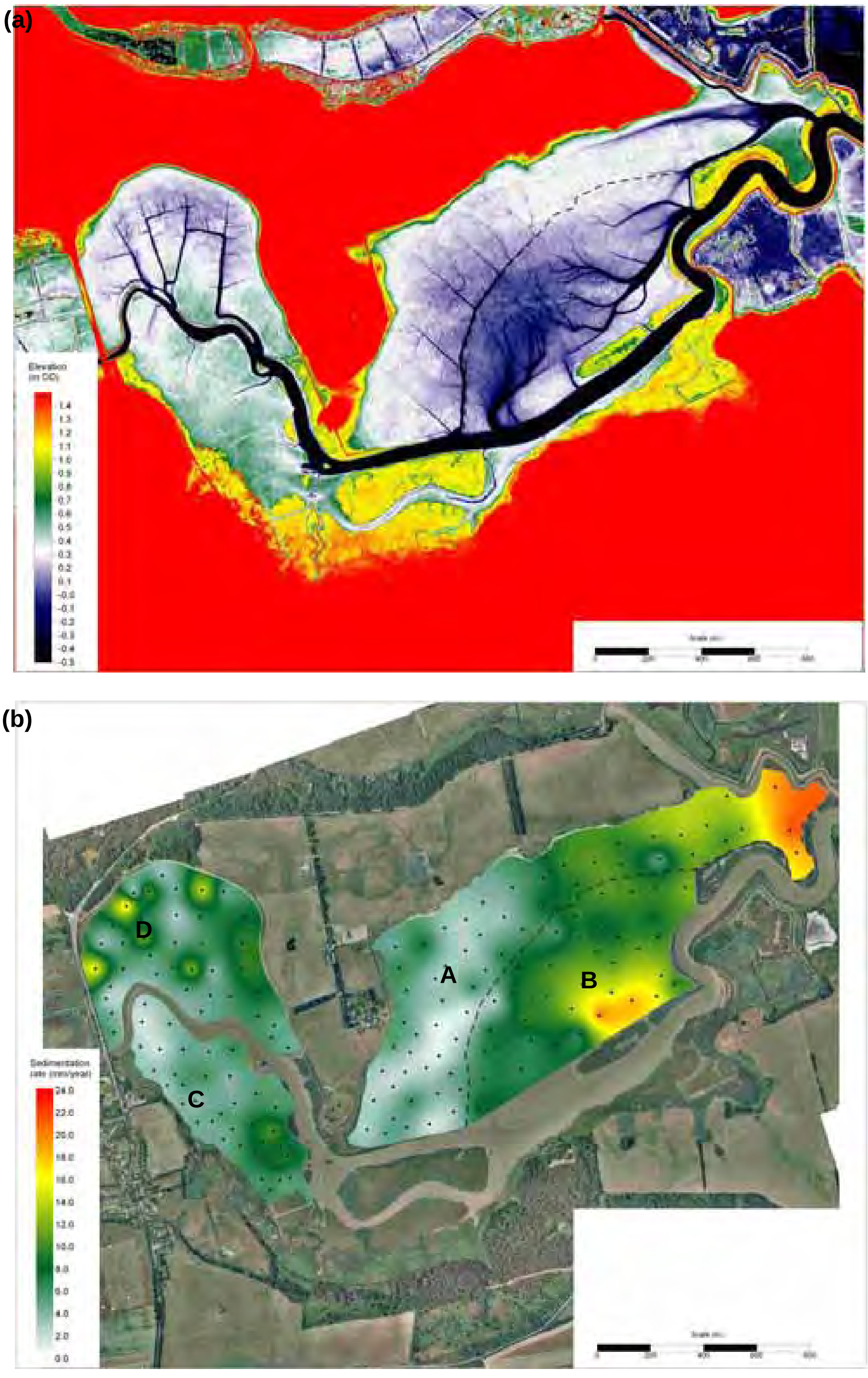


Figure 9.15 (a) Digital surface model of the inner Blyth Estuary constructed from LiDAR data flown in April 2003 by the Environment Agency; (b) average mudflat sedimentation rates over 65 years based on RTK GPS survey and mud thickness determinations above the former reclaimed land surface at 170 point locations on (A) Bulcamp Old Marshes, (B) Bulcamp New Marshes, (C) Angel Marshes and (D) Sandpit Covert Marshes. From Pye and Blott (2009c).

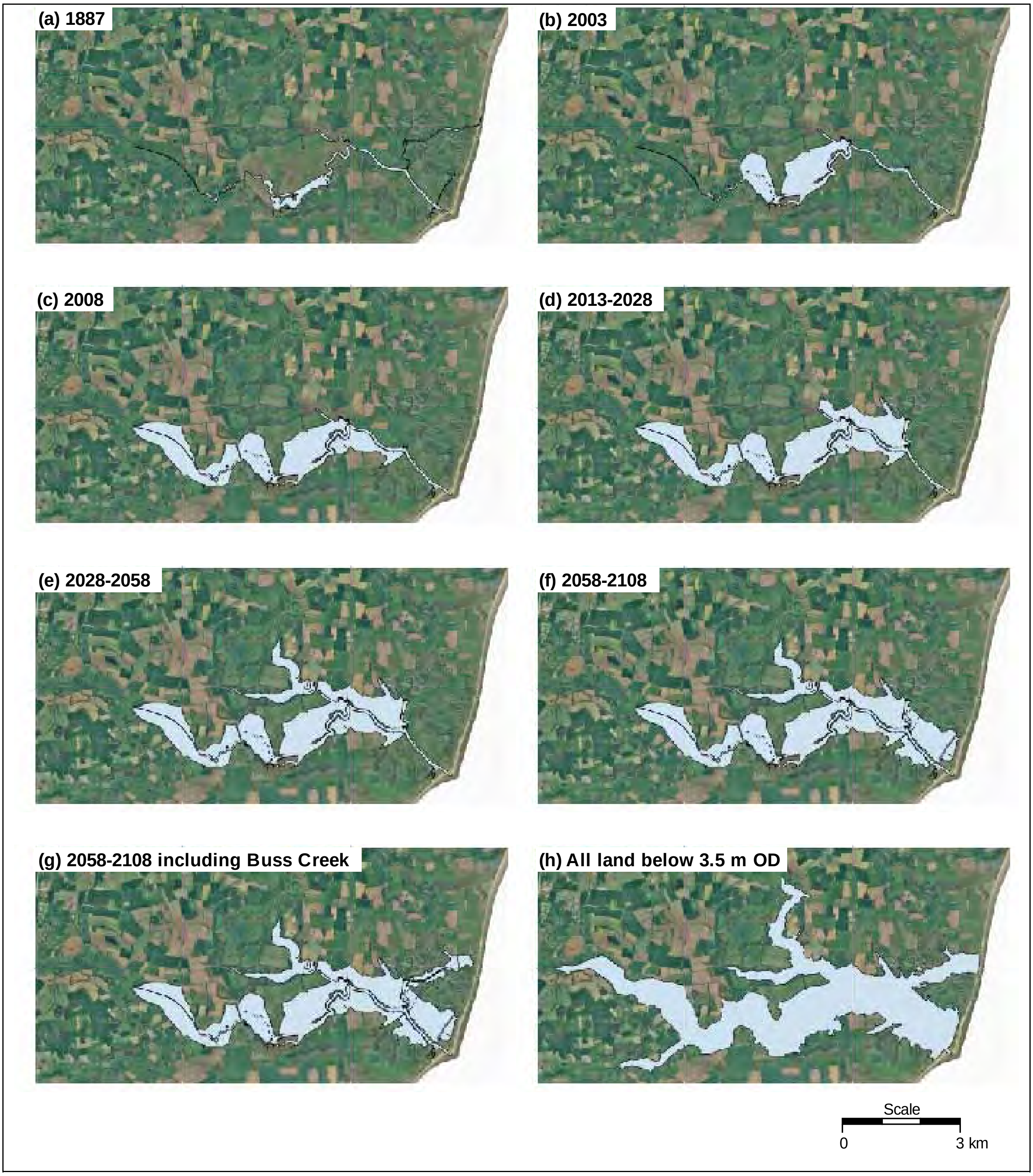
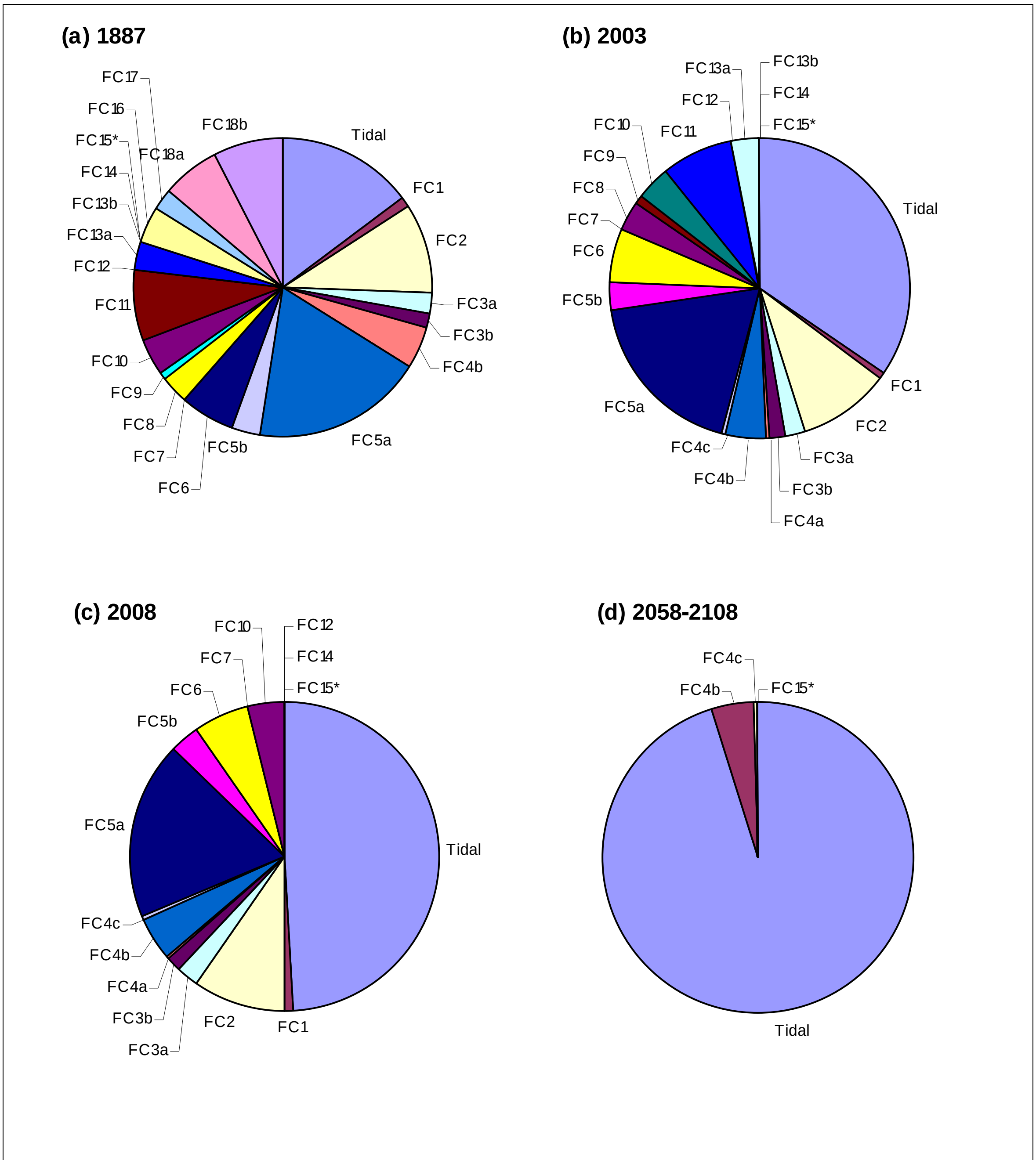


Figure 9.16 Changes in tidally flooded area of Blyth Estuary below present MHW between 1887 and 2008 (a to c), projected changes taking into account different future scenarios defined in the Environment Agency Blyth Estuary FRM Strategy Technical Summary Report (2007) for the periods 2013-2028 (d), 2028-2058 (e) and 2058-2108 (f), and the total area of land which could be flooded if no defences are maintained by tides equivalent to the present MHW (g) and 3.5 m OD (h). After Pye and Blott (2008).



* values partly estimated for FC15 due to incomplete LiDAR coverage

Figure 9.17 Percentage tidal volumes within Blyth Estuary for a tide reaching one metre OD at (a to c) different times in past and (d) a future scenario in 2058-2108 excluding Buss Creek as shown in Figure 9.16f (after Pye and Blott, 2008).

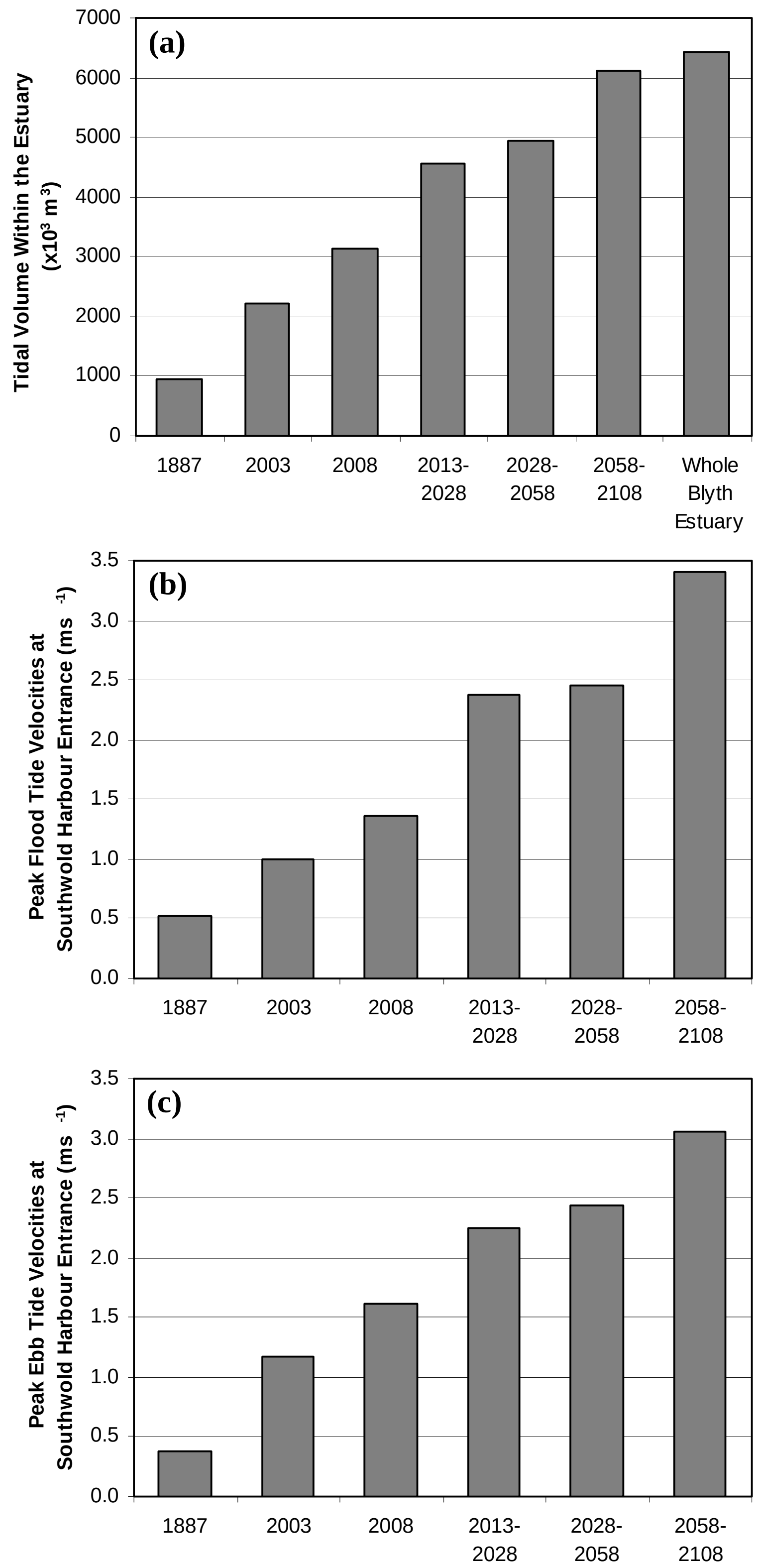


Figure 9.18 (a) Estimated tidal volumes, (b) flood tidal velocities and (c) ebb tidal velocities at the entrance to the Blyth Estuary at different times in the past, and for future scenarios, for a tide reaching one metre OD (after Pye and Blott, 2008).

10. Discussion of research

10.1. Applicability to coastal management

This research has focused on the characterisation and prediction of large-scale long-term change of coastal geomorphological behaviours. The framework established in Section 3 provides a basis within which the different approaches that have been developed during the project, such as systems mapping, proof of concept modelling, and geomorphological methods, can be used to investigate different elements of large-scale long-term behaviour.

Critically, this framework enables the findings from these individual but inter-linked components to be synthesised within the context of an expert geomorphological assessment (EGA, as described in Chapter 9) to better understand future evolution of the coast.

This approach has direct applicability and immense value in applied coastal management. It ensures that good understanding of the coastal geomorphological behaviour is gained before efforts are made to manage coastal issues, thereby ensuring that the best solutions are chosen. It also enables the consequences of change in coastal geomorphological behaviours to be considered with respect to the assets and features located within coastal systems. Thus, research outputs will be of value to the Environment Agency in its work in the areas described in Box A.

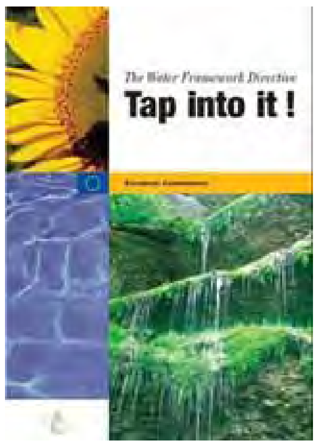
Box A – Policy drivers of Environment Agency business

Making Space for Water

Overview role in coastal erosion risk and its strategic management

Water Framework Directive

Understanding of "hydromorphology" and its relationships with biological and chemical quality



Habitats and Birds Directives	Floods Directive
Understanding of changes in geomorphological systems that sustain habitats which in turn support bird populations	Erosion or breaching of natural coastal features leading to increased sea flooding risk
	

Situations in which understanding of large-scale long-term coastal geomorphological behaviours could be improved through the outputs of this project are outlined below.

10.1.1. Shoreline Management Plans

With a focus on large spatial scales (coastal cells or sub-cells) and long timescales (up to 100 years), Shoreline Management Plans (SMPs) are the most obvious example of where research outputs are of direct relevance in applied coastal management. However, in developing a SMP further research is not usually carried out as part of the SMP itself. Instead, the SMP must draw from research, studies and monitoring that has taken place between successive reviews of the SMP and apply expert geomorphological assessment (EGA) in its interpretation during the update review of the SMP so that the following tasks can be undertaken:

- The coastal system can be understood in terms of its past evolution and present processes.
- Projections can be made of likely future evolution under different hypothetical scenarios of 'no active intervention' and 'with present management' to understand the boundaries within which management decisions will influence behaviour.
- The consequences of different generic SMP policies can be assessed.
- The consequences of preferred SMP policies for specific frontages can be assessed, in terms of local, larger scale and longer term implications.

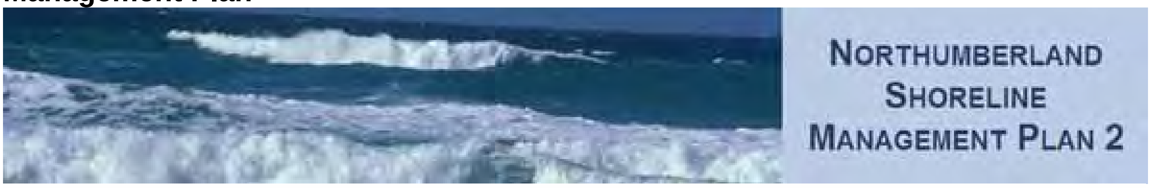
Present SMP guidance (Defra, 2006a) advocates the adoption of a so-called "behavioural systems" approach; this is further discussed in Appendix A. Many of the approaches developed in our project can usefully inform such an approach, as they are aimed at understanding the:

- Behaviour of different elements of the system (such as the geomorphological methods described in Chapter 8).
- Behaviour of explicit links within the system (such as the open coast and estuary links at inlets through the proof of concept modelling described in Chapter 7, or the systems mapping in Chapter 6).

- Large-scale and long-term behaviour of the geomorphological system as a whole (such as EGA as described in Chapter 9).

The following is an example of how EGA has been applied to the development of policy in a Shoreline Management Plan in North East England. In the Northumberland and North Tyneside SMP2 (Royal Haskoning, 2009a), which covers the coastline between the Scottish Border and River Tyne, through a good appreciation of geological context, understanding geomorphological behaviour, and awareness of the inter-connectivities gained through conceptualised systems mapping, large-scale long-term change along several frontages was determined to be governed principally by geological control at headlands, with embayments formed in between. In selecting policies, it has been necessary to use EGA to identify key features controlling behaviour and select the best management policy for those areas. Once set, it is then easier to define policy for adjacent coasts within the context of the governing controls and behaviour. A case study from this SMP is presented below to demonstrate this point (Box B).

Box B – Example of description of connectivity between features in a Shoreline Management Plan



Key Interactions in terms of Management Policy

Feature 1 St Mary's Headland	
Influence	The headland provides a strong control on shoreline evolution to the north-west and the south.
Management Options	The principal management options are to either hold the headland or to allow it to retreat to a new alignment (and perhaps then hold in this position).
Discussion of High Level Policy Decision Maintaining the headland in its present position makes holding the existing form of Whitley Bay easier in most places, although the transition from defended to undefended and then back to defended sections needs careful management to prevent outflanking. To allow the headland to retreat would mean that large sections of Whitley Bay would, over time, realign landwards in response, putting increasing pressure on existing defences and/or causing loss of assets along Whitley Bay due to erosion; in particular further lowering of the important recreational beach. Headland retreat (either in a managed manner or through No Active Intervention) would also result in the longer-term in the loss of recreational amenities (the access road, Trinity Road car park and toilet facilities) and impinge on the nature reserve at the headland. This policy is likely to cause loss of designated rocky foreshore habitat.	
High Level Policy: Hold the Line	

10.1.2. Managing a coastal system

The figure below shows one of the most interesting coastal geomorphological systems in the UK, namely Pagham Harbour in West Sussex. Here, an understanding of coastal geomorphological behaviours can help the Environment Agency, and its partner organisations, understand a number of key management questions relating to the area, such as:

- How did the spits and deltas at the mouth come into being and how have they changed over time?
- Why are there areas of coarser material on the coastline and finer material (such as salt marshes and mudflats) within the harbour?
- What are the implications of management decisions elsewhere along the nearby coast on the spits and deltas (or *vice versa*)?
- What are the implications of management decisions elsewhere along the nearby coast on the harbour frontages and habitats (or *vice versa*)?
- Will the spits remain stable landforms or will they breach?
- Will the configuration of the channel at the mouth remain the same?
- How will the whole system behave and evolve into the future in the light of climate change and other pressures?

These questions are all important in understanding the implications of future coastal geomorphological behaviour in terms of coastal erosion and flood risk, nature conservation, land use planning, the Water Framework Directive, and so on.

Application of the systems mapping (Chapter 6) in a workshop context would be a useful starting point for building consensus in understanding of this system. Particular aspects or links could then be further tested using modelling approaches developed in the proof of concept (Chapter 7) or specific geomorphological tools such as inlet stability assessments and historic trends analysis (Chapter 8), enabling the systems mapping to be refined if necessary. This could then be interpreted within the context of an expert geomorphological assessment (Chapter 9) and relevant scientific advice provided to the coastal managers, upon which decisions could be based.

11. Lessons learnt

11.1. Background

This project has sought to critically assess and further develop some of the approaches adopted. The real test of any method lies in its practical application to real situations experienced by coastal managers. During the project, some key lessons were learnt through the application of different approaches to case study examples. In case study applications and following reviews by members of the project team, refinements were made to the system mapping protocol described in Chapter 6. These findings are described below.

11.2. Follow-up consultation and trial use of a system mapping approach

11.2.1. Introduction

This project's main focus is on prediction of high level and long-term geomorphological processes but, as identified in the initial consultation process, this must include sufficient detail and understanding of systems to provide a framework from which more detailed analysis can be carried out, of use in day-to-day management of the coast. To test this usefulness for coastal managers, it was decided to trial the system mapping approach in two different situations.

Sefton Borough Council has been active in its approach to coastal management through involvement with various European-funded programmes and in addressing its own management of the shoreline. The council has most recently been involved with the Coastal Flooding by Extreme Events (COFEE) project. A document was produced to accompany a recent field visit as part of that project (Sefton DC, 2007), within which a series of maps and map-based information was developed. It was agreed that as part of the system mapping trial, the project team would consider this site and that this would be developed further by Graham Lymbery of Sefton Borough Council to examine what further insight might be derived from the system mapping approach.

The second trial made use of the Suffolk Coast case study. One section of the coast was taken covering the Blyth Estuary, which had an ongoing study commissioned by Suffolk Coastal District Council, to consider issues to be addressed in management of the lower estuary. In this trial, the aim was to examine how the system mapping approach could be used to develop a framework for assessing critical behaviour within the estuary and how the approach might used to consider interactions with the broader socio-economic system.

11.2.2. Sefton case study

11.2.2.1. Background

The Sefton coast is situated within the influence of the Mersey and Ribble Estuaries. Extracts from the COFEE site visit report show the principle features and issues (Figure 11.1).

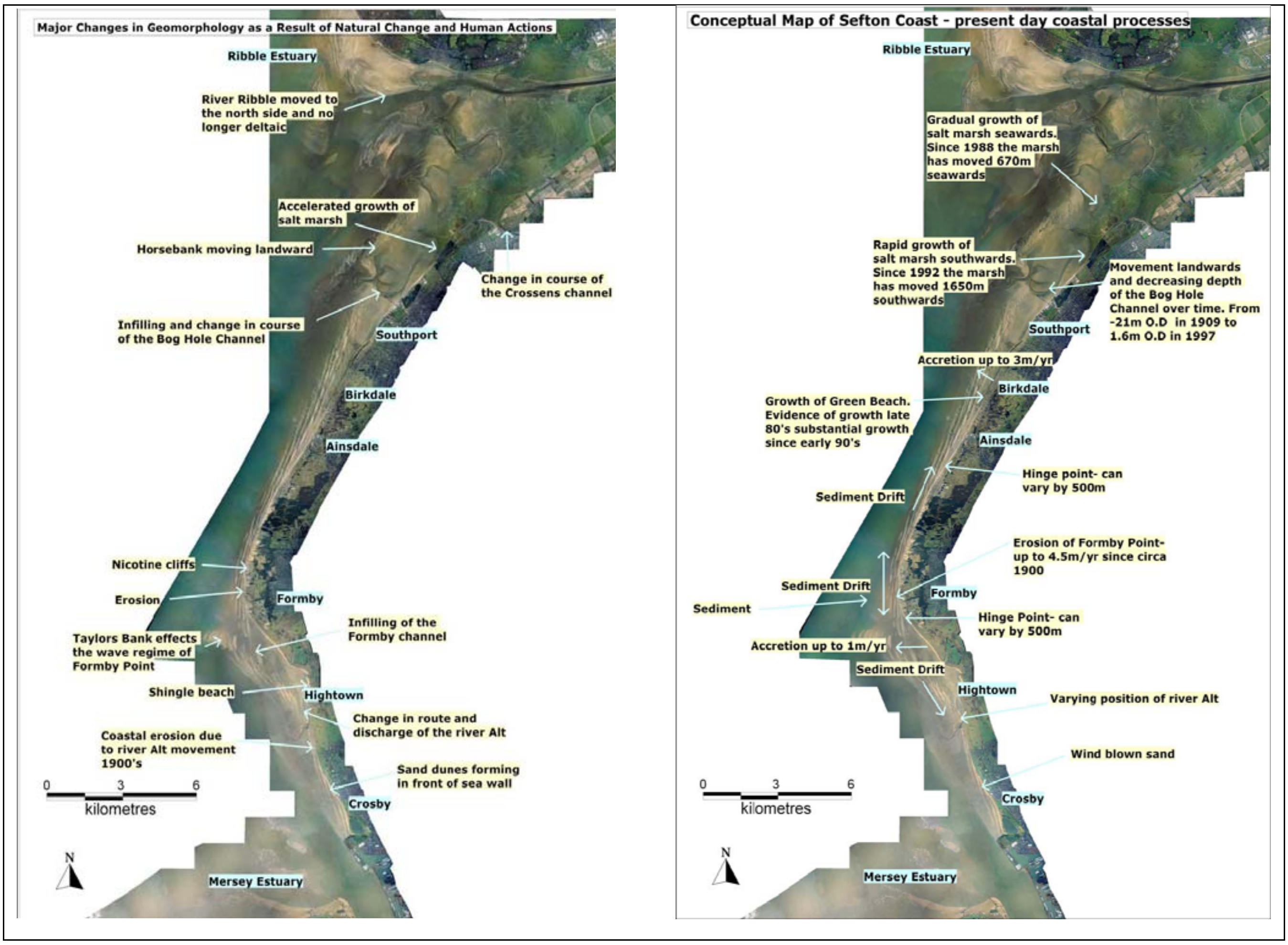


Figure 11.1 Figures showing major changes in geomorphology and assessment of present day processes (Sefton DC, 2007).

The approach taken in managing the Sefton coast has focussed on:

- building knowledge of how the system has and is responding;
- developing a conceptual model or hypothesis of the detailed processes and interactions;
- identifying, from this, areas of uncertainty and addressing this through detailed investigation;
- improving the conceptual model.

This has been based on extensive monitoring and analysis of historical information.

11.2.2.2. Aim of the trial

A draft version of Chapter 6 was provided to Sefton setting out the underlying approach adopted for the system mapping. The aim of the trial was to:

- See how easily the Sefton coast may be represented in the system mapping approach developed in this project.
- Examine whether the features and elements identified adequately represent those that occur on the Sefton coast.
- Examine to what degree the process of establishing how these features and elements are linked can add to understanding of the system behaviour in a manner useful to management and communication of coastal issues.
- Comment on the system mapping process.

A full assessment of Sefton coast was not intended; here, the intent was to consider how intuitive the use of systems mapping could be. As a starting point, an initial assessment and example was produced, based on the southern section of the frontage with the aim of a more comprehensive overview being developed by Graham Lymbery.

This initial assessment was prepared based on a process map for the southern Sefton coast as shown in Figure 11.2. The principal features are identified in Table 11.1.

Table 11.1 Identification of features.

Location	**Feature**	**Comment**
Ribble (not shown)	**Estuary**	
Ainsdale	Open Coast?	At what point does this stop acting as an open coast and more as a bay linked to the Ribble?
Formby Point	Cuspate Foreland?	Is this a headland or indeed just a bit of open coast formed behind Taylor's Bank? Or is Taylor's Bank a feature determined by the Formby Headland?
Taylor's Bank	Spit?	Given the sediment drift direction is this a spit or a barrier island?
Hightown	Bay?	Is this functioning as a bay and does this make Formby Point a headland? Or is it linked to Taylor's Bank?
Alt	Outlet	Is this a defunct estuary such that Hightown now acts as a bay?
Great Burbo Bank/training banks	Barrier Island	
Crosby	Headland	Artificial
Mersey Estuary	Estuary	
Mersey	River	How significant is this to the system?
Offshore	Seabed	

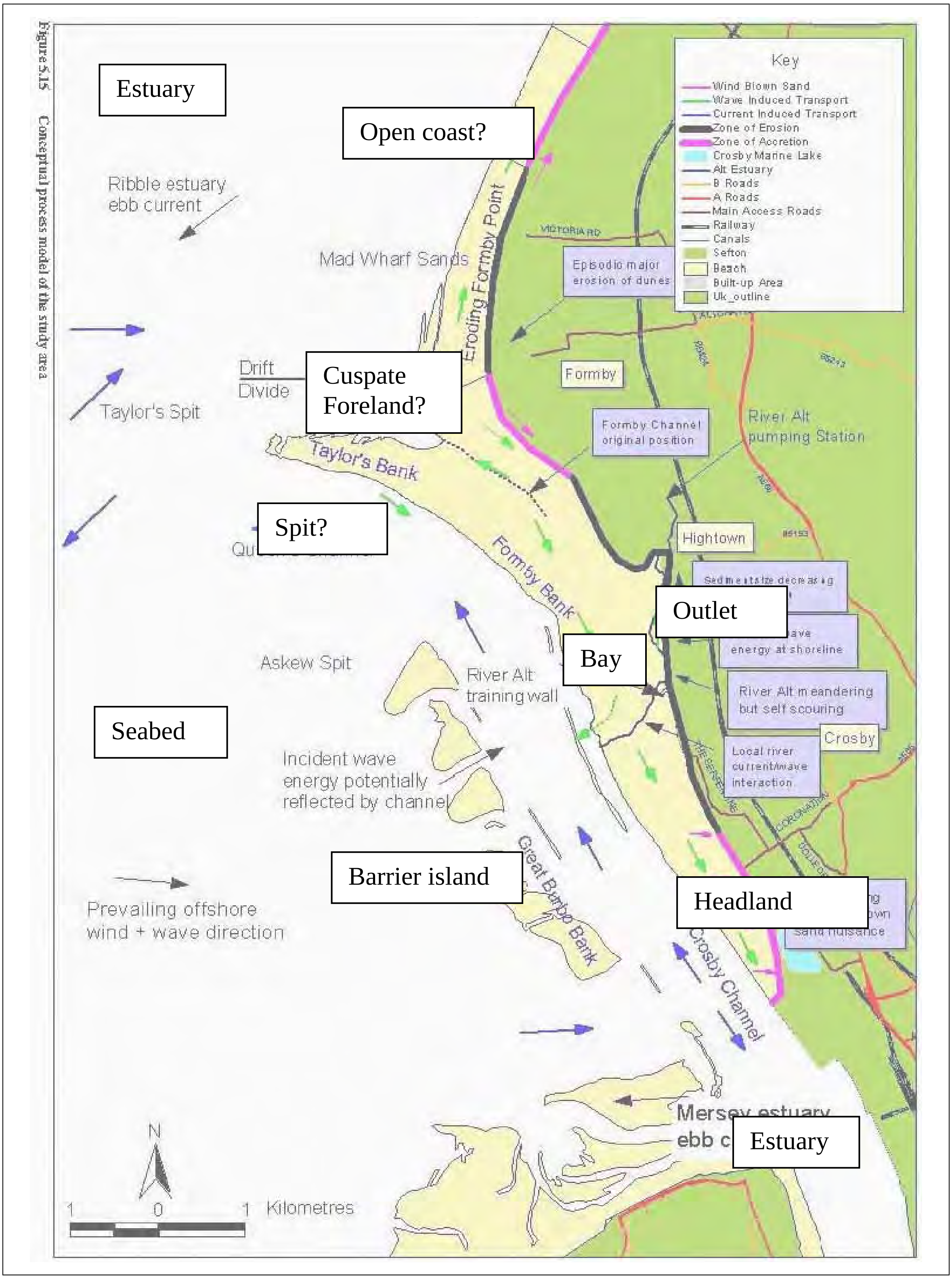


Figure 11.2 Initial definition of features.

Elements were identified associated with each feature as shown in Table 11.2. The mapping was undertaken in Excel[2] and is shown in Figure 11.3.

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[2] This demonstrates the non-software specific approach that has been developed.

Table 11.2 Identification of elements.

Location	Feature	Elements		
		Foreshore	**Backshore**	**Hinterland**
Ribble (not shown)	Estuary			
Ainsdale	Open Coast?	Beach	Dunes	Low lying
				High ground
Formby Point	Cuspate Foreland?	Foreshore platform	Dunes	High ground
Taylor's Bank	Spit?	Channel		
Hightown	Bay?	Beach ridge	Dunes	High ground
			Saltmarsh	Outlet/low lying
			Channel	Revetment
			Channel	Beach
Alt	Outlet			
Great Burbo Bank/ training banks	Barrier Island	Offshore bank	Training wall	Channel
Crosby	Headland	Channel	Seawall	
Mersey Estuary	Estuary			
Mersey	River			
Offshore	Seabed			

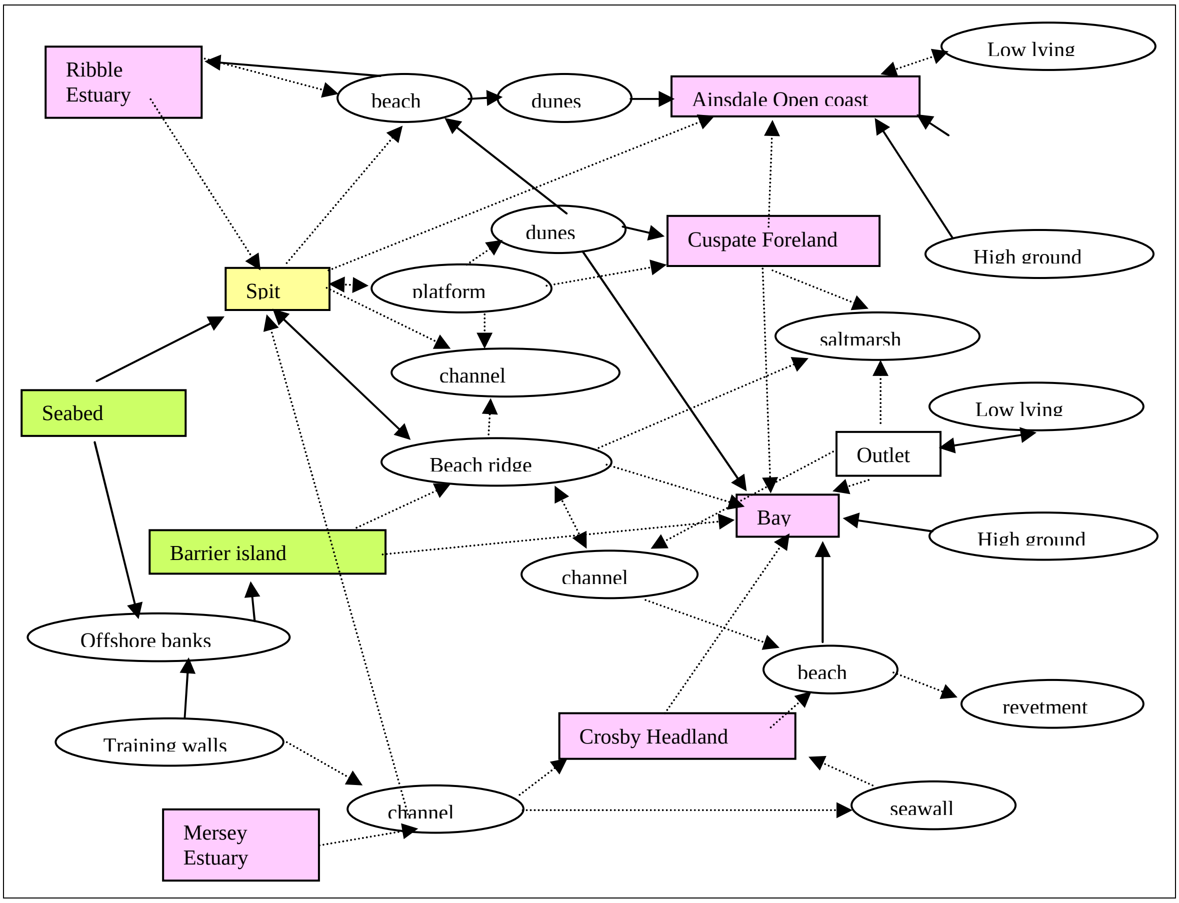

Figure 11.3 Initial system map.

11.2.2.3. Results of the trial

It was apparent in developing the initial example that the section chosen was complex and might better be described as a series of subsystems. This was not developed further. In part because of this, Graham Lymbery found it difficult to work back to a more generalised version of a system map for the whole coast. The principal barrier here was recognising the significance of various geomorphological features. This, as shown in the initial example, was found to be an issue with respect to several features, such as Formby Point and Taylor's Spit. Graham Lymbery felt that one needed to have a good knowledge of geomorphological terms before attempting to undertake mapping. In particular, he felt that one had to have a good understanding of the function of a feature so that, when mapped, its function within the system could be understood.

The process was, however, useful and highlighted in discussion certain points:

- There was a need to understand the function of geomorphological terms to understand how features and their interactions should and could be mapped. Through the process of having to think about these terms, one could start to understand the critical behaviours that link features.
- It is useful to work down through a system rather than attempting to work up from the detail.
- Further work could be undertaken (as described in Section 6 of the main report) on rationalising components of the system, once an initial map has been created.
- The process caused the user to think about system behaviour and this was a means of distilling instinctive knowledge.

Graham Lymbery voiced concerns that many coastal managers would be put off by the task. He was also concerned that mapping an existing system could lead to antecedent conditions being overlooked. In general, the approach could be useful but possibly more to those with a geomorphology background. Graham also felt that the text needed to be expressed in a less technical manner, with less reliance on people understanding geomorphological terms.

Finally, Graham Lymbery suggested that geographical mapping was more helpful in that it linked the theoretical approach to observed patterns of behaviour.

It was concluded that the approach could be beneficial in three main areas:

1. In the SMP process in identifying broad-scale links.
2. In developing skills and training for coastal managers.
3. As a means of communication.

Where possible, note was taken of Graham Lymbery's comments in final drafting of Chapter 6 of this report and French and Burningham (2009).

11.2.3. Blyth Estuary case study

The second trial used the case study for the Suffolk Coast in considering critical behaviours of the Blyth Estuary.

The case study mapping is shown below in Figures 11.4 and 11.5, together with photographs illustrating the general system behaviour.

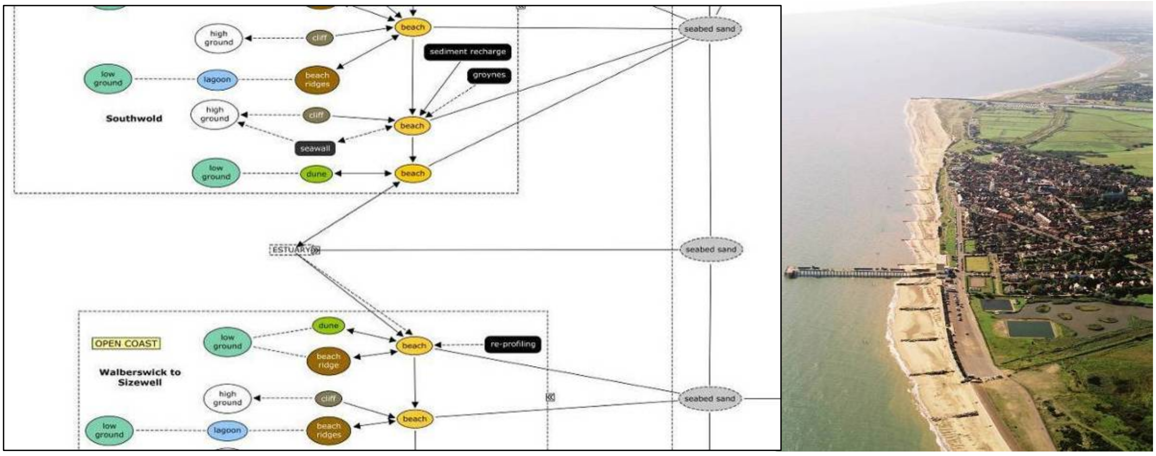

Figure 11.4 Open coast system.

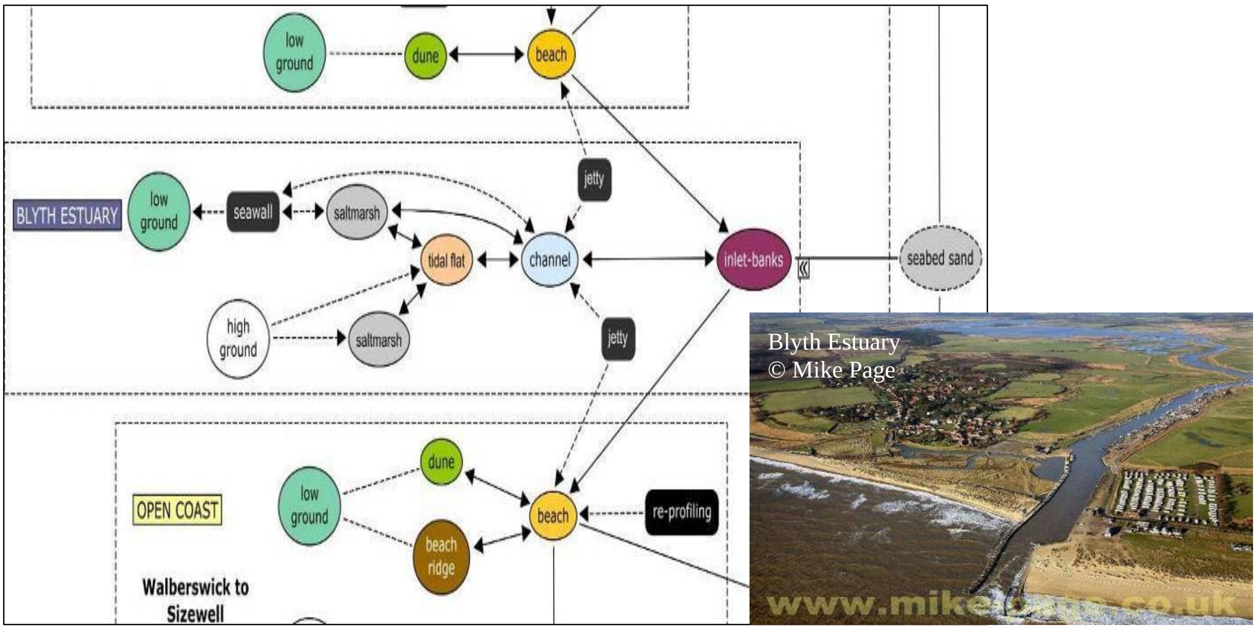

Figure 11.5 Estuary system.

The mapping was helpful in providing a framework for discussion and description of the estuary. In combination with the photographs presented above, the principal process could be explained together with the links between features. In particular the system maps used in this simple manner could highlight:

- Significance of the jetties in retaining beach sediment.
- At the same time, their interaction with the channel.
- Critically, the different ways in which the channel could be affected by the tidal flats and defence within the estuary.

In this manner, what was being seen on the ground, and what was observed in terms of behaviour could be distilled in a manner that highlighted the principal dependencies.

The approach was taken further in the study to extend the system mapping to some of the socio-economic factors critical to management. This is shown in relation to the overall economic canvas for the area in Figure 11.6.

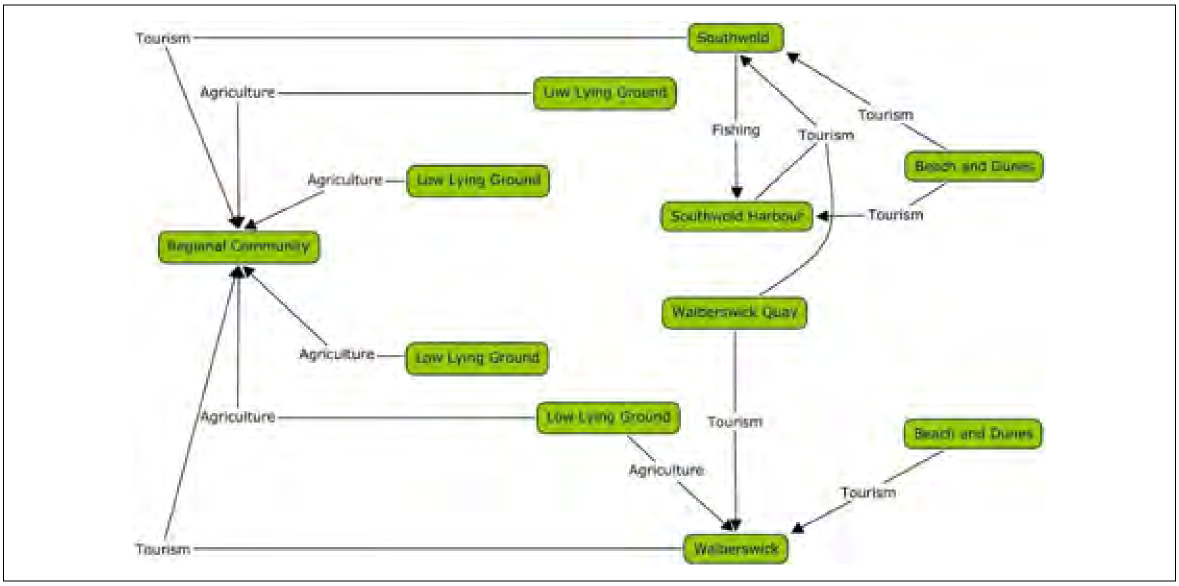

Figure 11.6 Principal economic features of the Blyth area.

Although this process, when taken down to the level of elements of economic interaction, was complex, it provided an initial framework for understanding how physical features could impact of the economic welfare of the area.

11.2.3.1. Results of the trial

Overall the trial demonstrated:

- The value of the approach in establishing a framework from within which to describe the critical behaviours of the system.
- The links between the observational analysis and the more theoretical understanding of geomorphology.

Although only developed in outline, the approach further demonstrated the potential for linking the geomorphological framework to critical management issues such as recreation, socio-economics and environmental systems.

11.3. Refinement of system mapping methods

11.3.1. Fine-grained sediments

As significant inter-tidal areas dominated by fine-grained sediment are located on the east coast of the UK, the mapping protocol was followed to map the fine-grained sediment system which, while more difficult to manage, is equally as important within the total coastal system. Here, the mapping process is intended to provide a systems diagram indicating the interactions between features/elements using the source, pathway, store/sink (or sediment cell) technique commonly used for coastal management.

Setting the boundaries for Stage 1 of the mapping procedure 'Region of interest selection' is particularly important for the fine-grained sediment system and is largely related to the nature of sediment transport pathway. In this example mapping covered the coast from the Scottish border to the Thames Estuary. Mapping over such a large area ensures that all potential features/elements of the system can be located and, as the structure is more important than the actual location of the system components, a topological map provides a more easily interpreted system representation. Initial mapping at this scale also has the benefit of providing a consistent base map to which other more detailed mapping can be related.

Having set the boundaries for the study, the section of coast was mapped using the features identified in Table 6.1 and conventions from Figure 6.5. In a deviation from the mapping protocol, connectivity was included at feature level but was confined to those features with direct relationships. This highlighted differences to the previous case studies in that not all of the coastal features are linked to the system being mapped. For example, the relationship between an estuary and the spit at its mouth is included but the more distant relationship to the headland which 'influences' the bay in which the estuary sits is not. This does not mean that there is no relationship but that it does not exist at this level of interest (see Townend, 2003). Consequently, some features will appear to be unconnected in Cmap tools but preserving them maintains the mapped system within the context of the coast as a whole. This method also emphasised that direct longshore relationships for fine-grained sediment are generally 'informative' and mass balance links more distant.

This process was found to be useful in distinguishing, using the conventions in Figure 6.5, those features which required whole or partial mapping at element scale to further define the system (Figure 11.7).

This approach significantly reduced the extent of onshore mapping required at element level. Focussing on those elements associated with fine-grained sediments - largely the components of estuaries with some elements associated with bays, open coast, river and spits/barrier island - further reduces the extent of mapping required. This simplifies the Cmap, making it easier to understand. Information on physical location for individual elements is included in the additional information visible when the element is passed over by the mouse.

Some redefinition of the offshore zone was found to be necessary as existing elements mainly related to beach-grade sediments. To highlight the nature of the seabed which formed part of the system, where fine-grained deposits were indicated by available information, it was additionally described as 'mud'. A new element was required to describe the holding of sediment in suspension. In FD 2117 this was included as 'sea' (ABPmer *et al.*, 2007). Here, it has been further defined as suspended sediment to indicate the nature of the sediment pathway and allow, as with previous case studies, offshore directionality to be shown.

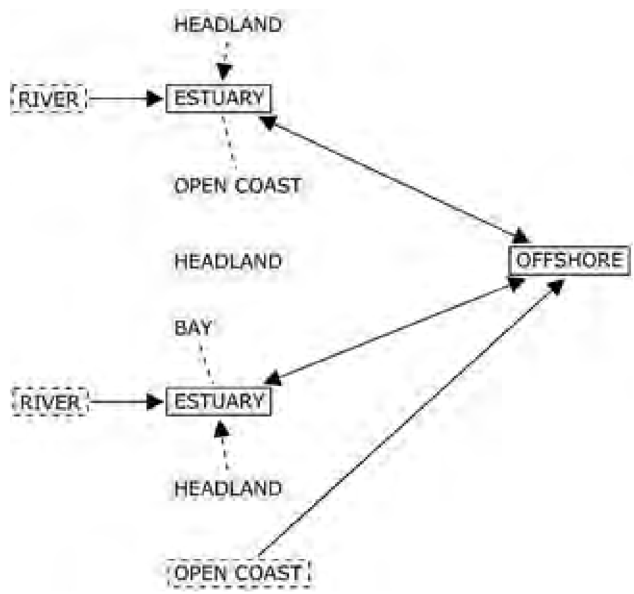

Figure 11.7 Example mapping of the fine-grained sediment system at feature level showing direct links.

Following the mapping protocol, links at element level were defined primarily according to current understanding of the sediment transfer pathways and were arrowed to indicate a direction of transport. Where this was unknown or unclear, non-directional arrows were used. Where there was known bi-directional transport, bi-directional arrows were used. On the East Coast of England this process resulted in the identification of four distinct sections (or sub-cells) defined by breaks or divergences in the continuity of the offshore drift system; (i) St Abbs-Flamborough, (ii) Flamborough to Winterton Ness, (iii) Winterton Ness to Bawdsey and (iv) Bawdsey to Margate. In addition, the relative input associated with cliff sections was indicated using the width of the connecting arrow. This was based on known cliff composition, length and height (from Hanson, 2000).

11.4. Feature mapping

As discussed earlier (Chapter 6) and reinforced by the case study mapping, it is not possible to produce 'plug in' generic feature maps as every situation is complex and knowledge/understanding can vary substantially. However, as discussed by Whitehouse *et al.* (2008), there are elements commonly associated with the most common behavioural systems on the UK coast. For example, an estuary feature usually includes channel, tidal flat, saltmarsh and low ground; a spit or foreland will typically include a beach and beach ridge. The primary inter-feature difference is one of emphasis, rather than the range of features and processes.

The 2008 inception report (Whitehouse *et al.*, 2008) detailed the component elements of some of the most common behavioural systems on the UK coast. These are generic and combine features likely to be found in such systems and could therefore be used to create an initial idealised 'template' for each feature.

For example, Figure 11.8a shows the elements which could be associated with a spit. With reference to the spit of interest, this can be modified to capture the presence or absence of individual elements and relationships between them (**Error! Reference**

source not found..8b and c).   This process is essential to system mapping as it captures understanding of the particular feature, and if achieved by consensus building, provides a common basis from which to develop other models, and identify areas of interest or interactions.

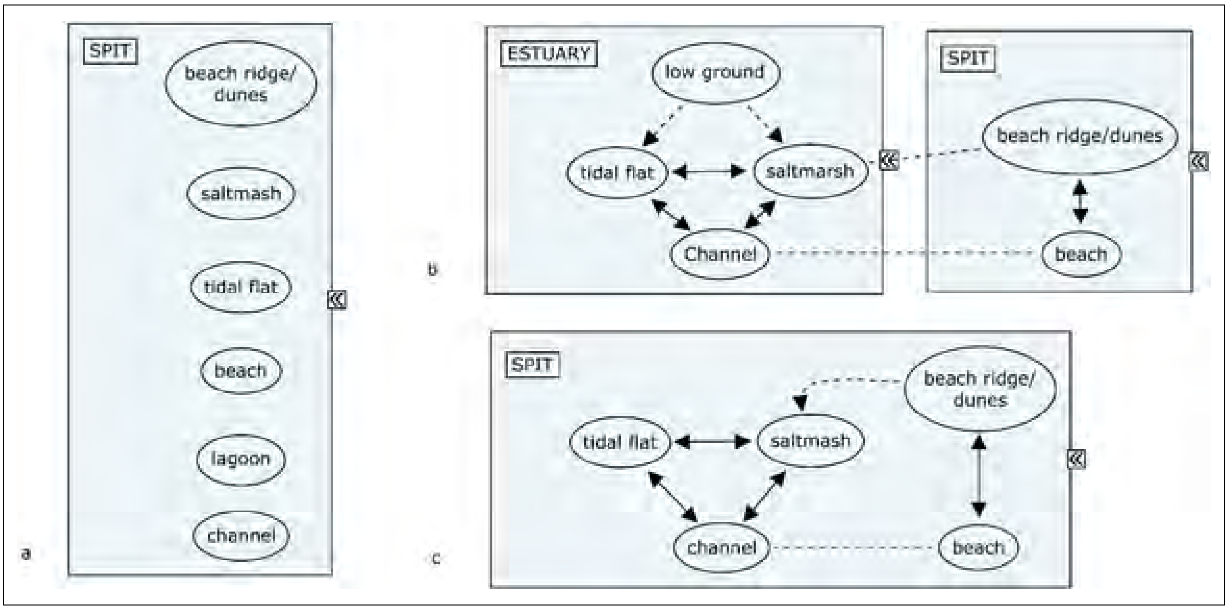

Figure 11.8 System diagrams showing how the SPIT template (a) can be amended, (b) for where saltmarsh and channel are primarily associated with a neighbouring estuary (such as the Humber) and (c) where no lagoon or estuary exists (such as at Blakeney).

Working from the basic template allows emphasis to be varied according to the purpose of the mapping.   For example, fine-grained sediment elements in **Error! Reference source not found.**.8c can be omitted from the feature map if the purpose of the mapping is to investigate sediment supply to the beach ridge. In this case, as indicated in the probability matrices in case studies 1-3 in Section 6.2, the main relationship of interest is between the beach and the beach ridge.

Other features, for example open coast and bay (**Error! Reference source not found.**.9), are more complex as they are more variable and can contain more than one of each element - see the Suffolk case study (Section 6.2.1). However the area should still be largely composed of the associated elements detailed in the inception report.

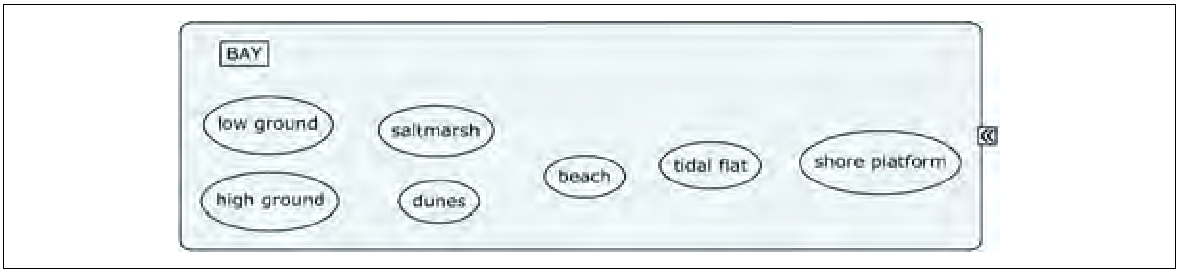

Figure 11.9 Elements associated with a bay.

11.5. What can be done now?

This project should help progress our understanding of coastal geomorphological change. Our holistic approach recognises the hierarchy of scales from coastal cells and sub-cells down to features and elements. This approach also aims to define all the components and interactions between them, to rank their relative importance rather than to assume this in an *a priori* manner.

The coastal system mapping (Chapter 6) provides a common framework for sharing understanding and a tool for capturing features and elements and their interactions, including the effects of human interference. Importantly, it provides a new, more transparent method to work with coastal experts and affected groups on these issues. Indeed, it is a valuable tool when used in a workshop context to formalize knowledge from different sources. This process of discussion and exchange should encourage the development of consensus, or make areas of conflict explicit in a commonly understood manner: a pre-requisite to resolving conflicts. While it starts as a qualitative model, the approach can evolve with our understanding, and quantitative results can be included where available; if management changes, the system map can be easily modified to reflect the new state.

The coastal system modelling (Chapter 7) provides a clear indication of what a quantitative geomorphological model should be composed of, including the interaction of elements. Proof of concept focuses on interaction by linking two relatively well-tested models of open coasts and estuaries: SCAPE and ASMITA, respectively. Our success in coupling the two models shows how new tools could be developed as defined by the coastal system maps. Interesting interactions are already apparent from our work, especially the stability of the simulated estuary. As configured, an estuary which is too small for the location appears to infill and ultimately disappears. As the estuary is increased in size and/or the littoral drift diminishes in magnitude, the likelihood of finding a stable form seems to increase. Hence, this exercise shows how we can develop more fundamental understanding of how coupled coastal systems behave. This predictive capacity is especially relevant for “morphological protection” as defined in the OST Foresight Report (Office of Science and Technology, 2004).

More generally, our work emphasises the importance of collecting data on coastal systems to analyse how the systems we observe today have come about. This includes data at many scales, including geological data, maps and charts, beach profiles and LiDAR. In exploring future change, one should consider a variety of methods which will typically depend on historic data for model set-up and calibration. Currently, a user chooses a range of methods and integrates them using expert judgement in the context of EGA (Chapter 9). Our expectation is that this situation will not change in coming years, but our work can help refine and integrate these methods.

One particular benefit of coastal systems mapping is to define interactions that are common, rare and never occur (and possibly also link to sites of coastal problems). On the basis of this understanding, we can map our predictive abilities for the common situations and focus research efforts where the benefits will be greatest.

11.6. What needs to be done in the future?

11.6.1. Systems mapping

Systems mapping could be further developed in a number of ways. In this research, the methodology was developed and applied to three case study areas. This proved beneficial in terms of formalising thinking and improving understanding of coastal geomorphological behaviour in these areas. Thus, the approach could be adopted across England and Wales to provide a common and systematic assessment, and a strong scientific basis for understanding key coastal features and links. The output from such an exercise would be an excellent complementary product to Defra's Futurecoast project (Defra, 2002) and together these would provide a sound starting basis for the development of future Shoreline Management Plans.

Current advice on Shoreline Management Plans (SMPs) has been reviewed in Appendix A. The use of systems mapping in future Shoreline Management Plans (SMP3) should bring benefits in creating consistent understanding of the coastline and in arriving at a consensus on the key links between coastal features.

The mapping approach could also be expanded to cover different types of systems. Our study focussed on physical systems, but in theory a systems approach could be applied to other sciences such as chemical and biological systems. Collectively, physical, chemical and biological systems interact to create the range of physical processes, geomorphological features, habitats and water quality around the coast. All of these aspects are of direct relevance to the Water Framework Directive and a combined (or layered) systems mapping approach could be of value to the Environment Agency in establishing inter-connectivities and scales and modes of functioning within that context.

Widening this thinking, the approach could also be developed into other thematic areas, such as recreation or economic links along the coast. With each theme assessed on a separate 'canvass', it would then be possible to overlay canvasses to establish wider networks of influence within the context of Integrated Coastal Zone Management. This approach has started to be developed following research on some coastal/estuary studies, with the aim of boosting clarity of decision-making and building consensus on preferred management decisions.

11.6.2. Proof of concept

One of the main strengths of the proof of concept modelling comes from its inclusion of holistic sets of elements and explicit representation of interactions between them. At present, however, few such elements are available in a quantitative sense to behavioural modellers and therefore additional modules are needed. These include:

- Dune modules – linked to beach modules and incorporating Aeolian transport processes.
- Spit modules – linked to beach/cliff of beach/dune and estuary modules and including sediment supply, spit growth and response to sea level rise.
- Ebb-tidal delta modules – linked to offshore sand banks and adjacent coastlines.
- Tidal flat and salt marsh modules – incorporating sedimentation.
- Nesses – linked to littoral drift and cross-shore exchanges of sediment.
- Hard rock cliff and rocky shore platform modules – to test emerging issues from several Shoreline Management Plans associated with the submergence and net loss of rocky foreshore habitats.

Furthermore, having tested the predictive potential of linked SCAPE and ASMITA models here, there is now opportunity to apply such approaches to real case studies.

Improvement is required in how sediment budget is captured for fine sediments as well as sands.

11.6.3. Expert geomorphological assessment (EGA)

There will always remain a need for EGA, since some management issues are bespoke and not governed by historic analogues. For example, there are many areas where future coastal geomorphological change will be governed by driving forces that have not been experienced in that area since the last Ice Age. In particular, large sections of the north-west coastline have historically been subject to relative sea level fall and plentiful sediment supply, leading to extensive accretion. Longer term projections associated with climate change predict a sea level rise, leading to a future where coastal geomorphological behaviour will be very different to past observations. Some sections of coastline are so heavily influenced by local activities, such as disposal of colliery waste in Northumberland and County Durham, that site-specific EGA will be required to understand the likely future behaviours.

Wider awareness of the role of EGA in understanding coastal behaviour is needed amongst coastal managers to avoid the pitfalls of inappropriate techniques being used to assess large scale and longer term changes. Many of the geomorphological methods described in the research are worthy of further application and development. This can relate to the need for further field measurements to provide better quantified approaches (such as the barrier inertia method) or development of existing concepts through numerical coding or establishment of a wider empirical evidence base.

Data needs have been highlighted for the methods and tools studied here. The usual requirements are a complete baseline nearshore bathymetry tied in with coastal profiles or complete coverage of the intertidal, supratidal and hinterland areas (for example, with LiDAR). Information will be required on the sediment grades present, the layout and characteristics of geological controls, and physical parameters relating to waves, tides, winds and river inflow. To support historical analysis, old charts and modern epoch datasets are required. Along with process studies, it will be useful to have a record of anthropogenic influences and the sediment fabric, geochemical properties of the sediments and biological datasets (flora and fauna) which will all help to improve our understanding of the historic context that shaped a stretch of coastline.

To support future management of coastlines, it will be important to continue to obtain high quality datasets.

12. Overall conclusions and recommendations

1. Predictive capabilities are the essence of a versatile approach to understanding how the coastal system will evolve. At present, a wide range of tools and techniques are available for coastal managers to explore historical coastal developments and predict future change. The large volume of disparate tools and information highlights the need for a systems-based approach linking behavioural and process models to reconcile the different spatial and temporal scales. A range of coastal features and elements was brought forward (Chapter 5) to provide a basis for describing coastal systems in a consistent fashion.

2. Using these features and elements progresses our understanding and prediction of change in coastal geomorphological behaviour. In particular, the framework established in Chapter 3 provides a basis for the use of different approaches to investigate different elements of large-scale, long-term behaviour. It is strongly recommended that this framework and its constituent components are further disseminated to the wider industry.

3. Systems mapping (Chapter 6) was developed here as a method for gaining understanding and explicitly capturing features and elements and their interactions, including the effects of human interference. It provides an excellent base for sharing knowledge and building consensus when used in a workshop environment. Training for coastal managers in the use of such approaches is recommended. A tutorial has been produced as part of this project (Burningham and French, 2009). The method was used with aerial photographs and Google Earth images here, but could be used with LiDAR images.

4. The systems mapping approach could be developed in areas such as chemical and biological systems, within the context of the Water Framework Directive, and, using different thematic canvasses such as economics and recreations, within the context of the broader Integrated Coastal Zone Management. Proof of concept modelling (Section 7) successfully linked two pre-existing reduced-complexity behavioural models, namely SCAPE and ASMITA. Opportunity now exists to apply the method to real sites.

5. Quantified development of other coupled elements, such as dunes and beaches, hard rock cliffs and rocky shore platforms, tidal flats and salt marshes, and nesses, is recommended. Such modules could be built into the linked approaches developed here in a similar manner as for SCAPE and ASMITA. The fine sediment fraction also needs to be tracked and developments will be required to achieve this.

6. Existing geomorphological methods evaluated here (Chapter 8) provide valuable insights into different elements or links of the overall system. Further development of these methods is recommended for their inclusion in future modelling.

7. Our study confirmed that current practice involves taking outputs from a range of tools (such as systems mapping, modelling and geomorphological methods) and integrating them within the context of expert geomorphological assessment (EGA; Chapter 9). This situation is not expected to change in coming years, but our work should help refine and integrate these tools and methods. To support EGA in the future, it is recommended that dissemination and skills training are carried out.

8. Our results should help shape future development of risk-based coastal management techniques and Integrated Coastal Zone Management, Shoreline Management Plans, strategy studies and project appraisal. Potential links to RASP (Risk Assesment for Strategic Planning) and NaFRA (National Flood Risk Assessment) are presented in Sections 2.3.1 and 2.3.2 of this report. These will also apply to other versions of quantified risk assessment (such as Hall *et al.*, 2000).

12.1. Implications for SMP3

The following recommendations are made for the next round of Shoreline Management Plans (SMP3):

1. The current approach could benefit from inclusion of system mapping techniques developed here. Use of the systems mapping approach in SMP3 will bring benefits in creating consistent understanding of the coastline and in arriving at a consensus on the key links between coastal features.
2. Expert geomorphological assessment (EGA) will continue to be a mainstay of SMP studies. This will be supported by a range of datasets, assessment methods and predictive approaches as is presently the case.
3. System modelling, such as that carried out here, has shown that insight for coastal management can be obtained using coupled models to represent the coastal and estuarine features.

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Appendix

Appendix A Review of Guidance for Shoreline Management Plans

1. Introduction

A Shoreline Management Plan (SMP) is a document that forms an important element of the strategy for flood and coastal erosion risk management: "*SMPs provide a long-term vision for a sustainable coast where future decisions can be taken with confidence using the best available evidence*" (Defra, 2008).

The SMP is the first step in a hierarchical order of initiatives, culminating in the realisation of a given plan which might or might not include some kind of engineering or management intervention. The SMP, which could extend to hundreds of kilometres of shoreline, is likely to yield a range of different management policies for different parts of the frontage (so called policy units), which become the subject of more detailed but geographically smaller studies (Figure A.1). Policies derived from an SMP for given groupings of policy units are developed through the preparation of coastal defence strategy studies (typically tens of kilometres). The strategy considers issues in greater detail and identifies the timing of any interventions (such as reconstruction).

The first SMPs were essentially coastal studies. Without further definition, they usually stopped within estuaries at the boundaries demarcated by Schedule IV, "Waters excluded for the purposes of definitions of sea and seashore" of the Coast Protection Act (1949), usually not far from the estuary mouth. Moreover, being significant features in terms of sediment cell definitions, estuaries often defined the boundaries between neighbouring cells or sub-cells and, hence, the boundaries of SMPs themselves (such as the Humber). Unsurprisingly, these "no man's lands" were seldom examined to the same level of detail as the adjoining coasts. Thus we see the motivation for, and the emergence of, some Estuary Shoreline Management Plans (eSMPs).

Economic issues concerning estuaries are generally linked to the risk of flooding, whilst flooding and land erosion issues are commonly important to the coastal areas. This significant but oversimplified distinction affects the approach to determining morphological evolution. With this and other distinctions in mind, it is convenient to discuss coastal and estuary SMPs separately; this also fits more readily with a review of the Defra guidance on the preparation of SMPs (Defra, 2006), in particular two of the Appendices in Volume 2 of the guidance:

- Appendix D: Shoreline interactions and response
- Appendix F: Integration of estuaries

2. Coastal SMPs

Particular Issues

Typical issues likely to arise in coastal SMPs are listed below (list is not exhaustive):

- Continued protection of short lengths of frontage on an otherwise retreating coastline; important considerations include: effect of isolation on sediment yields; obstruction to longshore drift as the defended land becomes outflanked by the retreating coastline on either side; threat of undermining of defence structure as ground beneath comes under threat of erosion; eventual consequences of withdrawal of defence.
- Continued protection of long lengths of coast; many of the above listed points apply, together with: effect of eventual piecemeal removal of defence structures.
- Effects of sea level rise/climate change; important considerations include: prospect of inundation of previously undefended coastlines or coastlines defended to an inadequate standard of protection to cater for future conditions.
- Following from the last point: step changes in coastal behaviour in the case of breaching and the formation of tidal inlets.

These examples highlight the need to apply geomorphology to provide not only better answers but: answers to discrete as well as broad-scale issues; answers to ongoing and transient processes; above all, greater confidence in decision-making.

Defra Guidance Appendix D

Defra (2008) advocates the adoption of a so called "behaviour systems" which *"involves the identification of the different elements that make up the coastal structure and developing an understanding of how these elements interact on a range of both temporal and spatial scales*". This is a good generalisation of the principles implicit in the business of predicting morphology.

Appendix D (Defra, 2008) goes on to discuss delivery of the baseline understanding of coastal behaviour and dynamics (section D.2.3), which is subdivided into (a) coastal processes and (b) defence assessment (not reiterated here as the reader can refer to the full text in Appendix D). These sections provide a useful guide and checklist. Possibly more emphasis could be placed on gaining a sound understanding of underlying geology; the subject must not be overlooked or underestimated. Several methods (such as log spiral bay model) simply do not recognise the existence of a geological barrier to sediment driven shoreline evolution.

This section of Appendix D includes a useful table outlining the residual life of various defence types subject to grade (the definition of grade is, however, difficult to locate).

The guide wisely recommends that the "*understanding derived…needs to be communicated in a transparent fashion*". This could be regarded as obvious but again should not be underestimated. Morphological evolution is more likely to come under public scrutiny when a change of policy is mooted. Methods therefore need to be both scientifically correct and well presented. They must be commonly understood (at least by the coastal scientific community), honest (no unrealistic expectations), and in line with common sense. Without consensus, even the most sophisticated study will amount to little if it does not support the bigger objective of achieving good shoreline management in practice.

Appendix D (Defra, 2008) deals next with an "assessment of baseline and policy scenarios." This section (D.2.4) is split into (a) analysis and (b) consideration of management techniques. Arguably, this part of the document seems to fall short of what it might be expected to convey. The emphasis tends to be on the general principles of policy scenario assessment and an expansion of definitions rather than an explanation of how these thoughts relate in determining/informing policy assessment. Nevertheless, the heading of the analysis section and expansions which follow are relevant and should be observed in terms of: controls, sediment budget modifications, backshore response, feedbacks and management techniques. This section of the appendix focuses on shoreline evolution with respect to sediment movement. Shoreline evolution from flooding and the future development of tidal inlets are important

In the section describing "consideration of management techniques", four types of measure are highlighted:

- hard defence (such as seawall embankment);
- soft linear defence (such as managed shingle barrier);
- retention of beach (control structures);
- replenished beach.

These measures can be more fundamentally considered under two headings: those which seek to control or somehow work with the underlying coastal processes, and those which accept the consequences of coastal processes and deal with these consequences. This distinction is important when examining the geomorphological response of a given management technique; in particular, it focuses thinking on the issue of sustainability.

In Section D.2.5 of Appendix D, "additional techniques and tools" are discussed. This section overviews the study methods further described in Annex D2 to the core document. Box D2 provides a useful guide to the typical levels of accuracy in predicting shoreline position. Our report would suggest that the stated "probable maximum error in accuracy of prediction" by numerical modelling (for example, using wave-driven sediment process models), at ± 20 per cent, is optimistic. At a SMP level of study, there will be limited scope for calibrating shoreline models against (discrete) observed behaviour. On the basis of an uncalibrated or coarsely calibrated model, a figure of ± 50 per cent (or a factor of 0.5 to two) would be more realistic.

Two useful annexes are provided in Appendix D (Defra, 2008): Annex D1 deals with data and information, whilst Annex D2 deals with techniques. So, whilst the first annex discusses source of information, Annex 2 examines a range of methods of analysis. This work provides a useful resume but perhaps what is not emphasised or explained is how these techniques, which are generically different, can be used in combination (for example, expert based geomorphological extrapolation and numerical modelling).

At the beginning of this report, we outlined the distinction between those parts of the coast for which a given policy is certain (such as 'do nothing' at an open natural cliffed coast) and those for which future management policy is less certain (usually those for which defence is likely to cease at some point.) A similar distinction can be made in the selection of methods, whereby the broader scale methods are applied over the wider/whole coast, whilst the detailed techniques are reserved for specific problem or issue related areas. Figure A.2 suggests a generic order of methods.

As noted earlier, the broad scale nature of certain geomorphology tools means that they will probably encompass wider areas than that of the specific issue(s).

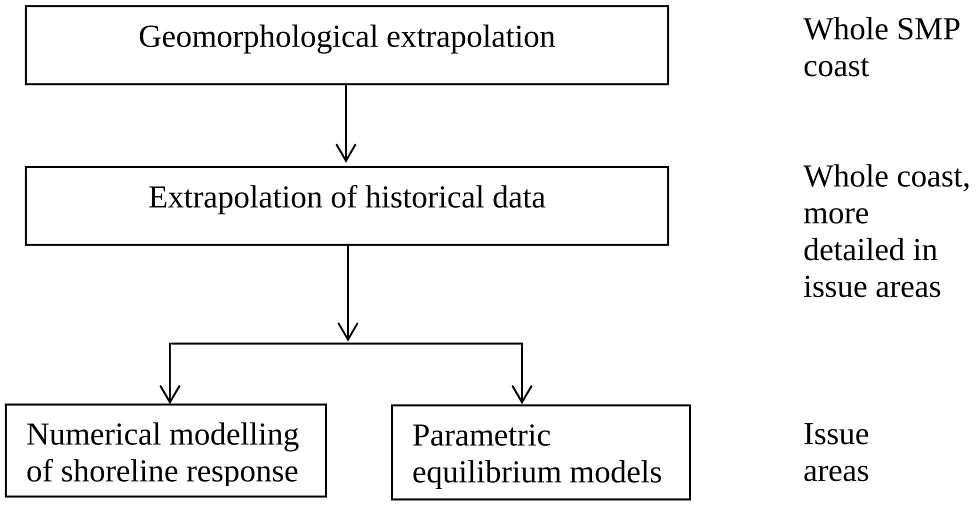

Figure A.1 Generic ordering of methods – coastal SMP.

3. Estuary SMPs

Particular Issues

Particular issues likely to arise in estuary SMPs are listed below (list is not exhaustive):

- Retreat of flood defences allowing land areas to flood, resulting in increase in tidal volume and hence increased pressures on downstream areas and defences.
- Changes in defences or other structures in the estuary can alter the local hydrodynamics and have an impact on the environment.
- Estuaries provide important inter-tidal habitat areas.
- Interaction between an estuary and the open coast means that the two should not be considered in isolation in the preparation of eSMPs.
- Effects of sea level rise/climate change; important considerations include: prospect of inundation of previously undefended shoreline defended to an inadequate standard of protection to cater for future conditions; influence on estuary morphology including, for example, landward migration of the estuary, and the impact this has on hydrodynamics throughout the system.

As with coastal issues, whilst these examples indicate the need to apply geomorphology to help resolve site-specific issues, they also highlight a more coherent dependency between various factors – a characteristic feature of estuaries and one which influences the approach to geomorphological study.

Defra Guidance Appendix F – Integration of estuaries

Appendix F (Defra, 2008) is fundamentally different in its stated purpose to that of Appendix D. The latter "*provides supporting information on the assessment of shoreline interaction and response and outlines methodologies and tools that can be used in such assessment and their application*", that is, guidance in doing the SMP. However, the estuaries' appendix appears to be directed at decisions on the integration of estuaries in the SMP process, rather than the SMP process per se. Pontee and

Cooper (2005) state that the guidance is "*intended to guide the user through a structured thought process rather than laying down quantitative threshold criteria*".

In light of this, the appendix seeks to equip the reader with the thought processes necessary to answer three precise questions for a given estuary:

1. Should the estuary be included in the SMP process?
2. If so, how should it be included?
3. How far upstream should the estuary be included?

Appendix F describes a fairly comprehensive method for responding to the first of these questions – should an estuary be included in the SMP process? The inputs to this process are derived from a series of so-called Estuary Guidance Tables (EGTs) that enable the reader to qualitatively estimate the following factors:

- significance of water exchange;
- significance of sediment exchange;
- significance of management issues.

Each of these criteria is considered in terms of its significance to the estuary and the open coast. Our report would question the importance of this significance being related or relative to that of the coastal regime. Put more simply, if there were significant shoreline management issues in the estuary, and these issues were influenced to some degree by the physical estuarine environments (water and sediment movement) then an SMP type of approach could be adopted. A stand alone estuary SMP is a possible outcome from Question 2 in any case. Appendix F includes a graphical procedure (EGT5) which leads the reader through this logic, using scores derived from the earlier EGT tables to arrive at conclusions on whether an estuary should be included in an SMP.

On Question 2, Appendix F suggests that practicality is the main issue (EGT6). Examples of where it is not practical to include an estuary within an open coast are: where the estuary is sufficiently large to necessitate consideration of its process and management policies outside of the open coast SMP; and where the estuarine management issues are too complex or diverse to consider within the open coast SMP.

Appendix F also suggests a pragmatic and practical approach to Question 3. The last EGT table sets out fundamental questions on the practical extent of the estuary in terms of the principal determinants: tidal limit and/or suitable alternative limit, the latter including non-cohesive sediment exchange, wave penetration, continuity of risk zones.

Appendix F cross-references to CHaMPs and mentions designated habitat areas in the context of risk zones that cross the coastal/estuary interface. Otherwise, and arguably, the EGTs say little about the significance of the natural environment (not unimportant in estuaries due to the usually large intertidal area) in terms of responding to the three questions. This would need to take a higher profile in some circumstances, whether the attribute crosses the coastal/estuary interface or is contained within the estuary itself.

The methods outlined (Question 1 in particular) are perhaps rather cumbersome given the stated objectives to determine whether, how and to what extent an estuary should be included in an SMP. Nevertheless, the exercises described under the EGTs provide a valuable precursor to an estuary SMP (howsoever it is incorporated) as they provide a first-pass evaluation of the key parameters that define an estuary and its shoreline management regime.

Apart from setting out a methodology to determine the three questions, Appendix F contains a useful collation of data in the annexes. These cover:

- Annex F1: Review of estuary types, influences and decision support tools.
- Annex F2: Analysis of *Futurecoast* database of estuary parameters.
- Annex F3: Example application of guidance.

Annex F1 is reviewed in Section 4.2.3.

Annex F2 provides an analysis of the *Futurecoast* database estuary parameters.

Annex F3 to Appendix F includes some worked examples on the use of EGTs to resolve the three questions on incorporating an estuary into an SMP.

Overview and comment on Annex F1 (Defra, 2008)

Annex F1 contains a useful resume of so-called decision-support tools (methods). This provides an overview of: (a) desk-based methods, including analysis of existing data, empirical and theoretical relationships; (b) field-based observations, and (c) numerical model-based investigation.

Arguably, the decision-support tools part of Annex F1 is the most useful section of the document in terms of advising on the use of morphology principles in the preparation of a SMP. This section suggests some generic ordering of the tools in terms of the spatial application and predictive capacity (realistic horizon). Some important points are worth emphasising here, as follows:

- Field studies (described as though taken for direct interpretation) may be required to set the boundary conditions, or calibration data, for numerical models. As these exercises invariably take (in study terms) a long time to procure and carry out, they need to be planned at the outset and usually initiated as one of the earliest items in the SMP preparation.
- If created, a hydrodynamic model of an estuary is likely to have a large coverage, possibly greater than that of the SMP itself. There may be logical and logistical advantages in this, not least the opportunity to use known far-field boundary conditions. The model, whilst being used for short to medium-term processes, and possibly those connected with localised schemes, has the capacity to examine knock-on effects elsewhere in the estuary (such as increased flow speeds at the mouth in response to upstream realignment) and the cumulative impacts of schemes. Hence, for estuary application, the numerical model is likely to have a different (higher) place in the generic order of studies than depicted in Figure A.2. The preparation and operation of a 2-D or 3-D hydrodynamic model is a comparatively expensive study, especially if accompanied by field investigations. The benefits gained and scale of the issues involved must be considered carefully in deciding on the inclusion and scope of this work.
- Empirical and broad-scale methods (such as regime theory) can boost understanding of the longer term evolution of an estuary, and hence the ambient evolution into which shorter term/scheme driven changes can act. In essence, these methods belong to the geomorphological extrapolation stage indicated in Figure A.2.

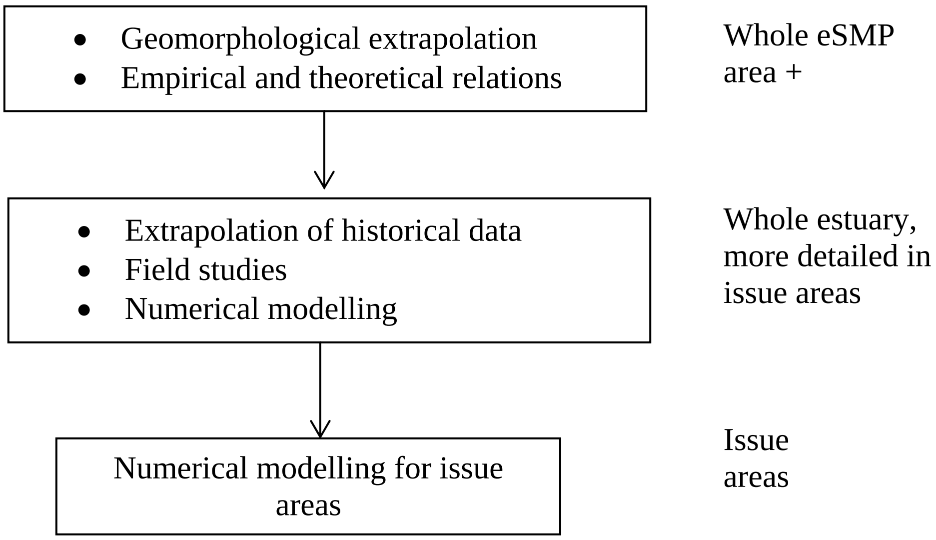

Figure A.2 Generic ordering of methods – adapted for eSMP.

Summary of existing framework for studies

The guidance for existing SMP studies recommends a structured thought process to determine the baseline understanding of coastal behaviour and dynamics and to evaluate the need for inclusion of an estuary within an SMP.

Methods/tools to analyse shoreline interactions and responses are categorised as: geomorphological extrapolation, numerical modelling of shoreline response, extrapolation of historical data, and parametric equilibrium models. These are all desk-based or numerical-model based approaches.

Decision support tools for estuaries – to boost understanding of processes and morphology - are categorised as desk-based, field-based or numerical-model based. A range of empirical and theoretical relationships are listed which can be considered as part of the desk-based approach.

Conclusions

The following conclusions are drawn from the review in light of the work completed in this project:

1. The present SMP approach could benefit from inclusion of system mapping techniques developed here. Use of systems mapping in future Shoreline Management Plans (SMP3) will bring benefits in creating consistent understanding of the coastline and in arriving at a consensus on the key links between coastal features.

2. Expert geomorphological assessment (EGA) will continue as a mainstay of SMP studies. This will be supported by a range of assessment methods and predictive approaches as is presently the case.

3. System modelling, such as that carried out here, has shown that insight for coastal management that can be obtained using coupled models to represent the coastal and estuarine features.

References

Defra. (2006). *Shoreline Management Plan Guidance*. March 2006, published in two volumes. www.defra.gov.uk

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