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

Predicting large-scale coastal geomorphological change

Science Report: SC060074/SR2

  

Product code: SCHO0809BQVN-E-P

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Our work includes tackling flooding and pollution incidents, reducing industry's impacts on the environment, cleaning up rivers, coastal waters and contaminated land, and improving wildlife habitats.

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Predicting large-scale coastal geomorphological change

1. Relevance of the new findings to coastal management

A new practical framework and methodology for creating new models capable of predicting long-term and large-scale geomorphological evolution has been developed. This has addressed some of the shortcomings in the existing capability to predict broad-scale change in coastal and estuarine environments. The outputs of the study enable clear and consistent understanding of the geomorphology to support the management of complex coastal environments. This is supported by an evaluation of selected practical modelling and analysis techniques for the prediction of mid to long-term coastal geomorphological evolution including management interventions. The resulting reports include a comprehensive description of how the results of geomorphological studies can be incorporated through the process of Expert Geomorphological Assessment (EGA) to improve the confidence in the decision making process.

2. The audience

The research, which was funded by the Environment Agency's Science Programme[1], is relevant to professionals working in flood risk and coastal erosion risk management. It was tailored through consultation to meet the needs of users with particular focus on the development of Shoreline Management Plans (SMP) and related scale studies, including those listed in the following table:

Category of user of the research
• 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

In addition a review of the current guidance on the inclusion of geomorphology in SMPs was completed and recommendations were made on how to include the results in future rounds of SMP development.

[1] Environment Agency Science Project SC060074

3. Purpose of this extended executive summary

This purpose of the extended summary is to assist uptake of the research through explanation of the following:
4.1 The research drivers
4.2 The proposed framework for assessment
4.3 The role of Expert Geomorphological Assessment
4.4 The geomorphological basis for understanding coastal behaviour
4.5 A demonstration of coastal system mapping to support coastal management
4.6 Review of relevant analysis techniques
4.7 Demonstration of combined coast and estuary modelling
4.8 Highlighting the practical relevance of the results
4.9 Recommending the next steps to develop the research

4.1 Research drivers

The strategic role of the Environment Agency with respect to coastal erosion and flood risk management requires the delivery of appropriate and sustainable management of coastal erosion and marine flood risk, particularly over long timescales and within large scale systems. Geomorphology has a direct affect 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, for example 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. Evaluations of complex coastal systems, such as those that include open coasts and inlets, a coast and estuary or coast and offshore banks require the flow and sediment interactions to be determined for a realistic assessment of likely future change.

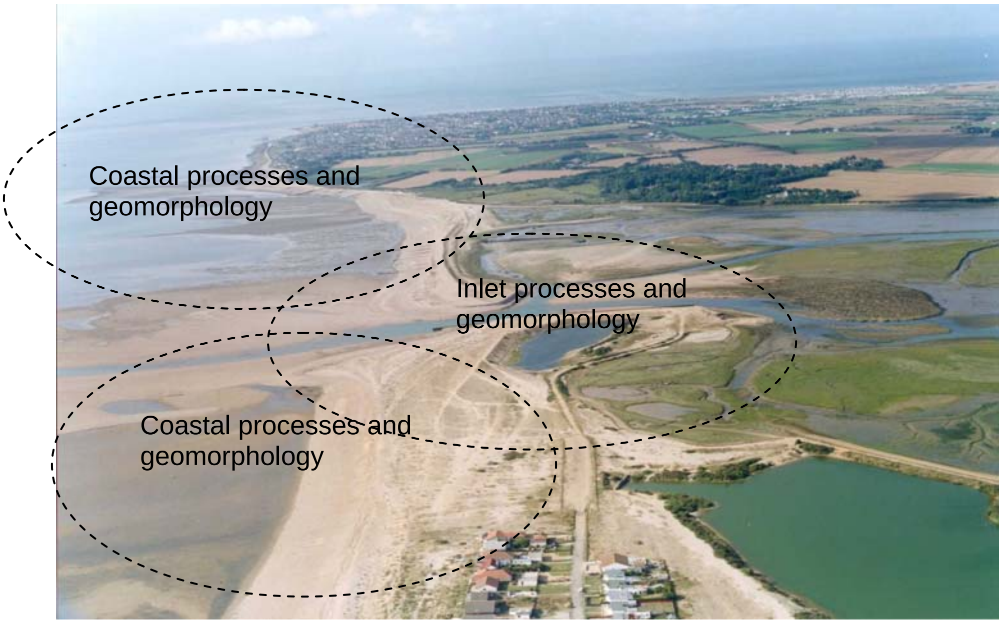
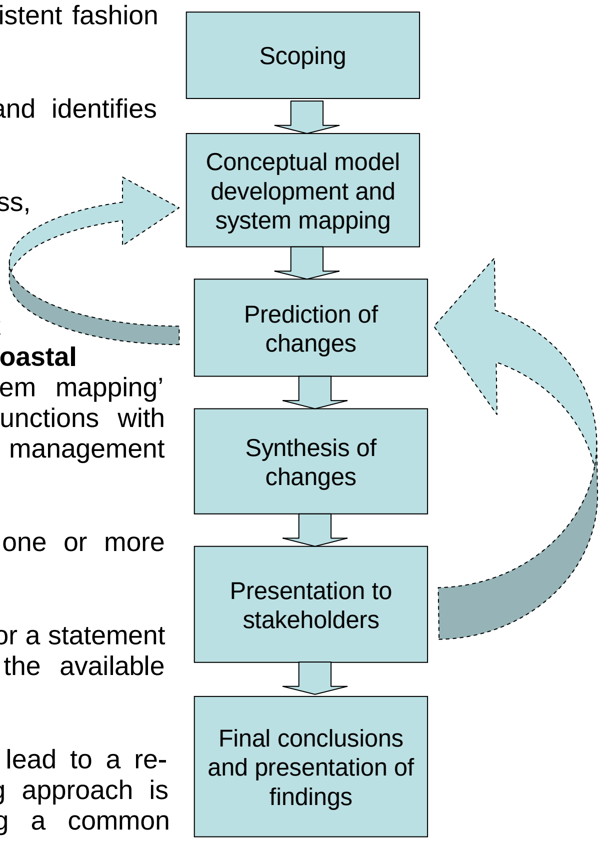


Illustration of two adjoining coastal geomorphological features

4.2 Proposed framework for assessment

The proposed analysis framework (right) can be applied in a consistent fashion for any location.



The **scoping phase** sets out the key issues and questions, and identifies available data.

Conceptual model development is a key step in the study process, which leads to a consistent and testable hypothesis for how the coastal system is behaving and how it will develop in the future.

This stage is linked to a new element developed in the current research which is a clear and graphical way for **mapping of coastal geomorphological systems** and their interactions. This 'system mapping' approach is useful when discussing how a coastal system functions with interested parties and stakeholders, for instance during shoreline management planning.

The next step is to undertake **prediction of changes** using one or more appropriate techniques.

The results are brought together and interpreted to form the basis for a statement of the changes that are expected through **synthesis** of all the available information.

The results are **presented** to stakeholders and discussion may lead to a re-evaluation of the outcomes. At this stage the system mapping approach is considered useful in a workshop environment for confirming a common understanding or highlighting points of disagreement or uncertainty.

Following a refinement of the analysis and results the **final conclusions** can be brought together and **presented** to stakeholders.

4.3 The role of Expert Geomorphological Assessment (EGA)

The interpretation and integration of the results from geomorphological studies is undertaken through the process of Expert Geomorphological Assessment (EGA). EGA allows the full range of management issues to be considered, from those with precedent to those which are bespoke and not governed by historic analogues. For example, there are areas where future coastal geomorph-ological change will be governed by driving forces that have not been experienced since the last Ice Age. Also large sections of the north-west coastline have historically been subject to relative sea level fall and plentiful sediment supply, leading to extensive

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

The seven stages in Expert Geomorphological Assessment

accretion. Longer term future projections associated with climate change are likely to be for relative sea level rise, leading to a future where coastal geomorphological behaviour will be very different to past observations. Also 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.

The evidence base requires professional expertise based decisions as well as the application of analysis and modelling techniques. A consistent and open approach to the development of a conceptual model and the explanation of data and prediction of change is required with EGA playing a central role in studies. The framework for assessment is directly supported by the stages of EGA.

The research has provided a wider awareness of the role of EGA in understanding coastal behaviour so that coastal managers can ensure the use of appropriate techniques to assess large scale and longer term changes.

4.4 The geomorphological basis for coastal behaviour and management

The management of a coastal feature such as an open beach, spit or estuary requires identification of the geomorphological elements present and the analysis of the past, present and future behaviour of the feature and its associated elements. The coastal system comprises features which interact over a wide range of timescales. The geomorphological elements (e.g. beach, seacliff, saltmarsh) which form the basic building blocks of the coastal system and as such are the starting point for any study. The coastal system will also be constrained at a larger scale by geological controls, e.g. headlands, and supply of sediments forming the main geomorphological features.

Coastal geomorphological behaviour relates to landform features and land forming processes that are shaped by atmospheric, terrestrial and marine processes. Analysis of behaviour is underpinned by the conceptual model which provides a hypothesis that can be tested thus adding rigour to the evaluation. In order to quantify the geomorphological evolution of a stretch of coastline, it is necessary to analyse the state of the system in terms of:

- the present day nature of the coastline and its composition;
- its origins and past state;
- its controlling and forcing mechanisms; and,
- its behavioural characteristics.

The geomorphological behaviour of the coastal system as a whole, features within the system and the linkages between component parts has been described in the first report (see Report 1 in Project Outputs) resulting from this project and analysed in the second.

A standardised approach to the description and analysis of coastal features was proposed based on the list of 13 features given in Box 1.

The features are built from geomorphological elements which are the building blocks of any assessment. The 17 elements listed in Box 2 were defined and used in the system mapping. These elements are well known but those marked with * have been described in a standardised format for the first time in Report 1. Box 3 shows the information contained in the standard description for each of the selected elements.

This provides a stepping stone to generic tools that can be applied at any location.

Box 1: Defined features (Report 1)
Offshore
Open coast
Headland
Bay
Spit
Cuspate foreland
Inlet
Tombolo
Barrier island
Estuary
River
Updrift coast
Downdrift coast

Box 2: Defined elements (Report 2)
Sea cliff*
Coastal dune*
Coastal lagoon*
Beach*
Shore platform*
Tidal flat*
Saltmarsh*
Channel*
Inlet-associated bank*
Headland-associated bank
Offshore bank*
Beach ridge
Offshore reef
Seabed sand
Seabed gravel
Low ground
High ground

Box 3: Information summarised for each element (Report 1)
Definition
Function and attributes
Formation and evolution
General form
General behaviour
Forcing mechanisms
Evolutionary controls
Behavioural timescales
Interaction and exchanges with other geomorphological elements
Management approaches
Modelling and analytical tools

4.1.1 Representing management techniques

The representation of management techniques and interventions in coastal systems has been described in Table 1, based on analogues of natural processes in Report 2. This is a helpful way of thinking about management since it puts the natural behaviour and management techniques on a compatible basis. In addition the influence of outlets and tide locking by structures built across inlets were assessed.

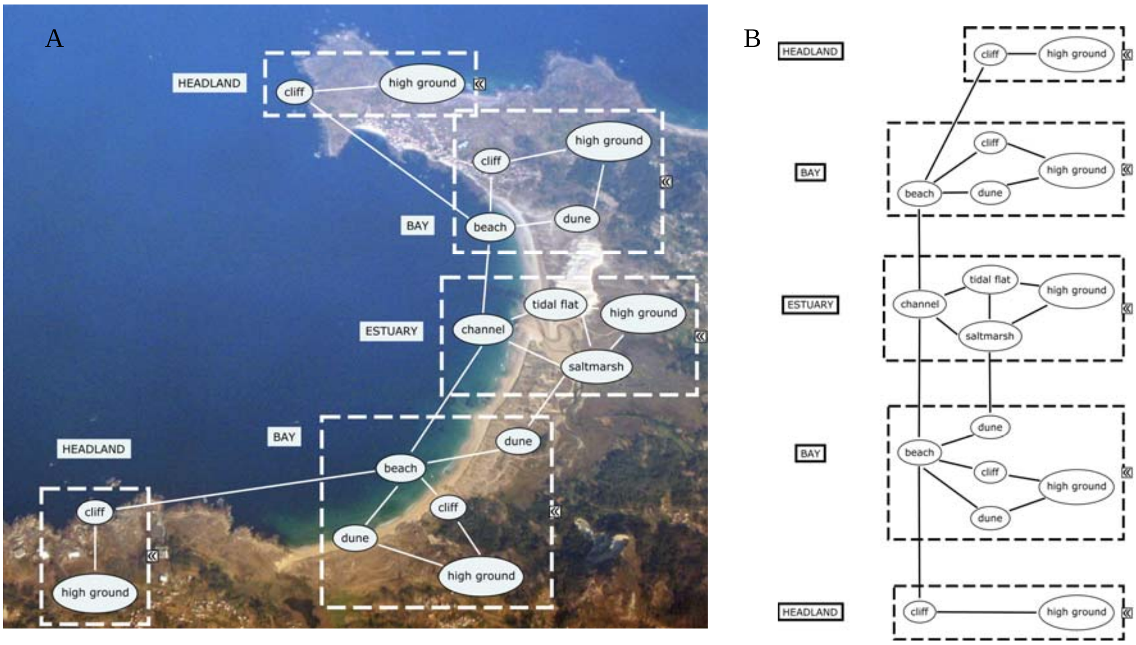
Table 1: Management techniques related to type of management and shoreline management policy

		Management technique		
		Hard defence	Soft defence	No interference
Shoreline Management Policy DEFRA (2006)	Hold the existing line	Long terminal groynes Short groynes Seawalls and revetments Breakwaters and reefs	Recharge Recycling Bypassing Beach re-profiling	
	Advance the existing defence line	As above, plus Reclamation embankments	Recharge	
	Managed realignment	Different engineered breach mechanisms and embankments	Use of fine grain dredged material (form of recharge)	No maintenance
	No active interference			No maintenance

4.5 A demonstration of system mapping to support coastal management

A clear and graphical way to map coastal geomorphological systems and their interactions has been developed which is useful when discussing and refining our understanding of how a coastal system works with stakeholders.

The mapping approach is scale independent and a useful starting point for analysis of geomorphological systems and for strategic planning. It helps the construction of baseline knowledge and formal understanding, highlights uncertainty and removes the black box nature of existing coastal prediction methods. The approach has been applied to contrasting coastal locations and easy-to-follow guidance on the approach has been produced (see the Project Record listed in Project Outputs).



Example of coastal system mapping – a geographical map and a linear representation of the same system (built using Cmap tools – see Box 4)

4.5.1 Case study applications

Three systems mapping case studies were produced and are described in Report 2. These were:

1. Firstly, the 73 km stretch of the **Suffolk** coastline between Lowestoft and Landguard Point (i.e. the entirety of coastal sub-cell 3c). 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.
2. Secondly, application at Alnmouth Bay, in **Northumberland**, showed how the system mapping approach can be applied at a smaller scale (approximately 15 km) on a section of coast characterised by a less continuous littoral drift system and more marked geological controls; and,
3. Finally, Cardigan Bay in **Wales** was used to demonstrate the application of the approach at a larger scale, on the 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.

The system mapping allows aggregation of features and elements and the linkages between them (Box 4). It can be most easily carried out over the backdrop of a map, aerial or satellite photograph, LIDAR or bathymetric data. This produces a map in a geographical frame of reference and this can be linearised to form the basis for a clear presentation and analysis of the linkages and interactions between elements.

Box 4 - The 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 the representation of the interactions between these components in diagrammatic form. The features and elements provide the basis for these components. This could be undertaken as a pencil and paper exercise. However, construction of system diagrams is easily accomplished with the aid of specialist computer software and, to this end, we utilised CmapTools (available as freeware from: http://cmap.ihmc.us). The second stage involves the analysis of connectivity between the components.

An independent assessment of the approach was completed at another location (Sefton) which confirmed the usefulness of the approach in the SMP process. It formalises the process of identifying broad scale linkages, it can help in developing skills and training for coastal managers and also forms a means of communication between stakeholders.

Previously available approaches did not always allow a full consideration of the possible impacts of coastal management options and climate change in strategic planning and decision making. The research has delivered a practical approach for considering coastal geomorphology in a consistent fashion by developing a system map as a basis for the consolidation of knowledge and formulation of a conceptual model.

4.6 Commentary on relevant analysis techniques

A range of analysis techniques has been evaluated by the project (Report 2). For each technique a description, summary of metadata, and example applications have been provided. The techniques described (Box 5) fall broadly into four types:

Box 5: Analysis techniques evaluated in Report 2
Historical Trend Analysis and Future Change Extrapolation
Bruun rule and related methods
Equilbrium bay shape
One line models
Coastal profile models
Coastal area models
Breaching of shingle barrier beaches
Tidal inlet stability
Reduced complexity systems models

1. **Behavioural models of coastal change**: Historical Trend Analysis and future change extrapolation, the Bruun rule and equilibrium beach shape. These models reproduce the observed behaviour of a feature of the geomorphology – 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 that seen in the past.

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 least 20 years to develop predictive process-based numerical models of coastal evolution covering periods ranging from storms to decades. These models 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, etc.) to sediment concentration and flux without calculating the full details of the

turbulence or force balance on each grain. There are still major gaps in our understanding of long-term morphological behaviour 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[2] provided 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 a shortfall in our scientific knowledge and data.

3. **Change of state models**: Shingle and barrier inertia models for the breaching of barrier beaches and inlet stability tools. Behavioural and process-based models assume that the features and elements being modelled will be preserved and will not change state during the course of the modelled period. 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.

4. **Systems-based models**: including SCAPE and ASMITA. This class is a more recent development of geomorphological modelling that is of particular relevance to this project. Such models are built to describe the elements and interactions of holistic coastal or estuarial systems using behavioural or process-based modules. Because these elements interact they can be applied with conditions such as increased rates of sea level rise that might be experienced in the future. Because the processes are described in reduced complexity, model run times are fast enabling long term simulation. Feedback between model elements constrains the overall model behaviour, preventing unrealistic runaway behaviour.

The usual requirements for data are a complete baseline nearshore bathymetry tied in with coastal profiles or complete coverage of the intertidal, supratidal and hinterland areas (e.g. 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 datasets are required. 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) since these data all help to generate improved understanding of the historic context of why a stretch of coastline looks like it does at the present time.

It was concluded that many of the geomorphological methods assessed in the research are worthy of further application and development. This may be through further field measurements to provide better quantified approaches (such as the barrier inertia methods) or the development of existing concepts through additional numerical coding or establishment of a wider empirical evidence base. Systems-based behavioural modelling holds much promise for the development of broad scale predictive capability.

4.7 Demonstration of combined coast and estuary modelling

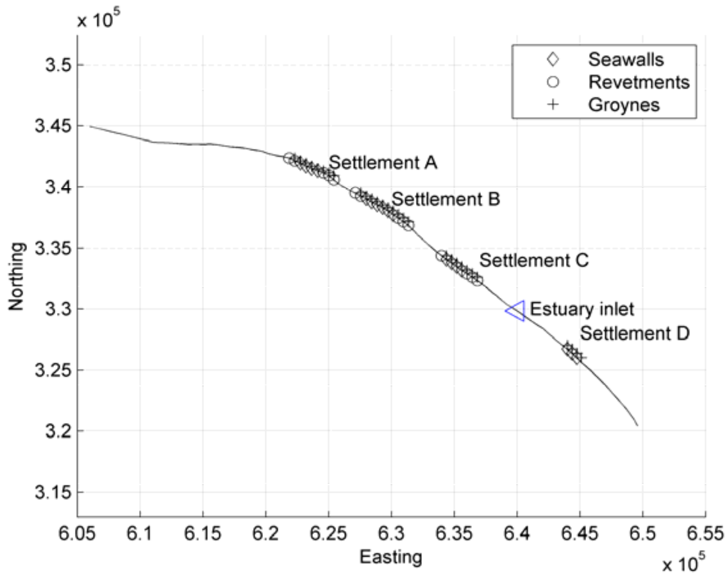
Behavioural systems models have been implemented to proof of concept level for a fictional but realistic coupled coast and estuary system (see the Project Record listed in Project Outputs). This demonstrated that a system map based conceptual model can be developed and formalised into numerical model form. It is a good 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 how existing models can be linked to assess different coastal management scenarios.

This study used existing systems-based behavioural models (SCAPE and ASMITA[3]), which were linked through the exchange of sediment. This demonstrated the benefits of a coupled modelling

[2] Southgate, H.N. and Brampton, A.H. (2001). Coastal Morphology Modelling: A Guide to Model Selection and Usage. HR Wallingford Report SR570, June 2001.

[3] (1) SCAPE and (2) ASMITA are two models describing (1) soft cliff, shore platform and beach behaviour and (2) estuary delta, channel and intertidal response

approach to evaluate geomorphological behaviour at SMP timescales (up to 100 years), including sea level rise and management interventions. Small modifications to the way in which sediment was handled by the models allowed for the coupling of the models (Project Record).



Settlement locations and estuary location in proof of concept case study

4.7.1 Addressing management questions

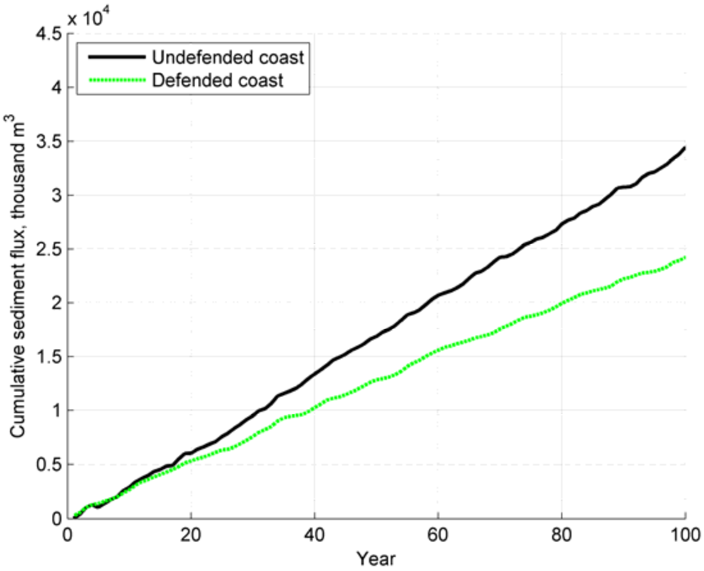
In the realistic case study it has been shown the results can be used to inform the answers to practical coastal management questions such as:

1. If existing structures fail at settlement A, how much cliff recession will occur over the next century?
2. If present management policy (defend) is continued at settlement A, how will the shore platforms evolve over the next century?
3. If present management policy (defend) is continued at settlement A, how will wave loading on the existing structures change over the next century?
4. If settlements A, B, and C are defended for one century, will this affect sediment flux to the estuary? **See Box 6**
5. If 380 hectares are reclaimed from the estuary what will be the resulting loss of intertidal habitat?
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?
7. Would such interventions affect the downdrift shoreline at settlement D?
8. Which of the options (1) retreat estuarial seawalls or (2) retreat estuarial seawalls and allow coast protection structures to fail causes least flooding?

These questions are answered for the specific case studied in Report 2.

Outputs from similar modelling exercises will enable better planning of coastal works and improve understanding of the consequences of not intervening. It will help coastal practitioners, including Local Authorities, the Environment Agency, Defra and others involved in strategic planning to assess risks, and plan for future change. The modelling involved description of elements including cliffs, beaches, shore platforms, intertidal flats, channels and ebb tidal deltas. New modules are required to describe other elements such as dunes, spits, marshes and nesses.

Box 6 If settlements A, B, and C are defended for one century, will this affect sediment flux to the estuary?



Answer: Defence construction and maintenance will, over the course of the century, reduce sediment supply to the estuary by approximately ten million cubic metres.

4.8 Practical relevance of results

The results of the research lead to the following conclusions:

1. The proposed framework for geomorphological studies can be applied in a consistent fashion to coastal and estuary management.
2. Expert Geomorphological Assessment (EGA) provides a sound basis for evaluating past, present and future behaviour within testable conceptual models.
3. The description of geomorphological features and elements provides a common basis of understanding and for assessing the role of management interventions.
4. System mapping provides a clear and consistent basis for formalising understanding about a coastal system, for sharing that information and having debate amongst interested parties and stakeholders about common areas of understanding and resolving areas of disagreement. The system mapping techniques will deliver benefits in the next round of Shoreline Management Plans (SMP3).
5. The range of existing behavioural models of coastal change, process-based models and change of state models, and associated analysis techniques, have been assessed and are shown to be worthy of further application and development.
6. The systems-based behavioural modelling approach offers a means of developing predictive capacity at the broad scales required by coastal managers. They can be implemented in conjunction with EGA to evaluate complex interactions that otherwise cannot be handled.
7. The systems mapping approach provides a means of developing such systems-based models from the conceptual models used by geomorphologists.
8. Confidence in the predictive capability of systems-based behavioural models can be built through the normal processes of model calibration and validation, and through further case studies.

4.9 Next steps

The systems-based behavioural modelling approach should be applied to real sites, in conjunction with systems mapping and Expert Geomorphological Assessment, to demonstrate its utility. Further work is required to develop new behavioural systems models for other types of coastal system, such as those that include dunes, offshore sandbanks, and inlet features.

The results of the completed research described in the Project Outputs should be disseminated and coastal managers need to be guided in how to apply the techniques in their own work. This will demonstrate to coastal practitioners, from Local Authorities, the Environment Agency, Defra and others involved in strategic planning to the benefits to be gained when assessing risks, and planning for future change. In the long term the outputs described will enable better planning of coastal works and better understanding of the consequences of not intervening. Recommendations have been made for further application and development of the methods which have been assessed in Report 2.

5. Acknowledgements

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6. Project Outputs

Report 1:
Whitehouse, R., Balson, P., Blott, S., Burningham, H., Cooper, N., French, J., Guthrie, G., Hanson, S., Houghton, A., Leggett, D., Nicholls, R., Pye, K., Walkden, M. (2008). *Characterisation and prediction of large scale, long-term change of coastal geomorphological behaviours: Inception Report.* Science Report – SC060074/SR1. Bristol, Environment Agency, 121pp.

Report 2:
Whitehouse, R., Balson, P., Beech, N., Brampton, A., Blott, S., Burningham, H., Cooper, N., French, J., Guthrie, G., Hanson, S., Nicholls, R., Pearson, S., Pye, K., Rossington, K., Sutherland, J., and Walkden, M. (2009). *Characterisation and prediction of large-scale, long-term change of coastal geomorphological behaviours: Final Science Report.* Science Report – SC060074/SR2. Bristol, Environment Agency, 281pp.

Project Records:
Walkden, M.J. and Rossington, S.K. (2009). Characterisation and prediction of large scale, long-term change of coastal geomorphological behaviours: Proof of Concept Modelling. Environment Agency Project Record – SC060074/PR.

French, J. and Burningham, H. (2009). Mapping the connectivity of large-scale coastal geomorphological systems. Coastal system mapping with the Cmap Tools tutorial. Environment Agency Project Record – SC060074/PR.

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