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Coastal morphological modelling for decision-makers

Report – SC090036/R

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Professor Doug Wilson
Director, Research, Analysis and Evaluation

Executive summary

This report provides guidance to coastal practitioners on coastal processes and the morphological models, methods and tools that can be used to help understand coastal change. It is written for non-specialists interested in coastal processes and coastal management, and charged with decision-making at the coast. It provides guidance for 3 types of stakeholders: coastal managers, coastal engineers and coastal modellers.

To understand why and how the coast is evolving and how human interventions or climate change might affect that evolution, coastal engineers and managers need a combination of evidence, expert local knowledge and some form of predictive model or tool. To select, apply and interpret that tool appropriately, they need a clear understanding of the specific coastal processes active in the area of interest, their potential impacts and significance, the factors likely to influence them, and their patterns and rates of change at different spatial and temporal scales. This report provides guidance and context on each of these issues.

Establishing an appropriate modelling framework is fundamental for delivering a robust outcome-focused approach, whose results decision-makers can understand and have confidence in. This guidance sets out good practice for the morphological modelling process from commissioning a model and early conceptual modelling, through appropriate model calibration and validation, to interpretation of the results and uncertainty analysis and sensitivity testing. It seeks to help decision-makers to understand how different model types might be used to answer the following typical coastal management questions.

- **Q1 Expected trends**. What is the likely trend of change in geometry of the coastal feature (for example, beach, cliff, dune, barrier beach) and how is that likely to change naturally (that is, assuming current climatic and management conditions) in the future?
- **Q2 Management impacts at site**. What is the likely future impact of different coastal management interventions on the feature?
- **Q3 Management impacts nearby**. What is the likely future impact of different coastal management interventions on adjacent frontages and further afield?
- **Q4 Climate change impacts**. What is the likely impact of climate-related changes on the feature in the future?
- **Q5 Storm impacts**. What is the likely future short-term impact (for example, beach lowering) following a storm (extreme wave and/or tidal and/or surge event)?
- **Q6 Recovery after storms**. To what extent might the feature recover -in the short term (for example, beach rebuilding) following an extreme storm (extreme wave and/or tidal and/or surge event)?
- **Q7 Estuaries**. What is the likely future impact of estuarine change on coastal morphology?
- **Q8 Landward flood risk**. What coastal morphological changes might have an impact on landward flood risk?

The guidance describes the different types of morphological models, methods and tools available. These range from those that are fully data-oriented (that is, they rely on existing datasets) to those that are fully process-oriented (that is, they model the coastal processes explicitly) and have high predictive capability.

The model classifications can be described at high level as follows:

- Coastal and Estuarine Systems Mapping (CESM)
- geomorphological data analysis
- data-driven models
- parametric models
- process-based numerical models
- behaviour-based numerical models
- emerging techniques

The guidance evaluates the generic spatial and temporal applicability of each model type, their relative usability and developability, and their potential for linking to other model types to provide additional functionality. It describes typical outputs, benefits and limitations, and provides examples of specific academic or industry tools (with links to where more information can be sourced) and illustrative case study applications.

Through a series of tables and commentary, the guidance explains the capability of the different model types to help decision-makers understand beach, cliff, dune and barrier beach evolution and change under present, future climate or human intervention scenarios, the impact of estuarine change on the coast and the impact of morphological change on coastal flood risk. This ‘mapping’ of ‘model capability’ against ‘key coastal management issues’ for the coastal features (that is, addressing Q1 to Q6 above) is summarised in the table below.

The report examines Q7 (Understanding the impact of estuarine change on coastal morphology) in terms of the exchange of sediment between the estuary and open coast, and the potential for linking models of both in order to best account for the interactions. Q8 (Understanding the impact of coastal morphological change on landward coastal flood risk) is addressed through defining the following potential relationships:

- changes in bathymetry leading to changes in wave and water levels
- changes in beach levels and structure toe levels affecting local water depths, overtopping rates and structure stability
- changes in beach profiles and cross-sectional areas affecting the extent to which it can protect shore platforms and cliffs from erosion
- changes in barrier beach and dune profiles and cross-sectional areas affecting their ability to withstand breaching

Case study material demonstrates the potential value of understanding the interdependence between flood risk and morphological change, but also the sense of scenario testing to establish the potential range of likely impacts before investing significant resources in morphological modelling studies at a particular site.

Finally, the guidance describes how modelling can be used to help set appropriate Coastal State Indicators (CSIs) for a particular area and threshold levels at which point appropriate management actions need to be undertaken to manage risks to defined levels. Monitoring of such indicators can also allow further model verification and increased model confidence with time.

Summary of model type applicability in answering coastal management questions 1–6

Management question	Coastal feature	Model type															
		CESM		Geomorphological data analysis		Data-driven		Parametric		Process-based						Behaviour-based	
										Planshape		Profile		Area			
Q1 Expected trends. What is the likely trend in geometry of the coastal feature (for example, beach, cliff, dune, barrier beach) and how is that likely to change naturally (that is, assuming current climatic and management conditions) in the future?	Beach	N	F	N	F	N	F	N	F	N	F	N	F	N	F	N	F
		FD	FC	FD	FC	FD	FC	FD	FC	FD	FC	FD	FC	FD	FC	FD	FC
	Cliff	N	F	N	F	N	F	N	F	N	F	N	F	N	F	N	F
		FD	FC	FD	FC	FD	FC	FD	FC	FD	FC	FD	FC	FD	FC	FD	FC
Q2 Management impacts at site. What is the likely impact of different coastal management interventions?	Dune	N	F	N	F	N	F	N	F	N	F	N	F	N	F	N	F
		FD	FC	FD	FC	FD	FC	FD	FC	FD	FC	FD	FC	FD	FC	FD	FC
Q4 Climate change impacts. What is the likely impact of climate-related changes on the feature in the future?	Barrier beach	N	F	N	F	N	F	N	F	N	F	N	F	N	F	N	F
		FD	FC	FD	FC	FD	FC	FD	FC	FD	FC	FD	FC	FD	FC	FD	FC
Q5 Storm impacts. What is the likely future short-term impact (for example, beach lowering) following a storm (extreme wave and/or tidal and/or surge event)?								N, F, FD, FC				N, F, FD, FC					
Q6 Recovery after storms. To what extent might the feature recover in the short term (for example, beach rebuilding) following a storm (extreme wave and/or tidal and/or surge event)?																	
Q3 Management impacts nearby. What is the likely future impact of different coastal management interventions on adjacent frontages and further afield?										N, F, FD, FC				N, F, FD, FC			

Notes: F = future no change; FC = future different climate condition; FD = figure different management scenario; N = natural

Key:	Question can be answered with this type of model	Question can be answered up to an extent with this type of model	Question cannot be answered with this type of model

Acknowledgements

This report draws on work carried out during the Integrating Coastal Sediment Systems (iCOASST) project, which was funded by the Natural Environment Research Council under grant NE/J00541X/1, with the Environment Agency as an embedded stakeholder.

Contents

List of tables and figures

1 Introduction

This chapter explains the importance of coastal morphological change in decision-making for flood and coastal erosion risk management (FCERM) and introduces the role of coastal morphological modelling in helping to answer questions and find solutions to problems relating to coastal change. It also sets out the background to this project and the aims and structure of this report in providing a resource for decision-makers who are not themselves modelling experts.

Chapter contents

1.1 Coastal morphological change and decision-making at the coast

Changes in future coastal flood and erosion risk are intrinsically linked to the morphological evolution of our coastlines and estuaries as illustrated in Figure 1.1. However, the modelling tools available to quantify long-term morphological change are limited in their representation of the underlying physical processes and often poorly understood by those using their outputs to help make decisions. This guide seeks to address this issue by providing clear guidance to decision-makers. Improving people's ability to understand and model coastal evolution will have a direct influence on improving future investment choices.

Coastal managers and engineers make use of a mixture of data collection and modelling combined with expert judgement to help inform decision-making on their coastline. By using these approaches they seek to understand which coastal processes are occurring, and whether and how those processes should be managed in the future.

In considering options for action or inaction and their potential impacts, risks need to be minimised and opportunities maximised in the most cost-effective manner, while paying attention to environmental and engineering sustainability and multiple stakeholder interests. Modelling can be used to help identify the best indicators of important coastal change processes and the likely indicator thresholds at which point active interventions or management strategies should be initiated.

However, modelling is just one of the stepping stones in the understanding and solving of any coastal morphological problem. The complete process requires a number of integrated steps (Figure 1.2).

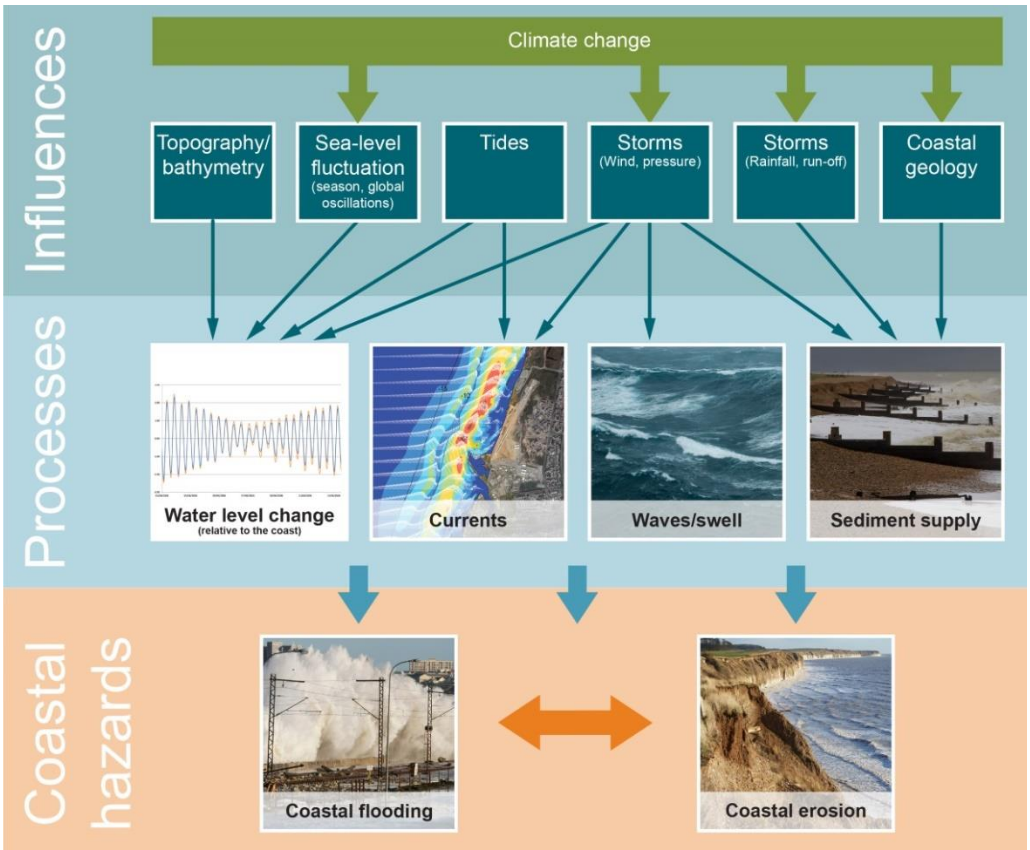


Figure 1.1 Drivers of coastal flooding and morphological change

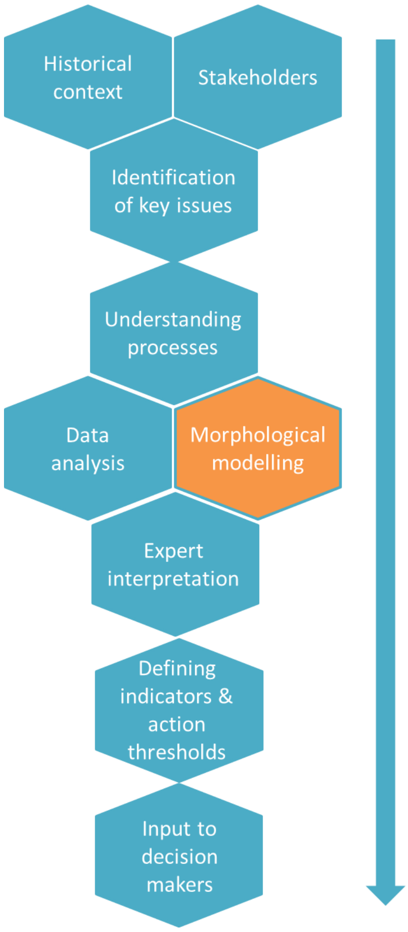


Figure 1.2 Role of modelling in coastal decision-making

For models to be used to support decision-making on the coast it is important to define clearly which questions the models need to answer. These questions in turn inform the choice of model and the manner of its application. There are many questions that coastal managers might be interested in for any particular stretch of coastline. Although these questions will often be apparent, they may need focusing for the purposes of providing input into the morphological modelling process. Box 1.1 provides some suggestions (based on consultation) as to typical issues that may need to be addressed. These questions are used in Section 6 as the basis for guiding users on the coastal model types that are more likely to be suitable.

Box 1.1: Typical coastal management questions relevant for morphological modelling

Q1 Expected trends. What is the likely trend of change in geometry of the coastal feature (for example, beach, cliff, dune, barrier beach) and how is that likely to change naturally (that is, assuming current climatic and management conditions) in the future?

Q2 Management impacts at site. What is the likely future impact of different coastal management interventions on the feature?

Q3 Management impacts nearby. What is the likely future impact of different coastal management interventions on adjacent frontages and further afield?

Q4 Climate change impacts. What is the likely impact of climate-related changes on the feature in the future?

Q5 Storm impacts. What is the likely future short-term impact (for example, beach lowering) following a storm (extreme wave and/or tidal and/or surge event)?

Q6 Recovery after storms. To what extent might the feature recover in the short term (for example, beach rebuilding) following a storm (extreme wave and/or tidal and/or surge event)?

Q7 Estuaries. What is the likely future impact of estuarine change on coastal morphology?

Q8 Landward flood risk. What coastal morphological changes might have an impact on landward flood risk?

1.2 Background to the guide

This report forms one of the outputs of a dissemination project for the original Integrating Coastal Sediment Systems (iCOASST) project, which was funded by the National Environmental Research Council (NERC) from 2012 to 2016 to help improve understanding of how the shape of UK coasts and estuaries is likely to change over the next century.

The iCOASST project produced a number of tools and models. While each is useful in its own right, the principle of the iCOASST approach is that better analysis and new insights should become possible by linking them. The iCOASST framework demonstrates how individual models can be linked to achieve a better system-level understanding of long-term coastal change. Two pilot model ‘compositions’ (that is, set of linked models) were developed to demonstrate this.

The iCOASST framework website[1] is hosted by the Channel Coastal Observatory. It describes in technical detail:

- all the elements of the iCOASST framework
- the pilot site model compositions
- each of the individual models

The model codes are hosted on the website, together with example model input and output datasets, and user guides. The aim is to encourage use and further development of the models by others in the coastal modelling community.

This guide builds on the need for up-to-date explanatory material on coastal modelling for coastal managers identified in the Coastal and Estuarine Systems Tools (CoaEST) project (Environment Agency 2011). The guide sets the modelling developments from iCOASST within the broader context of coastal morphological modelling resources on which a coastal manager might call.

1.3 Aim of this guidance

The specification and procurement of models and the interpretation of model results requires knowledge and experience. This document aims to provide end users with guidance on when and how to select and use modelling tools to answer coastal morphological process questions that will enable better decisions for the management of the coast.

It also aims to close the knowledge gaps between modellers, those scoping and specifying modelling, and those using model results for decision-making. In so doing it:

- promotes the use of the latest useful tools available to increase the quality of decision-making
- signposts and links typical coastal management questions with the most appropriate modelling techniques and tools
- facilitates communication and interaction between stakeholders, decision-makers and modellers
- engenders improved understanding of the model outputs, limitations, risks and opportunities by coastal managers and coastal engineers
- highlights to modellers the information required by end users to give them confidence in the model outputs and to be able to use them appropriately

The guidance focuses on the usability and applicability of morphological models rather than their quality. Guidance on evaluating model quality is provided in the Environment Agency's Standards for Modelling (CH2M Hill 2016) which, although focused on the forecasting and modelling flooding on open coasts, can also be applied to morphological modelling. In the case of the iCOASST models, an independent appraisal of their usability has been carried out, the results of which are available via the 'Model evaluation' tab of the iCOASST for end users web page ((https://www.channelcoast.org/iCOASST/icoasstforendusers/).

Two of the appendices to this report are provided to support relationships between end users and local researchers developing bespoke models for local coastlines. Appendix D provides a model evaluation proforma that can be used for evaluating and

[1] www.channelcoast.org/iCOASST/

checking model usability. Appendix E contains generic guidance on model development and the production of user manuals for use by the modelling community. They were developed in tandem with model development under iCOASST, using the lessons from the iCOASST experience to provide more generic support to both modellers and managers alike. Their purpose is to help to ensure that any new models are developed recognising the needs of both end users and those taking the development of the models further in the future.

This report deals only with coastal morphological models and not estuarine models or coastal flood risk models, although links between them are discussed in Section 6 with reference to answering Questions 7 and 8 in Box 1.1. It complements a number of other publications including:

- Beach Management Manual' (CIRIA 2010)
- reports from the CONcepts and Science for Coastal Erosion Management (CONSCIENCE) project (www.conscience-eu.net)
- reports from the FLOODSite project (www.floodsite.net)
- Characterisation and Prediction of Large-scale, Long-term Change of Coastal Geomorphological Behaviours' (Environment Agency 2009a)
- CoaEST Project Inception Report' (Environment Agency 2011)

The guidance also complements the Environment Agency's coastal flood modelling standards (CHM2Hill 2016).

By supporting improved understanding and decision-making, this guidance should help inform:

- Shoreline Management Plans (SMPs)
- Coastal and Estuarine Strategies (FCERM strategies)
- any future iterations of Coastal Habitat Management Plans
- Beach Management Plans
- Flood and Coastal Risk Management Habitat Compensation Programmes
- Catchment Flood Risk Management Plans
- River Basin Management Plans
- other plans that require information on short-term or long-term coastal change
- the design of new beach management schemes

1.4 Who is the guidance for?

This guidance is aimed at non-specialists who are interested in coastal processes and coastal management and charged with decision-making at the coast and who may be required to assess the needs for, commission and review the outputs from coastal morphological models. It is specifically targeted at 3 stakeholder groups:

- **Coastal managers** who need a high level overview of how coastal process models and decision support tools can be used to support or improve coastal management decision-making in their area.

- **Coastal engineers** who may not be modelling experts, but need to understand how relevant generic model types work, what questions they can answer, what data they need to run and what their limitations are.
- **Coastal modellers** who are interested in understanding the opportunities, drivers and overarching morphology modelling landscape. Although this guide does not provide detailed information on specific model set-up requirements and functionality, it does set out the information that modellers will need to communicate to decision-makers in order to support robust modelling procedures and confidence and understanding in the modelling outcomes.

Figure 1.3 summarises the roles of each group within the coastal modelling process.

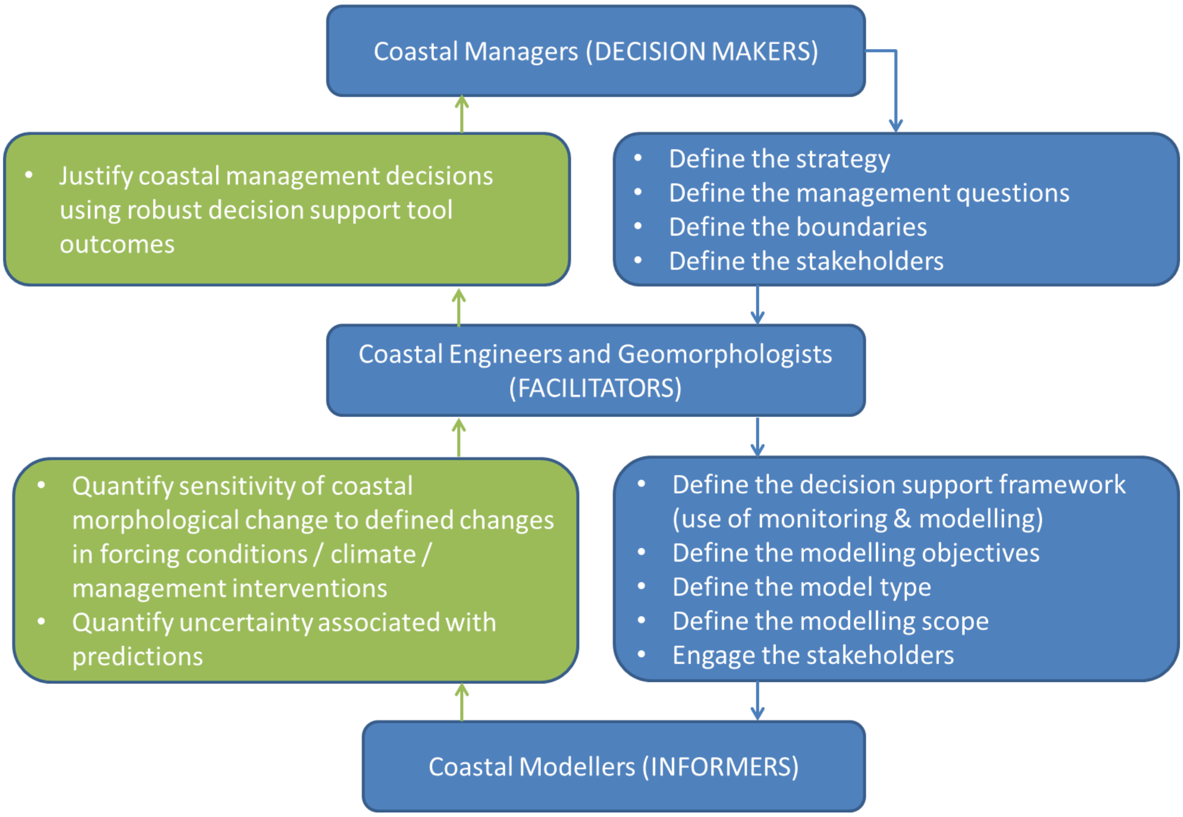


Figure 1.3 Roles in the coastal management process

1.5 Structure of the guide and how to use it

Chapter 2 provides the essential background information to coastal morphological change and its prediction using modelling.

Chapter 3 sets out the principal steps in the modelling process, how to take account of and understand modelling uncertainties, and the potential value of linking models together.

Chapter 4 gives a high level description of each of the different types of predictive models/tools and evaluates them in terms of their applicability and their relative usability.

Chapter 5 discusses the use of different model types and approaches in helping to answer a range of typical coastal management questions of relevance to decision-making.

Chapter 6 describes how morphological modelling can help in identifying the most appropriate performance indicators (for monitoring) and in establishing critical thresholds for action.

Although all the guidance will be of value to those requiring a general overview to coastal morphological modelling, individual chapters are aligned with specific themes as indicated in Figure 1.4. This also indicates which themes are likely to be of more interest to specific end users (indicated via the width of the user bar in the final column). Table 1.1 indicates the type of guidance available for the 3 stakeholder groups.

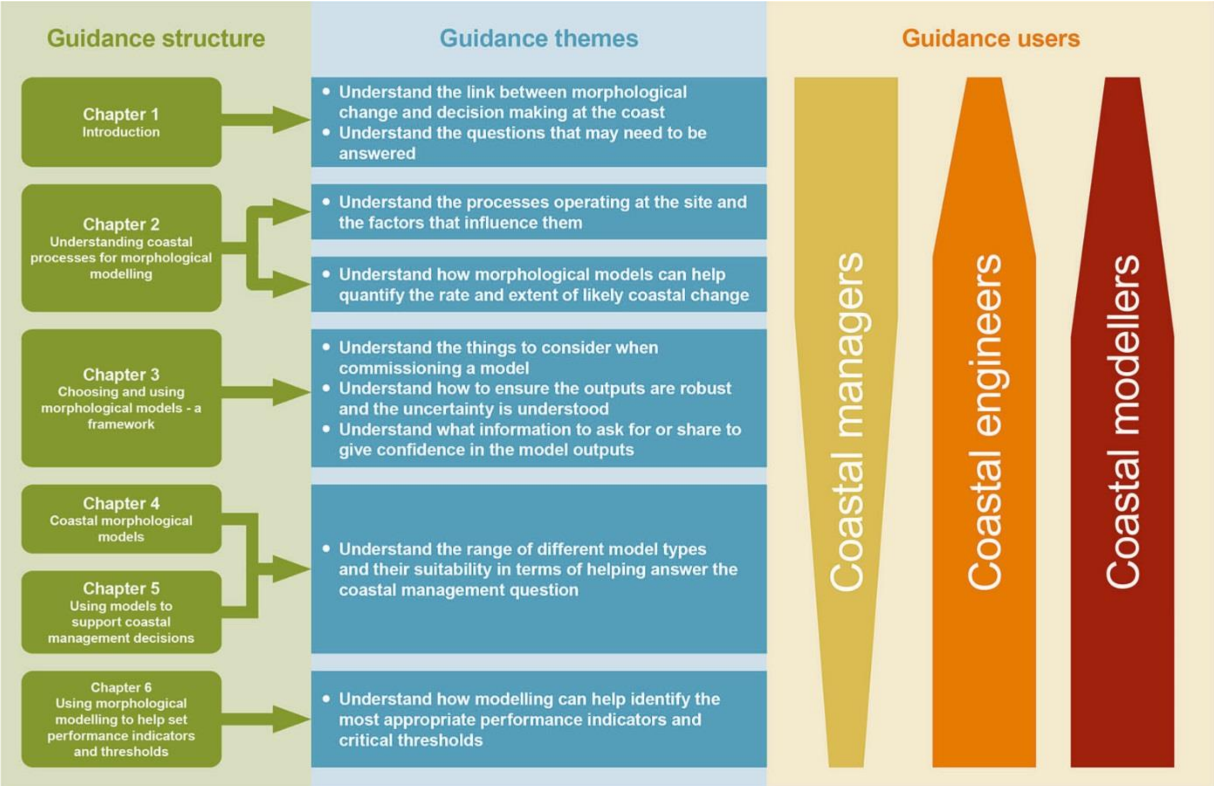


Figure 1.4 Using the guidance to support coastal morphological modelling for decision-making

Table 1.1 Guidance for the 3 stakeholder groups

Stakeholder group	Content
Coastal managers	• Value of coastal models in supporting or improving coastal management decision-making • Management issues that models can help answer • How modelling can be used to help identify the best indicators of coastal change and action thresholds to manage coastal erosion risks • Characteristics, benefits and constraints associated with different model types • Developing a decision-making framework which morphological modelling can support
Coastal engineers	• Coastal processes, drivers and the impacts of both temporal and spatial scale on the prediction of coastal change • How different generic model types work, what questions they can (and cannot) answer, what data they require and their limitations • Setting out a robust model commissioning process • Reviewing and interpreting model results
Coastal modellers	• The overarching morphological modelling landscape • The modelling information that needs to be conveyed to commissioning engineers and managers • Areas where further research is required

2 Understanding coastal processes for morphological modelling

Coastal processes are fundamental to understanding morphological change because they are critical factors in shaping the seabed, shoreline and hinterland. Human interventions and structures in turn tend to modify these processes – regardless of whether or not they were designed to.

To understand why and how the coast is changing, the potential effects of interventions and what needs to be represented in any model being used to predict that change, it is crucial to have an understanding of the specific coastal processes active in the area of interest. This chapter therefore describes the range and significance of different coastal processes, the landforms they generate, the factors that influence them, and their patterns and rates of change at different spatial and temporal scales.

Chapter contents

2.1 Why are coastal processes important?

> 'Coastal environments are among the most changeable on the Earth's surface' (Carter 1988).

The first step in considering how to predict morphological change is to identify the type of coast (including the component morphological features) and the links between those features and the coastal processes operating in the area.

Three key processes take place within coastal environments:

- **erosion** – by which sediment particles are removed by the action of wind, flowing water or waves
- **transport** – by which those particles are transferred from one place to another
- **deposition** of sediment

Each coastline has its own balance and equilibrium of erosion, transportation and deposition.[2] Most physical coastal changes are associated with the movement of sediments and any interventions that have an impact on that process (Figure 2.1).

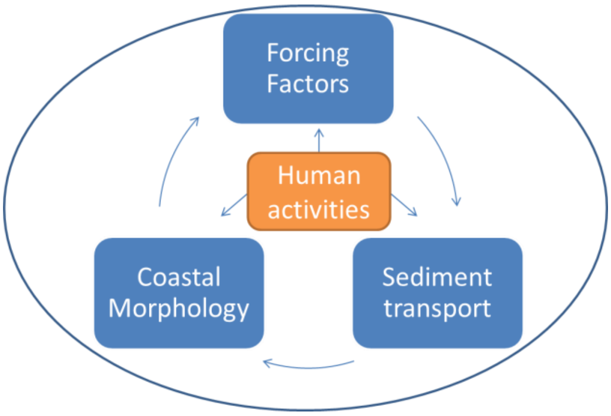


Figure 2.1 Principal inter-related components associated with coastal morphological change

Source: modified from Environment Agency (2009a)

Coastal sediment transport can occur in any direction. However, there is often a clear net trend in one particular direction over a defined timescale.[3] Sediment transport can occur:

- on the seabed (bed load transport)
- in the water column (suspended transport)
- at the interface between land and water (through wave action)
- in the air (Aeolian transport)

Understanding and quantifying transport rates is fundamental for predicting changes in morphology. However, transport rates are never steady and there can be significant temporal and spatial variations in both strength and direction (for example, during a tide or storm, during different seasons, under different current conditions). In most situations, however, it is not the instantaneous rate of sediment transport that is important but how the net sediment movement changes the morphology of a beach or of parts of the seabed (that is, erosion or accretion) in the long term (for example, over years or decades).

2.2 Links between coastal processes and coastal morphological features

Large-scale planform coastal morphological features are determined by the interaction between the operating coastal processes, the local coastal geology and any management interventions. They create coastal landforms that change in time as a result of ongoing coastal processes (Figure 2.2).

Most lengths of coast will consist of a combination of different coastal morphological features – often both natural and anthropogenic.

[2] Erosion of a beach is reversible by deposition, but erosion of a cliff is irreversible.

[3] This residual sediment transport is common in places of significant tidal asymmetry.

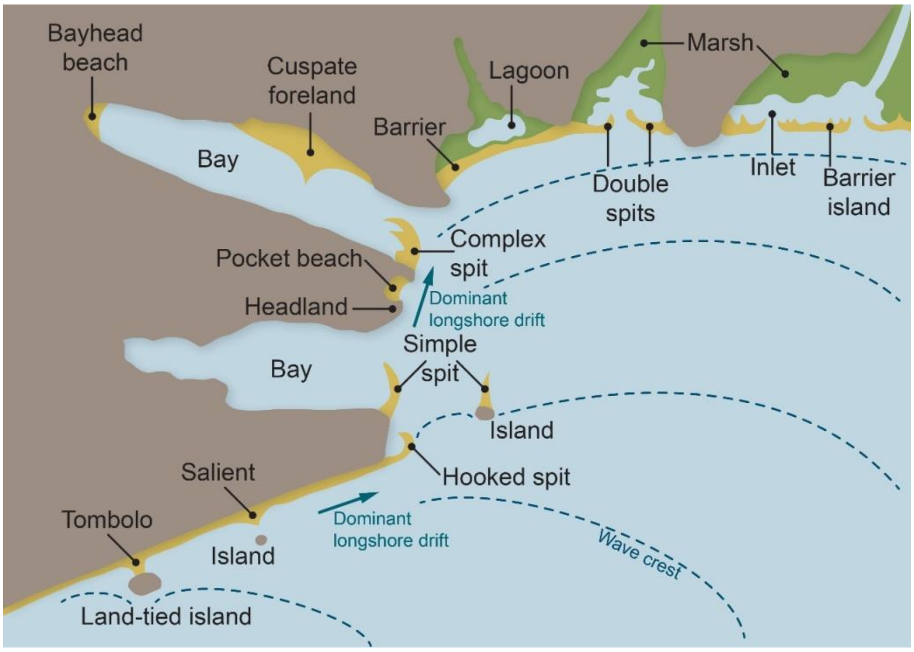


Figure 2.2 Illustration of different coastal features

Source: after CIRIA (1996)

Appendix A gives more information about the following main coastal features:

- beaches
- shore platforms
- natural backshore features
- barrier beaches
- estuaries

A conceptual framework for classifying and setting out the interactions among the components within the estuary–coast–inner shelf was developed during the iCOASST project (French et al. 2016a). This framework is described in Appendix B.

In places where there is an abundance of wave energy or ocean currents and/or a lack of sediment available for deposition, erosion of the coast will be the dominant mechanism of change. Erosional shores tend to be characterised by shorelines that are exposed to high energy waves, high exposure and limited deposition. Common erosion landforms include cliffs, wave-cut platforms, headlands and bays, caves, arches and stacks.

Depositional coasts are characterised by an abundant sediment supply that results in the net deposition of sediment and creation of new coastal landforms, despite the energy of the waves and ocean currents. They are most common where there are sediment supplies (for example, from nearby erosional coasts or estuaries) that are distributed by waves and tides at the coastline. Some depositional coasts also receive their sediment from offshore to nearshore transport (for example, Selsey Bill to Brighton on the Sussex coast). Some common depositional forms are spits, barrier beaches and bars.

The coast consists of 4 morphological zones:

- **Offshore**. In this zone, sediment motion induced by waves alone effectively ceases and the influence of the seabed on wave action becomes small in comparison with the effect of wind. In the UK, this is typically seaward of water depths of 20–50m depending on wave exposure.

- **Nearshore**. This zone extends seaward from the low water line to the position marking the start of the offshore zone. In this zone, waves steepen, break and reform during their passage to the beach. Sediment transport occurs both along and perpendicular to the shore via wave and current action. The nearshore zone is further divided into the swash area, the surf zone and the breaker zone, depending on which wave transformation process prevails.
- **Foreshore**. The foreshore is the part of the shore or beach that is wet due to the varying tide and wave run-up under normal conditions (that is, excluding the impact of extreme storm waves and storm surge).
- **Backshore**. This is the upper part of the active beach above high water extending to the limit of the beach. The backshore is dry under normal conditions, is often characterised by berms and may contain vegetation. The backshore is only exposed to waves under extreme events with high tide and storm surge. Backshore features present on a beach can consist of dunes or cliffs.

The main cross-shore morphological features are shown in Figure 2.3, which also depicts some of the main processes described below.

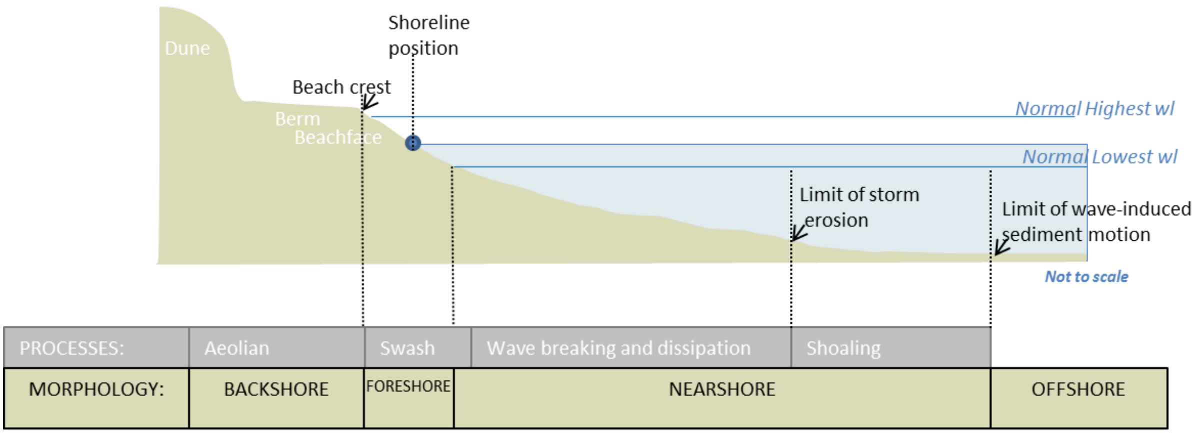


Figure 2.3 Beach cross-shore morphological features and processes

2.3 Factors influencing the rate and extent of coastal processes

The morphological development of coastal features depends on a large number of factors. It is also important to understand that sediment transport rates at a specific location may reflect conditions some distance away (for example, upstream in a river).

Relevant factors can include:

- the origins and characteristics of the sediments
- sediment sources and sinks
- the solid geology of the area
- coastal topography and bathymetry
- forcing conditions (for example, waves, currents, water levels, wind climate)

- climate change impacts
- human interventions that form part of the coastline management strategy

These inter-related factors are discussed below.

2.3.1 Origins and characteristics of sediment

The sediment on a beach consists of rock fragments of a wide range of sizes, together with some shell fragments and other biota. The most common sand composition is quartz sand with some feldspar. Each beach has its own unique sediment, which is a product of its regional and local environment.

The present day situation of all beaches is a snapshot of an ongoing evolutionary process which commenced towards the end of the last Ice Age (CIRIA 1996). Modern sources of coastal sediments are:

- cliffs
- shore platforms
- rivers
- other sources such as biogenic material (shells) and industrial waste products

It is vital to take into account where the sediment in the area of interest comes from and whether these sources have changed at all. This will influence the particle size distribution, which in turn will affect the permeability of the beach and therefore the way in which wave action shapes the beach. An example of this is set out in Box 2.1, which describes the storm response of beaches of different materials.

Box 2.1: Natural response of a beach profile to a storm depending on its sediment composition

Sand beaches (low permeability)

Milder wave conditions tend to move sand onto the beach, whereas storm waves (larger and more energetic than fair weather ones) tend to move sand offshore. The resulting differing profiles are expressions of the often seasonal cycle of wave energy. Unusually large storm events result in a disequilibrium profile and sand may be permanently lost to deep water (Figure 2.4).

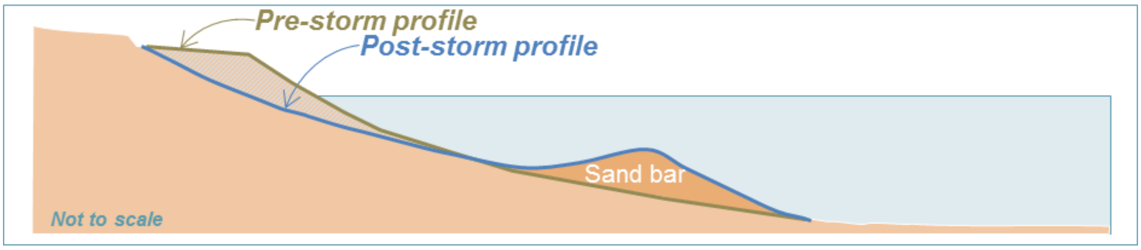


Figure 2.4 Sandy beach response to stormy waves

Shingle beaches (high permeability)

Shingle beaches respond much more quickly to changes in waves and water levels, making them one of the most effective natural sea defences, capable of dissipating in excess of 90% of all incident wave energy (Powell 1990). Shingle beaches will respond to a storm by accumulating a crest or ridge of material on the sub-aerial (that is, above the water level) part of the profile. Large storms can also draw material down the profile creating an offshore step (Figure 2.5).

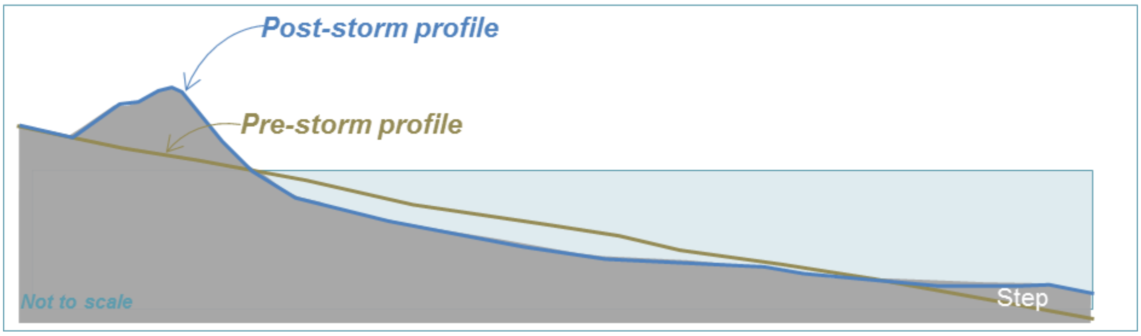


Figure 2.5 Shingle beach response to stormy waves

Various beach compositions can be recognised across a continuum from beaches that are mainly sand to those which are a mixture of sand and gravel.

In between these 2 categories, there are also coarse beaches which can be further divided into 'shingle upper – sand lower' or 'mixed sand and shingle beaches'. However, the latter classification is somewhat simplistic as mixed beaches are in effect themselves a continuum where a diverse range of different beaches can be found, with different along-shore and across-shore, with in depth and in time variation of the sediment sizes present. The relative proportions of sand and gravel in mixed beaches and their influence on the sediment transport across and along the beach is an area that needs further research, as it is currently poorly represented in modelling but has a direct application in the context of recharge schemes and their effective design.

2.3.2 Sediment sources (and sinks)

Sediment sources are locations that contribute sediment into a system such as cliff erosion, riverine sediment or beach recharge (Environment Agency 2018a).

Sediment sinks are locations that permanently remove sediment from a system – such as wind-blown sediment transport or areas of accretion.

Sediment stores are locations that might be able to temporarily hold onto sediment, but may also subsequently contribute back to the system under certain circumstances. Examples of stores are beaches, foredunes, saltmarshes, mudflats, spits, sandbanks and sandbars.

The main sources and sinks in a coastal system that can be quantified to produce a sediment budget are shown in Figure 2.6.

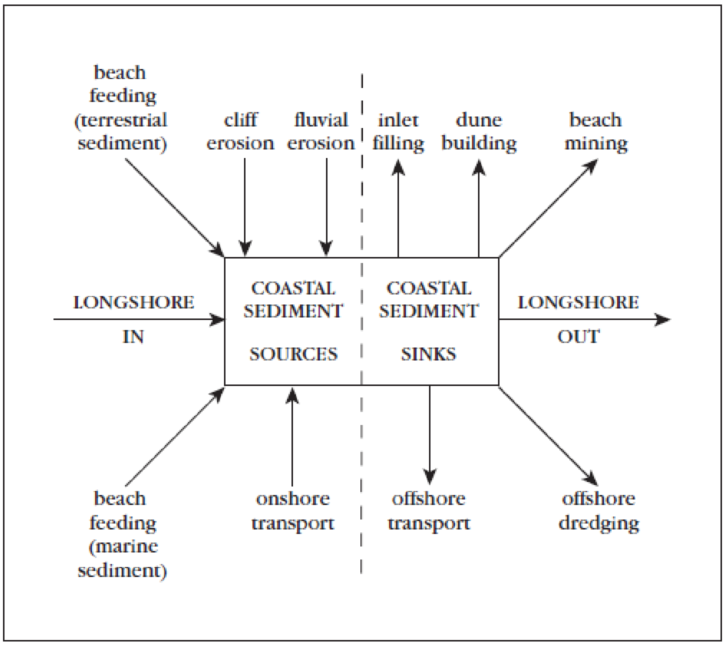


Figure 2.6 Sources and sinks of coastal sediment

Note the human element in the coastal sediment budget.

Source: May and Hanson (2003)

2.3.3 Coastal solid geology

The solid geology of both the coastal area and the nearshore will affect the development of coastal features. The resistance of the rock, and any lines of weakness within it (for example, faults or particularly well-jointed sections of cliff), together with its exposure to wind and waves will affect erosion rates. Sections of cliff that are particularly resistant to erosion protrude from the general shoreline alignment to form headlands. Weaker sections of coastline that are more easily eroded form bays. As the headlands protect the bays, sediment is deposited in bays to form beaches. In terms of their planshape, solid geology shapes forms such as pocket beaches, tombolos, cuspate forelands, spits and barrier beaches (see Figure 2.3 and Appendix A). In terms of profile, the effect of the underlying geology is more obvious in features such as reefs or the shore platform.

2.3.4 Coastal topography and bathymetry

The shape of the coastline and its orientation to oncoming waves is an important factor. An area of coastline may be influenced by a large ocean fetch but, because of its orientation, it may be sheltered from erosive wave action.

Swash-aligned, or swash-dominated, coasts build parallel to incoming wave crests, whereas drift-aligned, or drift-dominated, coasts build parallel to the line of maximum longshore sediment transport and are generated by obliquely incident waves (but not necessarily unidirectional). In general, swash-dominated coasts are smoother in outline than those that are drift-dominated, which tend to exhibit intermittent spits and sediment accumulations. Due to variability in the wave climate, few beaches are entirely swash-aligned or drift-aligned, but identification of the predominant characteristic can help in predicting likely future evolution (Defra 2002). These descriptions illustrate that coastal plan shapes are products of complex relationships between wave climate and sediment supply.

The bathymetry of the area will also have an important influence on the wave transformation processes. These are described in Appendix C.

2.3.5 Forcing conditions

Most erosion, sediment transport and deposition of non-cohesive sediments takes place in wave-dominated environments and, as a result, waves tend to be the most important forcing condition for coastal processes.

However, the mean water level, the tidal ranges, the wind climate and the action of currents or other inflows (that is, groundwater and/or fluvial) are also important influences and the majority of these factors are inter-related to some extent. Substantial sediment transport rates in water usually require waves to agitate the sediment, and currents to carry the sediment.

Further information about each of these forcing influences is given in Appendix C, which includes a detailed discussion of wave generation and transformation processes.

2.3.6 Human interventions

There are a large number of human intervention structures around the coastline. Some of these have been created for navigation purposes (for example, ports, harbours) and others are part of a coastal flood and erosion risk management strategy (for example, seawalls, revetments, groynes, offshore breakwaters). All of these will influence the natural coastal processes in the area and can have both immediate and longer term effects on the behaviour of beaches and the surrounding coast

It is important to remember that coastal structures far away from the area of interest, such as long harbour arms, might still have an impact as they will be modifying the sediment availability and sediment transport over a wide area. A river dam constructed for irrigation purposes is also likely to affect sediment transport opportunities and rates along the coastline adjacent to the estuary.

Human interventions on the coast can be divided into 4 categories.

Hard defences

Examples include:

- **Seawalls and revetments:** along-shore defences that 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)
- **Detached breakwaters and reefs**: shore parallel defences which tend to imitate the rocky islands or outcrops on the nearshore seabed

Longshore control structures

Examples include:

- **Long terminal groynes** such as harbour structures and fish-tailed groynes which obstruct the longshore drift and potentially divert both longshore currents and the sediment they transport offshore

- **Short groynes**: linear structures aligned perpendicular to the shoreline, built in groups (fields) and of a length (often 40–80m) designed to locally reduce the longshore drift rate at least on the upper part of beaches and/or to prevent tidal or wave-induced currents running along the face of seawalls, promenades and coastal cliffs

Soft defence (beach) modifications

Examples include:

- **Recharge**: 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
- **Recycling:** the process by which sediment is collected from areas of deposition on a beach and deposited further 'updrift' to fill areas of beach loss; an activity carried out at a wide range of intervals, but commonly at intervals of 6 months to 3 years
- **Bypassing:** the mechanical collection of beach sediment from one area where it has accumulated and redistributing it to another where beach widths have reduced (the movement of sediment is in the same direction as the net longshore drift**)**

Managed realignment

This is the deliberate process of altering the alignment of flood defences, frequently to create flood storage or to provide wave energy dissipation over and across a previously defended (often rural) area or to create habitat. Managing this process helps to avoid uncertain outcomes and negative impacts. It also helps to maximise the potential benefits and reduce both coastal flooding and erosion.

2.3.7 Climate-related changes

Any long-term coastal modelling and management decision-making should take account of likely climate change to ensure that solutions are resilient to changes and economically robust. Climate change is already a reality, but further global warming will exacerbate the impacts.

Of the climatic impacts, perhaps the most significant are those related to mean sea level. Sea level has risen by about 120m since the peak of the last Ice Age about 19,000 years ago. Since then ice caps have shrunk, returning water to the sea and the seas have warmed and expanded. Global average sea level is currently rising at the rate of about 3mm per year (Nerem 2018) and, if left to operate naturally, this change leads either to erosion or roll-back of beaches. Locally, effects such as settlement or isostatic changes (in the UK, most commonly rebound from glacial loading) mean that relative local mean sea level rise will differ from the global figures.

There are a number of other forcing conditions that are directly affected by climate change, although there is significant uncertainty regarding the extent of potential future changes. These conditions include:

- **Wind and waves**. Changes in low pressure weather systems (that is, storms) can have an influence on wind directions. This affects wave propagation that could alter beaches. Even a small change in the mean wave direction can greatly alter longshore drift rates and hence beach widths.

- **Extreme water levels**. If the high tide already reaches flood embankments or seawalls, mean sea level rise will reduce the width of the intertidal zone. Where the high water mark lies seaward of static defences, sea level rise combined with an inability for them to roll-back will narrow any intervening dunes, beaches or saltmarshes along a coastline. Both these cases of 'coastal squeeze' will diminish areas that are often of great environmental and flood risk management value. While the most frequently discussed environmental impacts are on plants and animals (for example, wading birds), there are implications for the amenity and recreational value of coastal resorts too.
- **Storminess**. There is uncertainty regarding the possible future frequency and intensity of severe storms under climate change scenarios and the consequential potential changes in extreme wave conditions and surges. If 'storminess' increases, there will be greater risks of flooding by waves 'overtopping' defences and of damage to beaches and coastal structures.
- **Rainfall and temperature**. Changes in rainfall and temperature will influence the weathering of the land surface and sediment supply to the coast, and may therefore increase (or reduce) the vulnerability of coastlines to erosion.

The implications of climate change for coastal management are usually tested through the use of scenarios (for example, Nakićenović and Swart 2000). Socioeconomic scenarios are used by analysts to make projections of future greenhouse gas emissions and to assess likely future vulnerability to climate change (for example, low, medium, high, business as usual, doubled emissions) (Carter and La Rovere 2001). Other 'scenario' types could be based on testing the impact of assumed changes in variables such as water level, wind and waves.

Predictions of climate change impacts on the coastline will have different levels of associated uncertainty for different scenarios. There is more confidence in sea level rise projections than changes in storminess for example. To assist routine practice, the Environment Agency has published relevant climate change allowances for the most important variables to be used in climate impact assessments (Environment Agency 2012). These are linked to the UK climate change projections, the next version of which are due to be published in late 2018.

2.4 Sediment 'littoral' cells

The location of sediment sources and sinks, the coastal solid geology, and the coastal topography and bathymetry all directly affect the zones (cells) within which the majority of sediment movement is contained. Box 2.2 describes the definition of these cells for the UK.

Box 2.2: UK sediment 'littoral' cells

The processes of erosion, transportation and deposition around the UK are largely contained within sediment or littoral cells. There are thought to be 11 large sediment cells in England and Wales as shown in Figure 2.7 (Motyka and Brampton 1993).

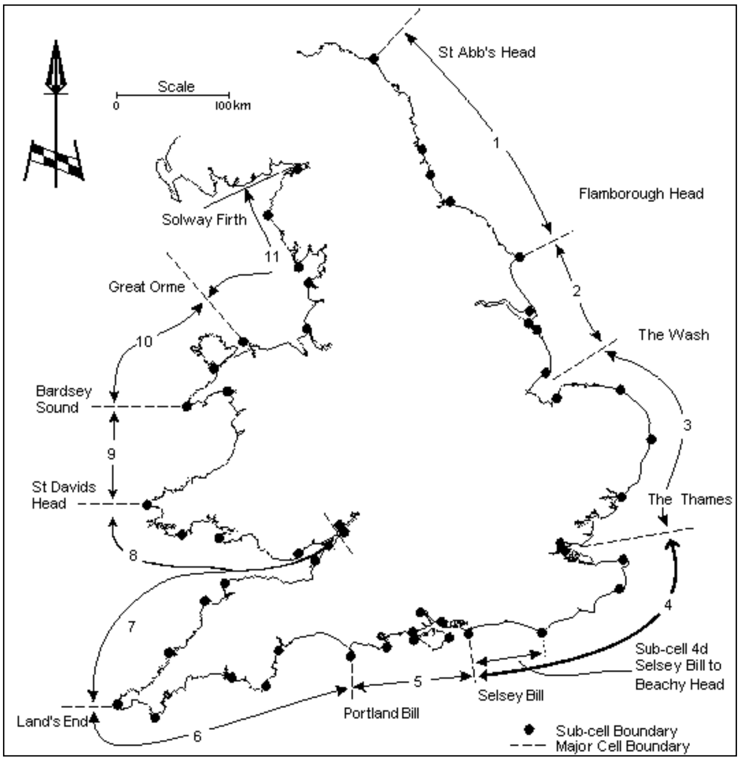


Figure 2.7 Major sediment cells and subcells around the UK

A sediment cell is generally thought to be a closed system, which suggests that no sediment is transferred from one cell to another. The boundaries of sediment cells are determined by the topography and shape of the coastline. Large features, such as the Llyn Peninsula in Wales act as huge natural barriers that prevent the transfer of sediment. In reality, however, it is unlikely that sediment cells are fully closed because of the constant variations in wind direction and tidal currents. There are also many subcells of a smaller scale existing within the major cells.

2.5 Representing sediment transport patterns and rates

The coastal zone is highly dynamic and sediment transport calculations in this area are complex. There are large uncertainties associated with estimating sediment transport patterns and rates, and any resultant erosion/accretion patterns. It is not unusual for 2 models to give results that differ by an order of magnitude or more, even with the same input conditions; this behaviour is called model structural uncertainty.

As well as model structural uncertainties, predictions of sediment transport are also subject to uncertainties related to the input data. In particular, the driving hydro meteorological conditions can vary in response to large-scale climatic conditions. For example, Blanco and Bampton (2017) showed a direct link between longshore sediment transport rates in Suffolk and the North Atlantic Oscillation.

There are a number of formulae available to estimate instantaneous transport rates (that is, transport rates in terms of volume of grains moving per unit time, per unit width of bed) under different forcing factors (for example, waves only, currents only, waves and currents combined). See Soulsby (1997) or van Rijn (1998) for a compilation, explanation and application of these formulae. Given that these formulae are for instantaneous sediment transport rates, the resulting rates then need to be summed over a sensible period such as a tide, a neap spring tidal cycle or a storm. Summing transport rates over longer periods can be done, but the assumptions that need to be made might increase the uncertainty of the derived sediment transport rates. Lastly, including the effects of the transport on the morphology itself and hence altering the subsequent transport rate can be very long-winded and often unreliable. It is complicated by the fact that calculated sediment transport rates vary considerably between formulae in most cases and that predictions of such rates are difficult to validate through measurements.

To quantify the sediment transport patterns on a beach, it is therefore necessary to simplify the transport processes. It is standard practice to represent the coastal processes in 2 different ways. These broadly fall into 2 model types (see Section 4.3.5):

- **Unidirectional models**, the use of which requires division of the movement of sediment into 2 components, one along the beach (**longshore transport**), and the other one perpendicular to it (**cross-shore transport**). In order to do this it is assumed that the beach is long and straight, with parallel contours and a plentiful supply of beach material, which is obviously a simplification of real life.
- **Coastal area models**, which calculate waves, currents and sediment transport at grid points covering the coastline and the nearshore bed. Coastal process-based modelling is not the only way to predict coastal change. Alternative modelling strategies that make predictions based on past observed changes or observed coastal change behaviours are also available.

2.6 Relevance of spatial and temporal scale for morphological change

Coastal change is driven by processes that vary significantly in both space and time. Beach and shoreline evolution occurs due to:

- seasonal changes in summer/winter wave environments
- extreme storm events
- changes in natural sediment supply and transport
- along-shore variations in coastal geomorphology (cliffs, sandy beaches, vegetated marshes, engineered versus non-engineered coastlines)
- elevated water levels caused by long-term sea level rise

The complexity of coastal change is, in part, due to the spatial and temporal interaction of these processes in shaping the evolving coastal landscape.

There are several facets to ‘change’, mainly progressive change and oscillatory change. Oscillatory change may arise where rapid erosion of sand during a storm season is followed by slow accretion during milder conditions, so that averaged over a year no net change is apparent. In contrast, progressive change indicates a consistent, continuing unidirectional trend.

It is not always easy to separate the oscillatory from the progressive change, making the prediction of change and the development of long-term management strategies challenging. In addition, the supply, transfer and loss of sediment to and from coastal systems is often most significant during episodic events associated with storms. Coastal features act as buffers to wave energy and are therefore sensitive to change over timescales ranging from seconds to years.

Determination of the appropriate spatial and temporal scales relevant to a particular coastal management problem is an important starting point. Figure 2.8 presents an overview of the different influences operating at the different spatial and temporal scales, as well as the resulting morphological features. In general, with increasing timescales, the spatial scale increases and the longshore sediment transport processes increase in importance compared with the cross-shore transport processes. Understanding the influencing factors at the site (Section 2.3), at the scales of interest, is therefore fundamental to the selection of the most appropriate model. These factors will include the effects of climate change and the impacts of management decisions.

A useful way of understanding the changes that need to be considered is to think of them conceptually as being divided into 2 types:

- short-term changes(often onshore–offshore) resulting from the effects of storms
- long-term changes arising from longshore and other larger scale trends in sediment movements

Although long-term change might be the main focus of the modelling, short-term (undesirable) morphological responses (for example, the response of a beach to a storm) may also need be assessed and combined with the long-term response in order to assess whether critical or threshold conditions (see Chapter 6) are likely to be encountered.

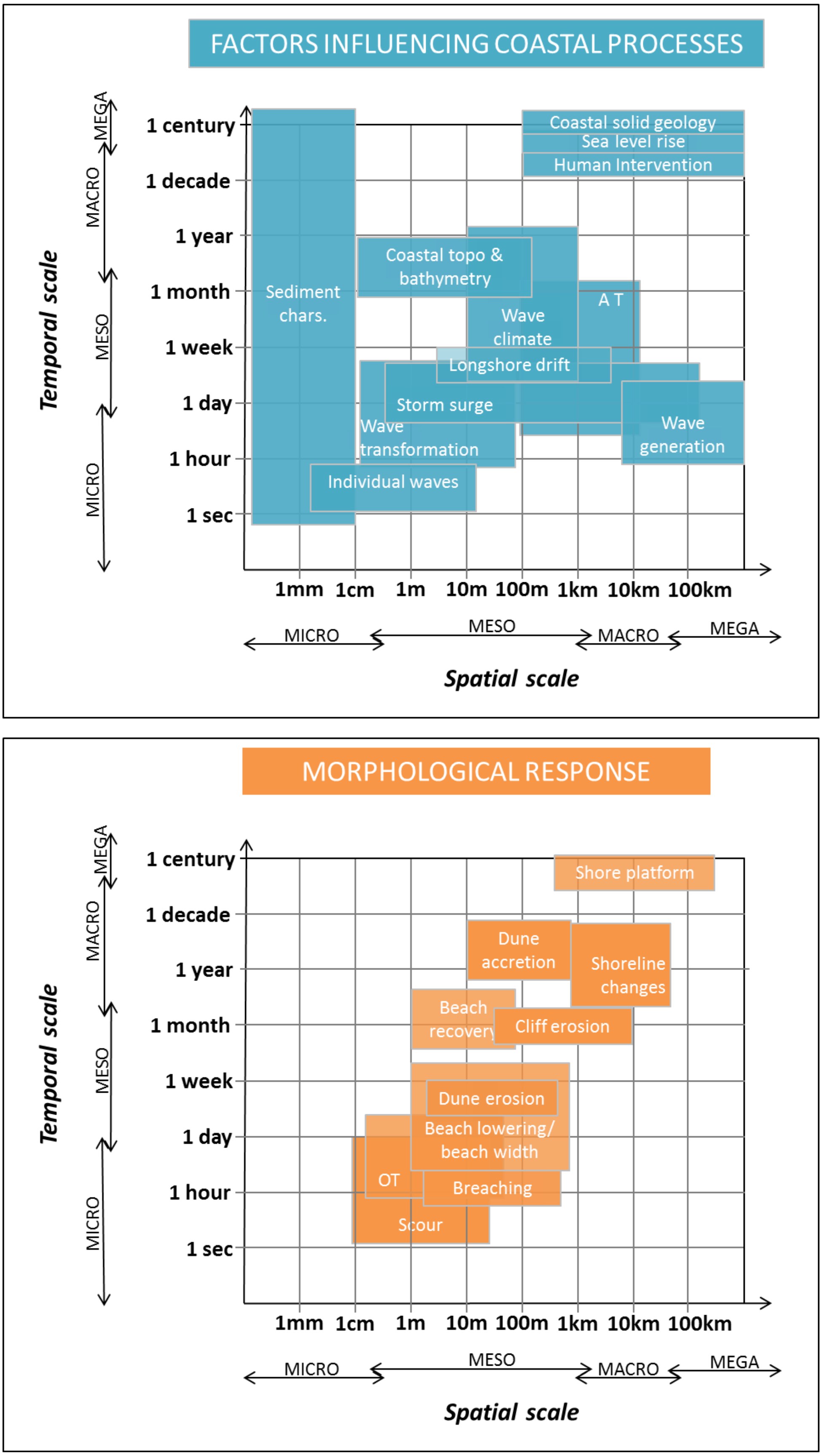


Figure 2.8 Influencing factors and morphology processes, and their temporal and spatial scales

Notes: AT = astronomical tide; OT= overtopping

3 A framework for choosing and using morphological models

Establishing an appropriate modelling framework is fundamental to delivering a robust outcome-focused approach, the results from which decision-makers understand and have confidence in. This chapter provides guidance on defining the modelling approach, agreeing an overall conceptual model in advance, and identifying the nature and type of the required input data.

The chapter explains the importance of ensuring that the selected model(s) are calibrated and verified, and how to understand and test the uncertainty associated with the results which emerge from the modelling.

It can also be used by modellers to help define the input, output and quality information that they need to share with clients to support confidence and understanding in the modelling outcomes.

Chapter contents

3.1 Nature and value of models

3.1.1 What is a model?

The terms 'model' and 'modelling' have become part of everyday literature, including for coastal engineering, although the assumed meaning of these terms is not always consistent. In general, the terms are used with reference to:

- **Conceptual models**. These represent a system using general descriptive rules, concepts and relationships.
- **Physical (scale) models**. These involve the physical representation of an object that maintains general relationships between its constituent aspects.

- **Numerical models**. These involve the representation of a system using mathematical concepts and language.
- **Statistical 'data-driven' models**. These rely solely on the statistical analysis of measurements, without initial knowledge of physical processes, to find patterns of change over space and time in selected indicators. These can then be extrapolated to form a prediction of future changes.

Several publications (for example, CH2M Hill 2016) also refer to a 'model' as being the application of an approach to a particular location, that is, the combination of site-specific information (existing topography, water levels, wave conditions and so on) and software that has been deemed appropriate by understanding the 'conceptual' processes operating at the site.

Terminology used in this guidance

M**odel** generally refers to software built to execute simulations (or representations) of a real process (thus excluding data-driven statistical analysis). As such, these models allow users to learn something about a given process by 'playing' with parameters of a model that represent physical change (for example: 'What happens if I do this'?).

C**onceptual model** is used when referring to qualitative representations of processes that aid basic understanding.

Other types of models – built as part of software but used to convey information only and not capable of predicting change or executing simulations (for example, mapping systems) – are referred to as **tools**.

3.1.2 Understanding the value of models and modelling

Models can help coastal decision-makers to understand and resolve a problem related to morphological processes. Models can be used to:

- understand coastal processes and their influence on coastal morphological change
- identify management interventions to manage morphological change
- understand the potential impacts of proposed interventions
- evaluate alternative intervention options
- optimise intervention and mitigation designs

Important characteristics of any model are:

- what it can achieve in terms of representing past or future scenarios
- whether it can represent future scenarios under different management developments or under different conditions related to climate change

After being properly calibrated and verified (see Section 3.6) for a specific site, a model may be applied in different complementary ways, depending on the modelling objectives.

- **'Forecast baseline' or change under natural conditions**. The model is used to predict what the future morphology would be if no changes are applied, so that the system is left to evolve under natural conditions (or under whichever management condition is already present). This is usually referred as baseline condition and serves as a starting point for subsequent future predictions.

- **Model sensitivity and uncertainty analysis**. Given a fixed input, the system's natural behaviour and/or response to a certain interference such as an engineering structure is assessed, preferably with an indication of the range of uncertainty. This is normally used in sensitivity testing (see Section 3.7).
- **Scenario evaluation.** On the basis of 'what if' questions, the possible consequences of proposed management developments in system are assessed and compared with the baseline condition.
- **Forecast morphology under different climate-related changed input conditions**

3.2 Commissioning a model

Selecting a modelling approach for a specific application is not a trivial task. It requires a thorough analysis of the problem under consideration, together with a clear definition of the objectives of the model prediction. In addition, the appropriate spatial and temporal scales of the problem must be determined and matched with those covered by the models available.[4]

Short-term process-based models are typically not well-suited to the prediction of longer term coastal evolution, as the physical processes relevant for the longer time evolution are generally not included. It is harder to model longer term evolution because it is made up of the residual effects of many short-term events which otherwise tend to largely cancel each other out.

Deciding on the appropriate model is usually done at 2 levels, that is:

- client
- modeller

These 2 levels are obviously inter-related, though the perceptions of policymakers and modellers might be different. To ensure the model delivers a robust and effective solution, a dialogue must exist between both in order to:

- define the problem
- ascertain whether a model is the best solution to evaluate the problem
- decide on the model to use and the scenarios to be modelled

To support this dialogue, Box 3.1 provides a list of questions to ask when commissioning models or when assessing proposal for models.

Although existing software tools may be appropriate, a bespoke modelling approach – potentially requiring the development of model code – may be proposed in some situations. This is more likely to happen when universities are undertaking research on coastal process modelling of their local coastline where the driver for research excellence may have led them to generate new code, even if this is not necessarily aligned with the needs of the practitioner. In such situations, care is needed to ensure that the new code is necessary and then that it is properly documented so that it can be used again after its initial creation. Appendices D and E contain materials to support

[4] See Section 2.5 for a summary of the different types of model.

relationships between end users and local researchers. Appendix D contains a model evaluation proforma, which can be used to evaluate and check model usability. A generic model user manual structure, together with recommendations for modellers on the process of model development, is provided in Appendix E. Both these outputs will help to ensure that any new models are developed with both end users and those taking the development of the models further in the future in mind.

Box 3.1: Questions to ask when commissioning modelling or assessing proposals for modelling

Specifying appropriate models is not easy, particularly when their procurement is mostly carried out by non-specialists. The following questions should help in this task.

- Has the problem been defined and the question(s) to be answered agreed on?
- Has the problem spatial area been defined? Is the spatial range covered by the proposed model/s?
- Have all the sediment sources and sinks to this area been considered, even if further away from the problem area?
- Which physical processes play an important role? Have they been described and are they represented by the proposed models?
- What are the relevant time scales for the problem and are these relevant for the selected model(s)?
- Have the models, their sequencing/linkages and the specific objectives of modelling been clearly explained?
- Have the data that are to be used in building, calibrating, validating and applying the models been specified? Where from? Over how long? Are they sufficiently accurate?
- How will the results be used? What results are required to answer the problem? Can the selected models meet these requirements?
- Does the modelling process include uncertainty quantification to support robust, risk-based decision-making?
- Have the models/modelling approaches been successfully used for similar situations?
- Are there other clients who can provide feedback/references?

3.3 Defining the approach

Establishing an appropriate modelling methodology is fundamental in obtaining valuable model outputs. If the modelling methodology is not appropriate and/or the model is not properly applied, the model results will be useless however advanced and accurate the model and however attractive the output animations. A simpler, well-established, conceptual model might prove more beneficial to decision-makers in some cases – particularly if available data are limited.

Identifying the relevant model processes and then selecting the correct appropriate model are crucial as poor decision-making at this stage becomes difficult to trace later in the modelling process and can become ‘concealed’ by parameter selection and refinement (see Section 2.6 for details of model calibration).

The model development and application process consists of a series of steps. These are summarised in the flow chart shown in Figure 3.1 and explained below.

The value of maximising the use of expert local knowledge in model development should not be underestimated and stakeholder involvement and feedback are fundamental at all stages in the process.

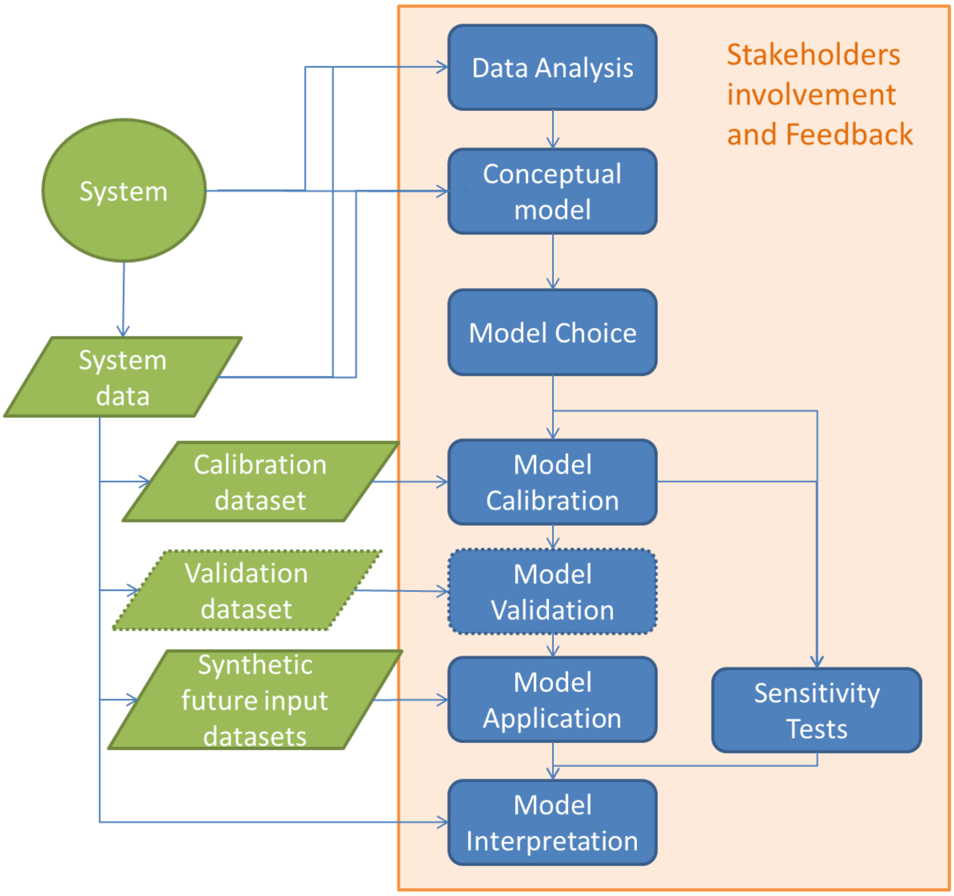


Figure 3.1 Modelling process including stakeholder involvement and feedback

3.4 Conceptual modelling

If morphological modelling is going to be effective and accepted as informative to decision-making, it is important to obtain early agreement on a conceptual (descriptive) model of the coastal system and the underlying morphological processes from all the important stakeholder groups,[5] including local coastal experts and geomorphologists. Correct understanding of the system will lead to the correct choice of predictive methods and will enhance confidence in the conclusions from the modelling study.

Conceptual models are often the starting point for subsequent detailed modelling. An incomplete or incorrectly focused conceptual model can lead to:

- incorrect assumptions about the system
- poor use of predictive approaches
- incorrect assessment of morphological change arising from management interventions

[5] Stakeholder engagement is the process by which different people or groups become involved in decision-making and action. Such stakeholders include those who influence the decisions and those who are affected by them. Guidance on stakeholder engagement is given in Environment Agency (2006).

Figure 3.2 shows an example of a conceptual model. An example of a tool to support conceptual modelling, the Coastal and Estuarine Systems Mapping (CESM) approach developed as part of iCOASST, is discussed in Section 4.3.1.

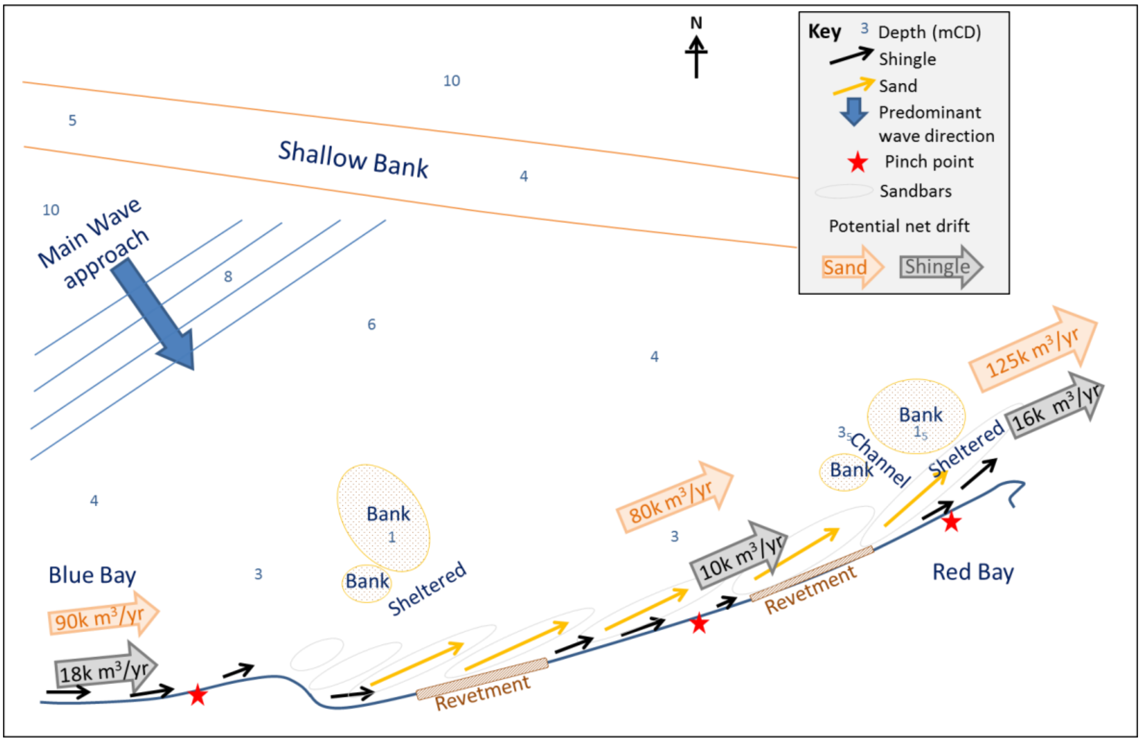


Figure 3.2 Example of a conceptual model of a littoral cell

3.5 Input data

An important step in the analysis process, whether it involves simple or complex models or no models at all, is to gather together all the available information that can be used to calibrate or run a predictive model. Such information can be divided into a number of categories including:

- measurements and a basic understanding of the historical and recent morphological changes in the study area
- details on past, existing and proposed intervention schemes or works
- measurements or predictions of waves, currents and so on that cause the morphological changes

Data are also required to:

- define the system's 'initial conditions'
- for model validation (see Section 3.6)
- drive the predictions of morphological change through time

3.5.1 Initial morphological conditions

The initial conditions are important because they provide an agreed starting point for the prediction of subsequent change.

Because coastal bathymetry is dynamic and evolves with time due to the forcing mechanisms, good quality and up-to-date data for nearshore and offshore coastal bathymetry are vital. There are 2 reasons for this.

- Any actual changes in offshore or nearshore bathymetry may alter the wave transformation processes (magnitude and direction) and these feed into the prediction of morphological change.
- Significant bathymetric survey errors can end up being interpreted as ‘morphological changes’ to the real bathymetry.

Unless a recent topographic/bathymetric survey of the area of interest is available, it is good practice to commission one at an early stage in the study. The extent of such a survey will depend on the budget and timescale available, as well as the limits of the coastal area over which the predictions are required.

It is also important to obtain data not only on topography/bathymetry but also on the availability and characteristics of sediment in the area (for example, depths of veneer sediments over underlying substrates, sediment size and distribution). Difficulties in modelling may arise when there is little or no sediment present to be transported. In this situation, ‘potential’ transport rates calculated by formulae will be much larger than actual rates. The possibility for this to occur should be investigated and, where relevant, sensitivity to transport rates should be tested.

3.5.2 Forcing conditions

Forcing conditions refer to the drivers of the morphological change such as winds and wave data. The data needed to represent these conditions in morphological models is usually obtained from other models, as shown in Figure 3.2 and described below.

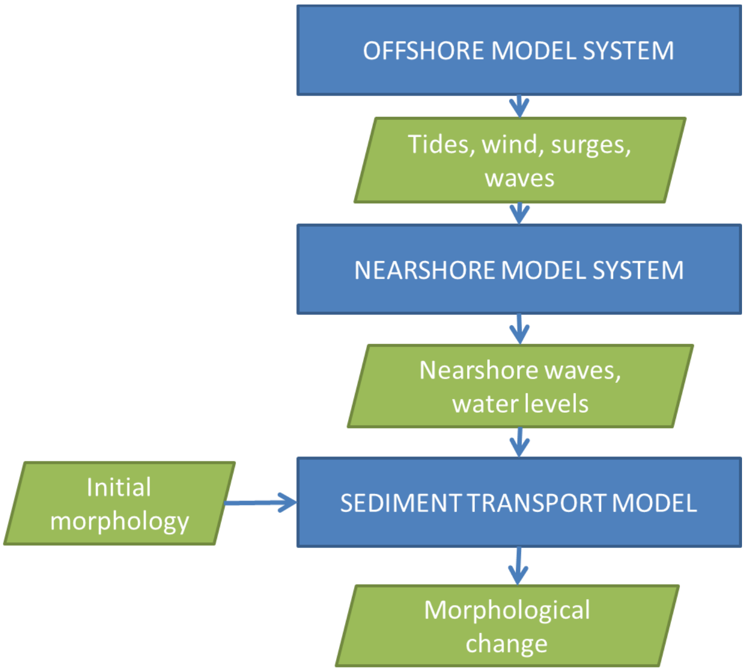


Figure 3.2 Schematic morphological model system

The forcing conditions may be required for either future conditions or for past conditions. When modelling is carried out retrospectively to estimate past wave conditions using measured or derived historical wind information, it is called wave hindcasting. Wave hindcasting is often used to provide the boundary (that is, input) conditions for historical coastal process analysis.[6]

The models that simulate these forcing conditions are typically split into 2 categories.

Nearshore model

This model (or system of models) is used to determine the time-varying water levels, currents and wave conditions at the coastal boundary of the morphological model. The nearshore model may consist of more than one model if models are 'nested' in order to accommodate small (but important) features within large area models without compromising efficiency when running the model (including run times).

Offshore model

This model (or system of models) is used to determine time-varying data at the offshore boundary of the nearshore model, including:

- hydrodynamic conditions (tides, surges and currents)
- wave conditions
- meteorological conditions (wind and pressure conditions)

The offshore model is typically a large-scale regional model (or system of models: meteorological, hydrodynamic and wave models) that is used to predict forcing conditions over large areas.

Figure 3.3 shows a schematic representation of the system of models that could be present within an offshore model, from climate models to coastal domain models, with the downscaling chain. Downscaling is the general name for the procedure used to take information known at large scales to make estimations at local scales (see Figure 3.3).

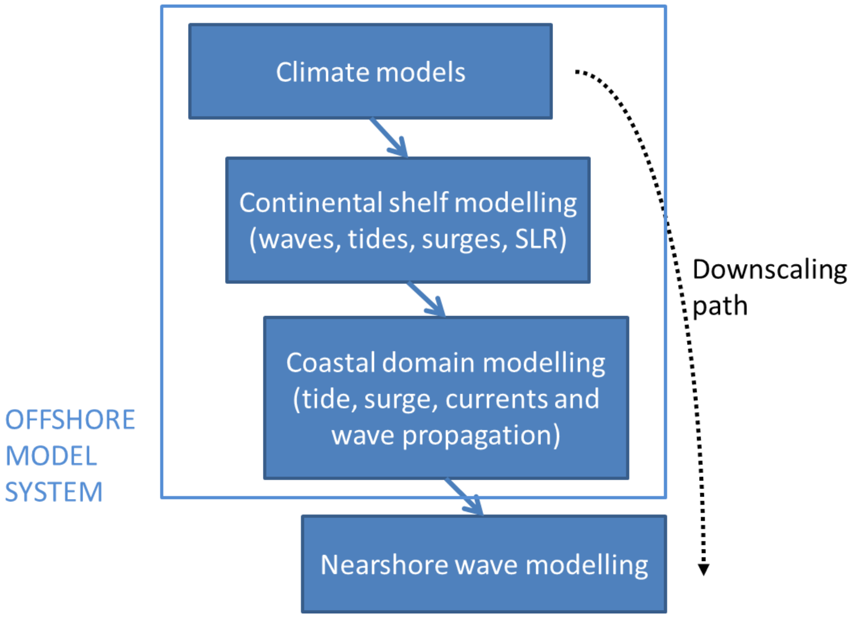


Figure 3.3 Offshore model components and representation of downscaling

[6] For UK waters, wave hindcast data for local authority and Environment Agency projects are available free from the CEFAS hindcast site (http://wavenet.cefas.co.uk/hindcast).

3.5.3 'Event' or 'time series' data

The input data required for a model will differ depending on the question to be answered as well as the data available.

For understanding and predicting short-term morphological responses, extreme storm event datasets are required. Whereas for understanding long-term morphological responses (that is, the mean condition and how it changes), long (for example, decades) of wave and water level time series are required.

To make long-term predictions of the shoreline position under a range of management scenarios, an average annual wave climate could be used (potentially with a climate uplift factor) and repeated over the number of years for which the prediction is needed. If measured or hindcast data are available, however, modellers should use actual long-term time series of wave data as an input. This makes it easier to take account of intra- and inter-annual variability of the wave climate. This in turn can provide model results with a higher temporal resolution and assist with providing more evidence with which to support future predictions.

How to derive the datasets needed as inputs to a model, including both short-term extreme event datasets and long-term time series is explained below. Section 3.7.2 contains a discussion of the associated uncertainties.

Short timescales (response to extreme events)

Coastal morphological modelling at short timescales (for example, for storm events) requires the characteristics of the extreme storm events that should be modelled to be specified.

As coastal morphology depends on many variables (see Section 2.3), it is likely to be important to consider the combinations of these variables (such as wave height, wave period, wave direction, water level) that might result in a given extreme morphological response.

Storm durations are also important and average storm durations have been shown to vary around the UK (Dhoop and Mason 2018). This may therefore require an analysis using multiple input variables (multivariate analysis) rather than just one variable (univariate analysis).

The size of event to be modelled should be defined using a risk-based approach. The degree of rarity of an extreme event (see Box 3.2) is usually described in terms of 'recurrence interval' or 'return period'.

There are a range of extreme value methods that can be used to derive more extreme events than are represented in the current period of record. These take into account the statistical variability in the data observed to date and are described below.

Box 3.2: Characterisation of extreme events

The severity of the extreme event can be specified in terms of its return period or annual exceedance probability.

- The **return period (RP)** is defined as the average number of years between exceedences of a particular high threshold event.
- The **annual exceedance probability (AEP)** is the probability that a given event is expected to be equalled or exceeded in a given year. This is often expressed as a percentage and is approximately equal to the inverse of the return period (that is, 1/RP).

For example, an extreme event with a return period of 100 years is likely to be reached or exceeded, on average, approximately once every 100 years (that is, AEP = 1%).

The **encounter probability** (PE) is the chance of encountering an extreme event of defined return period (*T* years) during an assessment period of *n* years. This is calculated as:

$$PE = 1 - \left[1 - \left(\frac{1}{T}\right)\right]^n$$

Univariate extreme analysis

Univariate extreme analysis is used to determine extreme values from a given individual historical set of data (typically a time series) for a single variable (for example, measured water levels or wave heights).

Extreme value predictions can be determined using standard, theoretically justified, methods for fitting extreme value distributions to a sample of extreme events from a given data record (see, for example, Coles 2001). The accuracy of the estimated extreme values depends on:

- the length of the record and its completeness – the longer the length of the record, the more likely that the sample will be representative; any gaps in the data will affect the quality of the prediction
- underlying accuracy in the dataset
- the robustness of the statistical fit to the data – can be measured by calculating the statistical confidence limits of the fit to the data and/or the standard deviation of the estimated return value
- the variability within the underlying data – modellers use particular coefficients to measure and capture this variability

All methods rely on looking at the largest events on record and using them to estimate how big other, even more rare events, will be. There is considerable uncertainty here and often the inclusion of a single extra storm/data point can change results significantly. It is therefore essential that decision-makers question whether this part of the analysis has been done robustly. The uncertainty is exacerbated by factors such as where the period of record fits within natural cycles of variability and by the non-stationarity of the climate in the long term.

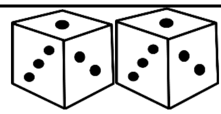
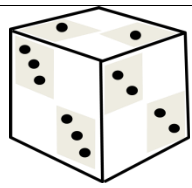
In addition, the extrapolation process does not contain any representation of the underlying physical processes. Care should therefore be taken to ensure physically plausible estimates of extremes are obtained. This is particular important for depth-limited wave conditions.

Multivariate extreme analysis

Multivariate analysis involves the study of more than one variable at a time, taking into account their dependencies. This is needed when an outcome is dependent on more than one input variable, and the relationship between outcome and input probability will depend on how linked (correlated) the input variables are. The way to undertake this type of analysis is to use joint probability methods.

The 'joint probability' is the probability of 2 or more variables occurring simultaneously. The variables of interest are usually linked in some (non-trivial) way (for example, high water levels and wave heights). Box 3.3 provides more detail on joint probability.

Box 3.3: Joint probability: what are the problems?

If you throw 2 independent dice, the probability of 2 sixes is $\frac{1}{6} \times \frac{1}{6} = \frac{1}{36}$.	
If you had 2 dice that are somehow directly linked (see diagram for an example) to always give the same outcome on both die with any given throw (that is, they are fully dependent), the probability is not $\frac{1}{6} \times \frac{1}{6} = \frac{1}{36}$ but rather $\frac{1}{6}$. This is because they are correlated.	

When considering the likelihood of extreme sea levels and wave conditions generating extreme beach responses, it is important to consider the degree of dependence between the variables (that is, how related they are). In general, the west coast of the UK, which faces the prevailing Atlantic storms, shows greater dependence between water levels and waves than the east coast.

In the case of coastal morphology, the principal influencing variables are:

- high water levels and wave heights
- period

A best practice guide describing the application of joint probability methods for these variables is available (Defra and Environment Agency 2005).

Advances in the underlying statistical methods (Heffernan and Tawn 2004) have been applied to coastal datasets around the coast of England on behalf of the Environment Agency (HR Wallingford 2015). A method to extrapolate offshore sea condition data to extreme water levels is set out by Gouldby et al. (2017).

In 2018, the Environment Agency commissioned a project to summarise the latest joint probability methodologies and how to apply them at the coast.

Long timescales (long-term responses)

Over time, climate-related changes can increase the impacts of current hazards. They can also bring new hazards to a local area, such as a shift from a stable to a receding beach or increasing rates of cliff recession. Increasingly, data on future climate and how that climate could affect the coast need to be incorporated in:

- hazard and risk assessments
- coastal management policies
- how those policies are implemented by practitioners

When making morphodynamic long-term predictions, it is desirable to use time series of the input forcing conditions such as wave conditions and water levels rather than average annual climates. Such time series would typically be in the form of successive descriptors of conditions (for example, in each three-hourly increment of time). For example, in a location like Suffolk where predominant waves are bimodal with respect to the direction (so that waves usually come from 2 littoral drift opposing directions, north-east and south-east), the use of the average annual wave direction would not be meaningful. Moreover, by using time series, the intra-annual variability and seasonality of the waves are considered as well as the inter-annual changes.

Long-term morphodynamic predictions are rarely carried out for periods less than 10 years, the norm being about 50 to 100 years. Wave and water level time series can be obtained (see Section 3.5.4) either from measurements or hindcast data, although these are rarely 50–100 years' long. Moreover, it is almost certain that future (wave and water level) time series will not be exactly the same as past time series (even if the average values are predicted to be the same). Several procedures therefore need to be applied to the available time series to adapt it for the correct temporal period and taking into account likely future trends. Procedures such as re-ordering the wave time series but maintaining the seasonality – also known as wave chronology – are quite common (Southgate et al. 2000), but do not take account of any climate change effects.

Even if a model is deemed to be very well calibrated and validated (see Section 3.6) for a specific application, there will always be uncertainty in the long-term driving conditions such as wind and waves, as it is impossible to predict the exact series of events or time series of wave and wind conditions that will happen in the future. To accommodate this future uncertainty in the modelling application process, the model (once calibrated) can be applied probabilistically (that is, carrying out many different runs, each with a different synthetic future time series) rather than deterministically (that is, based on an individual run, with a single future time series).This will deliver results as an envelope of possible morphologies instead of a single morphology. This technique is often used in morphological modelling of the long-term shoreline position under different management scenarios (that is, each of the scenarios are run for a number of plausible future wave/water level time series). Methods for creating synthetic time series are described in Box 3.4.

Box 3.4: Methods for deriving a synthetic time series

- **Using a Monte Carlo technique**. Here the factors to be varied are sampled from their statistical distribution in a random manner and not systematically. For example, this could involve creating a future time series of wave data by randomly selecting historic time series (for example, of monthly duration).
- **Using systematic variations**. For example, this could involve creating a future time series by modifying the wave height or wave direction by a given amount in order to create plausible climate change scenarios.
- **Using a combination of random and systematic approaches**. This method involves combining both these techniques to produce appropriate future scenarios.

The range of plausible synthetic future wave and wind conditions will depend on:

- the variability of these conditions across the area of study
- the decadal variations
- the inter- and intra-annual variability of the climate and its seasonality

The data analysis prior to the modelling task should shed some light on the importance of this variability and therefore on the preferred methodology for taking into account the uncertainty of the input data in time series derivation. For example, if there were offshore banks in the area that are mobile and have a considerable effect on the wave transformation, future wave scenarios should be derived with different positions of the offshore bars (HR Wallingford 2016a). The analysis should reveal the different percentages of prevailing winds which end up driving opposite sediment transport directions.

3.5.4 Data sources

Coastal morphological models require good quality data for their set-up, calibration and application.

Established datasets

The UK has a range of established datasets that can be used as inputs to coastal morphological models. These include:

- long-term records of tides
- a range of coastal monitoring data collected by regional programmes compiled at the Channel Coastal Observatory[7] including wind, wave and tidal data
- reanalysed high quality hindcast wave and wind data by the Met Office

The majority have systematically planned data collection programmes in order to maximise the benefits of such data to end users.

Data on morphological conditions

The current morphological situation of the coastal/estuarine area, as well as its historical changes, is essential to the morphological modelling. The morphological condition might be needed in terms of the shoreline position[8] and shoreline change, (including dunes and cliffs) or as elevation data (bathymetry and topography). There are several sources of data for these, using monitoring techniques that depend on the length and type of the coastline.

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[7] The National Network of Regional Coastal Monitoring Programmes of England (http://coastalmonitoring.org) has conducted such surveys (among other data collection) at least since 2011 (and in some cases back as early as the 1970s), via an integrated network of 6 regional coastal monitoring programmes, on behalf of the Coastal Groups of England. (A Coastal Group is a voluntary group made up all the most important partners and interested organisations involved in coastal management within a defined geographic area.) The boundaries of the 6 regions are based around coastal sediment cells (Motyka and Brampton 1993) and are thus inherently working with natural coastal processes. The data collection regime for the 6 regional programmes was designed using a generic risk-based approach but tailored to local requirements.

[8] The shoreline position is normally characterised by one or more longshore lines either defined by tidal levels (that is, mean high water springs, mean sea level, mean low water springs) or by the beach crest. Beach planshapes can be used to monitor storm response and long-term volume changes and to determine areas of potential risk.

LIDAR

Light detection and ranging (LIDAR) is a remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth. These light pulses – combined with other data recorded by the airborne system – generate precise, three-dimensional information about the shape of the Earth and its surface characteristics. LIDAR surveys provide a good source of digital elevation model (DEM) data when available and shoreline data can also be derived from it.

In the UK, the Environment Agency provides LIDAR composite digital terrain model (DTM) data (that is, DEM data without surface objects) at different resolutions.[9] The monitoring programmes carry out quality control on geomatics LIDAR data and also provide the datasets through the Channel Coastal Observatory's website.

Conventional survey techniques

For shallow nearshore data, a good source of data in the UK can be obtained from the Channel Coastal Observatory (http://coastalmonitoring.org). There are many sources of sea bed bathymetry, depending on the resolution required, the date and the area. A good start is the UK Hydrographic Office for deeper areas through the INSPIRE portal.[10]

Aerial photography

Aerial photography provides an important source of information on shoreline change. Images are available from the regional Coastal Monitoring Programme through the Channel Coastal Observatory website.

Photogrammetry involves the analysis of aerial photographs to measure common points and changes between photographs. There are some limitations to the use of photogrammetric data for determining shoreline change including:

- the dates and coverage of air photography of beaches vary
- the extent to which dates align with storm events may affect how useful photographs are in looking at longer term trends

Modern Structure from Motion (SfM) approaches in digital photogrammetry can be used to cost-effectively orthorectify historic aerial photography. They are also a low-cost method to obtain DEM information (Micheletti et al. 2015).

Satellite and remote-sensed data

These data are a growing resource for tracking and understanding coastal change. Historical imagery can be obtained from sources such as Google Earth Landsat.

Continued improvements in both the precision and coverage of satellite data and the analytic capabilities will allow satellite data to become more regular and cost-effective for mapping of shoreline change, as has been the case with LIDAR.

The extent of Earth observation data that can be used, now or in the near future, to update coastal change estimates, and the high level issues associated with using this type of data, is the focus of the UK GEOS Coastal Erosion and Accretion Project (Tabor 2018).

[9] https://data.gov.uk/dataset/80c522cc-e0bf-4466-8409-57a04c456197/lidar-composite-dsm-1m

[10] https://www.gov.uk/guidance/inspire-portal-and-medin-bathymetry-data-archive-centre

Maps and charts

Maps and charts are a good source of historical data and, provided the user is aware of the inaccuracies of old maps and charts, are often invaluable.[11]

When no other information is available, beach profile data can be used to infer shoreline positions at the resolution of the spacing between profiles (with the risk that important longshore features in between profiles might be missed).

Elevation information from historical charts (depth contours, or inferred depths from assumed slopes and distances from depth contours) can be converted into simple DEMs for long-term volume calculations.

Data types and formats

It is also important to understand the different types and formats of data that may be available and their likely value to coastal modelling and management decision-making:

DTM data

DTM data describing landforms and the sea bed are essential for understanding processes and modelling. The bathymetry of the nearshore is of interest to the coastal manager as this is where most of the changes occur. However, beaches are also affected by the offshore bathymetry (for example, by the presence and movements of banks on the seabed or approach channels).

Elevation data are also critical to the identification of low-lying coastal lands at risk of inundation from sea level rise and storm surge. For short-term events, morphology changes only the most up-to-date elevation data would be necessary for the modelling, but several historical sets of elevation data will inform the modeller about the ongoing and potential beach erosion or accretion.

Profile survey data

Beach profiles are surveyed section lines perpendicular, or oblique, to either the shoreline or a predetermined baseline. Beach profile data can be analysed and applied to:

- regional coastal studies
- studies of specific coastal units
- assessments and predictions of the performance of particular coastal defence schemes

The cross-sectional area of a particular beach profile line can be calculated from survey data. Profile areas can be translated into beach profile volumes along sections of coast, provided the adjacent profile lines are sufficiently spaced to ensure suitable beach representation.

It is important that the surveys not only extend down to low tide level but also below the low tide mark (these measurements could be undertaken less frequently). It is also vital to:

- monitor nearshore bathymetric feature changes such as sandbanks
- determine the lower limit of the beaches or beach 'toe'

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[11] An example data source is the historic map side-by-side viewer available from the National Library of Scotland (http://maps.nls.uk/geo/explore/side-by-side).

- monitor any ‘downcutting’ of the shore platform on which the beach sediment rests

Beach material

A beach sampling programme should cover potential variations cross-shore, longshore, vertically and seasonally. Information on beach composition is available through the National Network of Regional Coastal Monitoring Programmes of England.

Other data

Other data of potential value to the coastal morphological modeller include the following.

- **Beach management activities**. The regional monitoring programmes maintain records of beach management activities, although old activities might be hard to find even within the Coastal Groups.
- **Environment Agency published FCRM investment programmes**. These are a good data source for planned coastal projects such as beach nourishment.
- **Maintenance dredging and aggregate extraction**. For areas with licensed maintained dredging such as an approach channel, the associated data can be obtained from the relevant port. Each year, the Crown Estate publicises the removal quantities and areas of locations with licensed mineral extraction sites for marine aggregates.

Reports and books contain invaluable source of information. For example, ‘Coastal Morphology of Great Britain’ provides information on the historical coastal geomorphology of the UK (May and Hanson 2003). And a 1996 report commissioned by the Environment Agency provides a quantitative basis for estimating the volume and proportion of mud, sand and gravel input from coastal cliffs between the north shore of the Thames estuary and the Wash (BGS 1996). Their results, based on sampling from many locations, estimate the volume of each of these types of sediment that would be released by a 1m recession of the cliffs at various locations between those 2 estuaries.

3.6 Model calibration and validation

Model calibration, validation and sensitivity analysis steps are vital as they will influence the uncertainty associated with the model predictions and therefore the confidence that can be placed in the results. These steps can sometimes be overlooked, but they are crucial for decision-makers as they provide the only evidence that the results being used are likely to be valid. Model calibration and validation steps are presented in **Error! Reference source not found.** and described below.

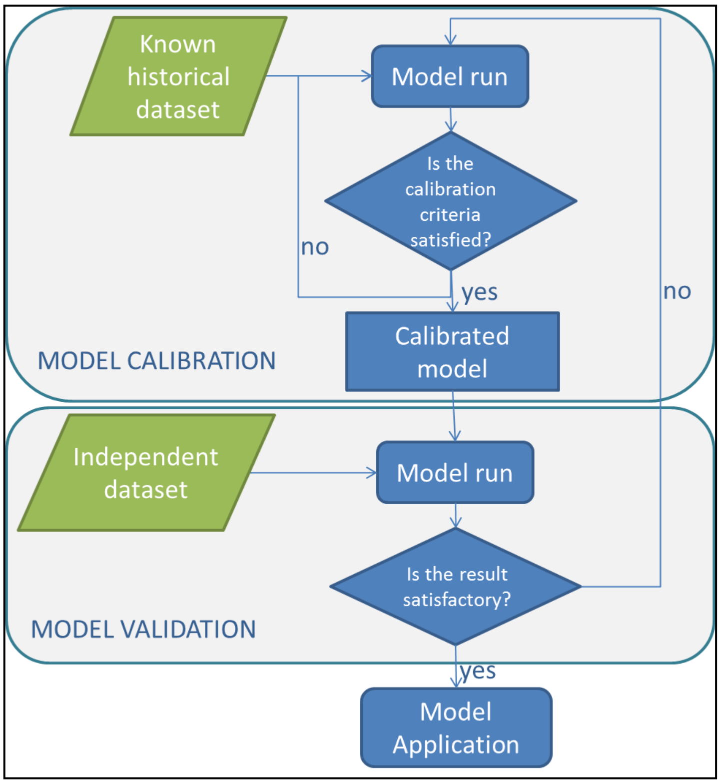

Figure 3.4 Model calibration and validation

3.6.1 Calibration

Calibration is the process of making changes to a model to improve the fit with observed data. It focuses on the comparison between model results and field observations. In principle, the smaller the deviation between the calculated model results and the field observations, the better the model. The deviations between the model and field observations could be for a number of reasons ranging from neglecting certain processes in the model that are important in real life to errors in the driving forces, or even data errors associated with the calibration data itself. Good and efficient calibration is strongly dependent on modeller experience.

Calibration relies on a good set of observed data where both model inputs and outputs are known. By applying hindcast driving forcers (usually waves and water levels), the model is used to predict a known historic outcome. By systematic modification of the different parameters of the model (within specified acceptable ranges) and even how the different elements of the model are put together, the model is run for hundreds of different combinations until a suitable one is found that gives the best alignment with the historic known result.

Although automatic calibration techniques are available, the range of models covered in this guidance are usually calibrated either manually or by combining both automatic and manual calibration. The calibration procedure will therefore be an iterative process and will involve trial and error.

A series of calibration 'criteria' should be specified in advance of the calibration work which set maximum deviations that are deemed acceptable to meet the project's requirements. The criteria are usually specified in terms of the outputs of a residual analysis – often stated as a 'skill score'. Residual analysis is the statistical analysis of the residuals or residual errors (which are the difference between model results and field measurements). The 'skill score' might be based on, for example, the average value of the residual error, the maximum residual error, the quadrates of the residual errors (sum of least squares) or the relative error. At times, weighting might be used to emphasise certain aspects or areas of the model application.

The calibration exercise is deemed to be acceptable once the calibration criteria have been met and the residual errors are not systematic (that is, the errors are random).

3.6.2 Validation

Validation is the process of testing the model to see if it can simulate other sets of observations not previously used for calibration to confirm that the model is likely to have some predictive ability.

The performance of the model should be checked by simulating at least one independent dataset. This therefore requires another input and output dataset, of similar quality to those used for the calibration process. It also relies on the same main processes being present during both calibration and validation datasets, as otherwise the model application would be different and the datasets incompatible.

The validation is carried out as a 'blind test' and is a linear process. Unlike calibration it is not iterative. Should the results from the validation not be satisfactory, the modeller will need to make a decision as to whether the calibration needs to be started again, or whether the problem arises from the initial choice of model.

Sometimes all available data are used in the calibration process itself so as to achieve the best possible results. This situation generally arises when available data are limited; in such cases, validation may have to be substituted by a sensitivity analysis (see Section 3.7.3). The decision to leave out the validation step needs to be a conscious and justifiable one.

Model verification

Model validation should not be confused with model verification. Model verification is the process of confirming that the model is solving the equations correctly (that is, the code is correct). The correctness of the model has to do with the capability of the model to achieve correct mathematical solutions to the governing continuum equations and is usually verified by usage of grid (or mesh) convergence testing (Roache 1998) As this report is for users of model results and not model developers, the model verification process is not discussed further. However, Roache (1998) is recommended for further reading on the verification and validation of computational models.

3.7 Understanding and testing the value of model results

The robustness of any model output is limited by the data used to run and calibrate it and the uncertainties associated with the formulation of the model itself (model structural uncertainties). This is usually casually referred to by modellers as 'GIGO' ('garbage in: garbage out'), emphasising that even the most advanced model is only as good as the quality of the input data and the model calibration. The predictive capability of models should become increasingly robust and therefore more valuable to decision-makers as the available input data improve up to the point where model structural uncertainties dominate the overall uncertainty.

Even with good input data, however, the complexity of coastal morphological behaviour still makes it difficult to generate accurate predictions, with all coastal morphological models having limitations of one kind or another. Thus there will always be significant uncertainty in outputs, particularly for long-term predictions, regardless of the model used (Environment Agency 2011).

3.7.1 Reviewing a model

The standard of presentation of results from models, particularly numerical models, has improved greatly in recent years. Some models even use ‘virtual reality’ techniques, combining model results with images of a coastline to visualise future situations. These techniques make it easier to interpret the results and use them to aid decision-making, especially for non-modellers. However, there is a risk that such imagery makes it harder to question the accuracy or interpretation of results. Coastal managers assessing modelling results should therefore question the fundamental information portrayed in the model results and ask themselves: ‘They are pretty, but are they correct?’.

A vigorous robust model review, including an evaluation of the uncertainty associated with model results, is a crucial element of the decision-making process. The following questions are important elements of any review.

- Have the key processes been identified (in collaboration with local stakeholders and experts)? Has a conceptual model been established as a result?
- How confident are stakeholders with expert local knowledge in the conceptual model (or representation of the coastal system)?
- Is the model selection and build well-documented and justified?
- Are the data used for implementing the model appropriate and accurate?
- How well is the model calibrated/validated with past information? Where? Over what duration? How accurately (for example, skill score[12])? Does it meet the defined acceptable calibration criteria?
- Are the model outputs appropriately sensitive to the model input parameter values?
- Have any sensitivity tests been carried out, for example, to understand uncertainties in the inputs or in climate change effects?
- How uncertain are the model results?
- Are the criteria for interpreting results and making decisions clear and appropriate?

Results, especially surprising results, should be discussed with stakeholders and explained in simple language based on the physics of the specific situation. Modellers should be prepared to be explicit about any limitations of their modelling, which should also be documented (in a clear manner).

3.7.2 Understanding and handling uncertainty

Uncertainty (or the level of confidence that can be associated with the model results) arises from a lack of knowledge or the ability to measure or calculate. Uncertainty gives rise to differences between the assessment or prediction of something and its ‘true’ or

[12] Skill score is a generic term referring to the accuracy and/or degree of association of prediction to an observation or estimate of the actual value of what is being predicted.

‘most likely’ value. All forecasts of complex natural systems are subject to uncertainty, regardless of the model used.

Two generic types of uncertainty need to be recognised and managed during the modelling process:

- **Natural variability**. An example is when future wave and wind conditions are not known and are subject to natural variability. This is also referred to as inherent randomness. It is not generally possible to reduce this type of uncertainty.
- **Knowledge uncertainty**. This relates to a lack of understanding about data inputs and the underlying physical processes captured within the models themselves. It is also known as model uncertainty. Examples include not knowing the exact spatial grain size distribution or not having a precise understanding of the physical processes associated with sediment (including grain to grain interaction), wave, tide or current dynamics – meaning that these elements are not handled well by models. In principle, this type of uncertainty can be reduced if more data are available or further research can be undertaken. In practice, however, resource and time constraints mean these uncertainties often remain and need to be accounted for.

Long-term historic data are improving, with regional monitoring programmes providing invaluable sources of information for the calibration and validation of morphological models. But even if there are good long-term historic data, there will always be uncertainty about future weather conditions (natural variability) and therefore future changes. In addition, there is the uncertainty arising from climate non-stationarity: the climate is changing and so the past may no longer be a reliable predictor of the future. Where there is substantial uncertainty, there are a range of techniques that can be used to address this and to help support informed decisions.

It is recognised that quantification of uncertainty can bring valuable information to the decision-making process and is crucial for risk quantification. Any modelling study, should therefore make some effort to try to understand and address uncertainty. This might include a review to identify the main sources of uncertainty. However, quantification of all the sources of uncertainty may not be possible.

Assigning probabilities to different variables or uncertainty parameters is well-established in research and in some aspects of environmental modelling. Where there are limited data to support estimates of probabilities, sensitivity analysis is often employed. Scenarios are specified and modelled outputs with the different specified inputs are compared. This may yield insights that indicate the results depend significantly on a specific value, in which case further data collation may be warranted. Alternatively, the analysis may indicate little sensitivity to a parameter value and the same decision would result whichever value was used. The use of sensitivity analysis is discussed in more detail below.

3.7.3 Using sensitivity analysis to manage uncertainty

Sensitivity analysis (see also Box 3.4 above) refers to the systematic testing of the model output behaviour in response to changes in the inputs, the initial conditions, model parameters and future climatic assumptions. The changes in input, initial conditions and parameters tested by the analysis should be realistic, with a fixed percentage of a nominal value normally being used.

There are different ways to conduct sensitivity analysis, depending on whether the interaction between different factors is taken into account. An appropriate sensitivity analysis framework should be selected by the modeller in collaboration with the client. Box 3.5 presents a simple example of the impact of model input changes on model outputs.

Box 3.5: Simple example for sediment transport of the importance of sensitivity analysis

Sediment transport rates are very sensitive to input data. Large differences in outputs can appear from relatively small shifts in inputs that can easily result from, for example, instrumentation errors, spatial inaccuracies, and spatial and/or temporal variations in bed composition.

The example below illustrates the issue by applying a simple sediment transport formula at a point with the following input data:

Water depth: 4m	Water temperature: 10°C
Salinity: 35 parts per trillion (ppt)	Depth-averaged current speed: 0.5m per second
Significant wave height H_s: 2m	Mean wave period T_m: 7 seconds
Angle between waves and current: 90°	d_{10}: 0.13mm, d_{50}: 0.20mm, d_{90}: 0.31mm

The percentage changes in transport rate as a result of sensitivity tests to changes in input parameters are presented in Table 3.1.

The analysis results shown are just for one prediction method. If the same input parameters were used within a different sediment transport formula, then the results would also be different – introducing a further source of uncertainty.

Table 3.1 Changes in transport rate as a result of sensitivity tests to changes in input parameters

Parameter	**Change in parameter**	**Bed load transport rate (kg m^{-1} s^{-1})**	**Suspended transport rate (kg m^{-1} s^{-1})**	**Percentage change in total transport rate**
Standard case	–	0.0485	1.04	–
Water depth	+10%	0.0448	0.995	–14
Water temperature	+5%	0.0480	0.684	–33
Salinity	–5ppt	0.0482	0.989	–5
Depth-averaged current speed	+10%	0.0559	1.41	+35
Wave height	+10%	0.0539	1.36	+29
Wave period	+10%	0.0477	1.02	–2
Wave/current angle	–10%	0.0492	1.04	0
d_{10}, d_{50}, d_{90}	+10, +10, +10%	0.0506	0.594	–41
d_{10}, d_{50}, d_{90}	–10, 0, +10%	0.0485	2.39	+123

3.8 When and why might linking morphological models be a good idea?

Any individual model will be best suited to specific situations (see Chapter 4). To address problems spanning different time/space scales and processes, however, Hanson et al. (2003) concluded that:

- more than one type of model is often required
- efforts should be directed towards model integration rather than enhancement of individual model concepts

The idea of putting models together is not new or only applicable to coastal morphological modelling. Techniques such as downscaling (taking information known at large scales to make predictions at local scales) have been used for years. However, it is important to define the terms used when referring to combining models so that the objectives and outcomes are clear.

3.8.1 Linking and coupling

Both these terms are used by modellers to refer to the combining of models together so that data is transferred from one to another, or exchanged in some way. These terms are usually preceded by another term such as 'static' or 'dynamic' linking (see Section 3.8.2) so that the type of exchange between the models is clear.

3.8.2 Static versus dynamic exchange

The difference between these reflects how the models transfer data.

A **dynamic link** exchanges data in computer memory at run time. This exchange can therefore be uni- or bi-directional (that is, one way or both ways) and can be very efficient as there is no requirement to write into files that then need to be re-read. Moreover, the dynamically linked models do not need to have the same spatial (for example, grid space) and temporal resolution (for example, time space) and representations, as the linking will take care of the spatial or temporal aggregations/extrapolations needed to pass data from one model to the other.

A **static link** is a more simplistic form of combining models whereby one model takes the output from another model as an input. The latter is mostly only one way and there is no feedback between the models as they are run independently. It also relies on models reading other models output files and is usually computationally inefficient.

The main disadvantage of dynamic modelling is that it requires modification of the model code (unless the models have been written from start with the idea of dynamic linking in mind), whereas static coupling can usually be achieved using an external code (or set of codes) that transfer the data. The task of converting models to include dynamic linkages should not be underestimated, especially for old codes, and requires specialist knowledge.

Static linking has been used for much longer than dynamic linking. The first major project to use dynamic linking was HarmonIT (funded by the EU) in 2001 where the main objective was to develop and implement a European open modelling interface to simplify the linking of hydrology related models.

Static and dynamic model linkages (Figure 3.5) have also been described (Vanecek and Moore 2014) as 'instantaneous' (for dynamic) and 'sequential' (for static).

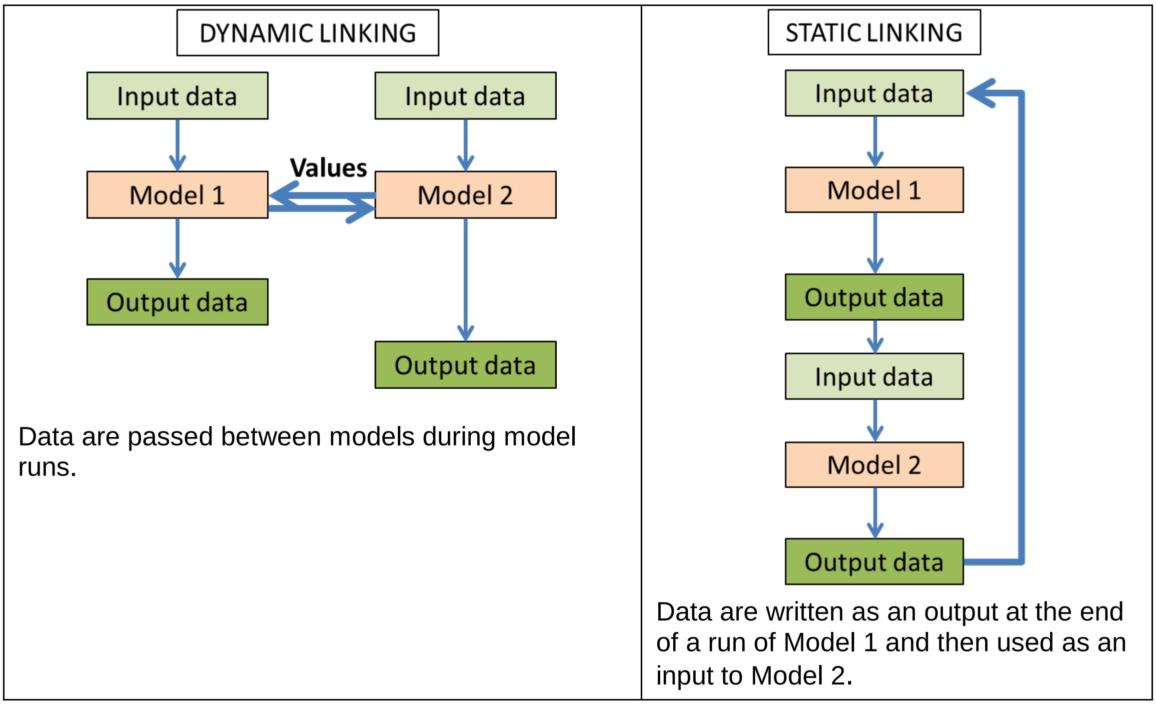

Figure 3.5 Dynamic versus static model linking

Notes: The wider arrows show the coupling between the models.
Bi-directional coupling is represented in both examples.

In terms of morphological modelling, there is room for all of these types of interaction among models and there are examples of all of them in applications from all over the world. Some examples are given in Box 3.6.

Dynamic linking is the most advanced way of coupling models, but it is also the newest. As such, several initiatives have been put into place to standardise ways of delivering it. One of these initiatives is OpenMI (Open Modelling Interface, www.openmi.org), which was set up as a software component interface definition conceived to make it easier to link models based on different concepts, with different spatial and temporal resolutions and representations (for example, one-, two- or three-dimensional). This initiative delivers the required aspects of the system framework, model and software integration. OpenMI was chosen within iCOASST to provide the dynamic linking between models.

OpenMI is not the only approach available for model integration. For example, Coastal Modelling Environment (CoastalME), which started its development within iCOASST, is a new approach to model integration. CoastalME aims to:

- identify the commonalities of existing large-scale behavioural simulation models – currently SCAPE (Soft Cliff And Platform Erosion) and COVE (Coastal Vector Evolution)
- provide a common quantitative framework able to incorporate different existing conceptual models

Box 3.6: Examples of model linking

- **ASMITA + SCAPE.** These models were coupled sequentially, in an static manner, to simulate how different adaptation to sea level rise management strategies would work for a realistic, but not real, coastal system (Environment Agency 2009b). Updated versions of these 2 models were linked dynamically as part of the iCOASST project (see Box 5.2).
- **UNIBEST + DELFT3D**. The coastal line model UNIBEST-CL+ and the coastal area model DELFT3D were coupled to improve the long-term shoreline prediction in the vicinity of breakwaters over a series of realistic but not real simulations (Koningsveld et al. 2005). The project's main focus was to determine if the Delft3D model, which models coastal processes in detail, and UNIBEST-CL+, which has a much more aggregated approach, could be combined to reinforce one another's strengths. The study concluded that, by coupling UNIBEST-CL+ to Delft3D, a more realistic prediction may be obtained of the coastline evolution in the vicinity of breakwaters (at least in a technical sense) from UNIBEST-CL+.
- **MIKE21 + CM**. The coastal area model MIKE21 was coupled with a simplified morphological updating scheme where the evolving cross-shore profile was described by a limited number of parameters to improve the morphological evolution around offshore and coastal breakwaters (Kristensen et al. 2013). The main advantages of the hybrid model concept over traditional two-dimensional models are that:
  - the profile distortion can be limited considerably because a parametric evolution is imposed on the profile
  - computer processing time is reduced because larger morphological timesteps can be used since the morphological elements are larger than the elements on which hydrodynamics and waves are solved

4 Coastal morphological models

This chapter describes the different types of morphological models, methods and tools, their usability, applicability, and implementation requirements and constraints. It also provides example applications of each model type. The chapter aims to support the decision-maker when evaluating modelling options and when commissioning a morphological model.

Chapter contents

4.1 Coastal morphological model types

There are various types of morphological models, methods and tools available with different levels of capability and ranging from the simple to the complex. These have been classified into the following types.

- **Coastal and estuarine systems mapping (CESM)**. This type of approach is used primarily as a platform for describing coastal systems and their components using a mixture of visual interpretation and/or data analysis. It typically employs a framework using geographical information systems (GIS).
- **Geomorphological data analysis**. This type of approach is used primarily for studying the geomorphological evidence in order to draw meaningful conclusions using a range of techniques such as historical trend analysis or sediment budget analysis.
- **Data-driven models**. This type of model is used primarily to analyse historic measurements, without prior knowledge of physical processes, using statistical methods of varying degrees of sophistication. They are also used to extrapolate the patterns found to derive predictions of future changes.
- **Parametric models**. This type of model is used primarily for predicting the shape of beaches in profile and in plan using simple formulae – mainly derived from experimental observations. The formulae are typically either based on the assumption of an equilibrium state (equilibrium models) or on a changing state (change of state models).
- **Process-based numerical models**. This type of model is used primarily for reproducing changes in bathymetry and beach profile/planform (via temporal and spatial integration), using models that are based on physical laws.

- **Behaviour-based numerical models**. This type of model is used to simulate known behaviours, such as the tendency for a beach to develop towards an equilibrium form, rather than simulating the physics from which this behaviour emerges. These models recognise that useful information can be obtained from simple models that seek to represent general behaviour without the need to understand the detailed processes.
- **Emerging techniques**. These models represent more embryonic approaches. Although not fully developed, they might be important in the future.

The models (especially data-driven models, parametric models, behaviour-based numerical models and process-based numerical models) have the potential to produce predictions that can be used to set or evaluate Coastal State Indicators (see Chapter 6).

Figure 4.1 maps these models and tools on a scale between being fully data-oriented and fully process-oriented. In practice, all models straddle the boundary between behavioural and process-based representation as no model includes all the physics involved. Even a detailed sediment transport model will take knowledge of input conditions (waves, currents, sediment characteristic, bedforms and so on) to predict sediment concentration and flux without calculating the full details of the turbulence or force balance on each grain. There is always an element of approximation in attempting to represent the behaviour of systems; however, there is clearly a spectrum from the most detailed process-based models to those that are wholly behavioural. The process-based models apply physical process modelling to small-scale processes, while the behavioural models apply behavioural modelling to the entire beach or entity modelled.

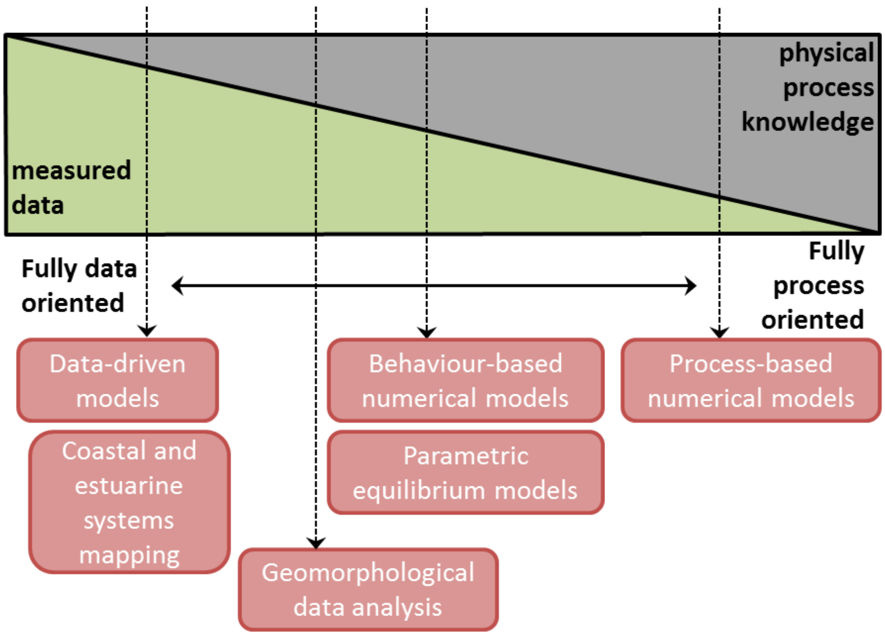

Figure 4.1 Model types within a spectrum ranging from fully data-oriented to fully process-oriented models

Source: modified from STOWA/RIZA (1999)

4.2 Model characteristics

The application scale (both spatial and temporal) of different model classifications, their relative usability and potential for linking are compared in this section through a series of tables. Each type is described in detail in Section 4.3.

4.2.1 Spatial applicability of models

The spatial applicability of models may be different depending on the processes that are being represented and/or the type of data that are used. It is usually only the spatial extremes that are inappropriate for some models (Table 4.1). This table is designed to allow end users to quickly check the suitability of a given model for a certain application.

Table 4.1 Spatial applicability of a model

Model type		**Spatial scale (order of magnitude) primarily covered by model type**					
		~1m	**~10m**	**~100m**	**~1km**	**~10km**	**~100km**
CESM				■	■	■	■
Geomorphological data analysis			■	■	■	■	■
Data-driven models		■	■	■	■	■	■
Parametric models			■	■	■	■	
Process-based models	**Shoreline change models**			■	■	■	■
	Cross-shore change models	■	■	■			
	Coastal area models			■	■	■	■
Behaviour-based models		← ■	■	Depending on model[1] ■	■	■	■ →
Emerging modelling techniques		← ■	■	Depending on model[1] ■	■	■	■ →

Notes: [1] The range of models covered by this model type is very wide and the actual spatial applicability would depend on the actual model.

Legend:

Spatial range not covered by this model type	■ Spatial range covered by this model type

4.2.2 Temporal applicability of models

The temporal applicability of models may be different depending on the processes that are being represented and/or the temporal nature of the data that are used. It is usually only the temporal extremes that are inappropriate for some models (Table 4.2). This table is designed to allow end users to quickly check the suitability of a given model for a certain application.

Table 4.2 Temporal applicability of model

Model type		Temporal scale (order of magnitude) primarily covered by model type				
		Days	Weeks	Months	Years	Decades
CESM						
Geomorphological data analysis						
Data-driven models						
Parametric models		←	Depending on model[1]		→	
Process-based models	Shoreline change models					
	Cross-shore change models		(3)	(3)	(3)	(3)
	Coastal area models			(2)	(2)	(2)
Behaviour-based models		←		Depending on model[1]		→
Emerging modelling techniques:		←		Depending on model[1]		→

Notes: [1] The range of models covered by this model type is very wide and the actual spatial applicability would depend on the actual model.
[2] See section on coastal area models in Section 4.3.5 for information on the special techniques needed to cover this temporal range.
[3] Cross-shore change models cannot be applied for longer than a storm's duration as they currently only deal with the erosion associated with storms but not with the accretionary periods that happen at longer timescales and are responsible for the recovery of the beaches.

Legend:

Temporal range not covered by this model type	Temporal range covered by this model type	Temporal range covered by this model type with special techniques[2]	Temporal range covered by this model only in case of dunes (CS-model)

4.2.3 Model usability

Model usability is defined here in terms of:

- ease of use for direct application
- ease of use for R&D /bespoke application
- computational complexity
- dependence on purchase of proprietary software platform

The level of technical skill required to use and apply specific models will be reflected by these factors.

The usability of models typically lies somewhere in a spectrum. At one end of this spectrum, there are models developed as a black box with an easy user interface but no chance to adjust the parameters and algorithms of the model. At the other end of the spectrum, there are models developed as academic/open source code which give a lot of flexibility to modellers to change or further develop the code but usually do not have a user interface. This usability has been divided into 4 categories for each of the model types (Table 4.3). Note that the same model type might have examples of similar models with different usability characteristics and therefore this can only be used as a general guide.

If a product is not commercial software, then it is generally not supported and can become vulnerable to becoming unusable because of changes in operating systems and so on.

Table 4.3 Usability

Model type		Ease of use for direct application	Ease of use for R&D /bespoke application	Computational complexity	Dependence on purchase of proprietary software platform
CESM		High	Low	Low	High
Geomorphological data analysis		High	Medium	Low	High
Data-driven models		Medium–High	Medium	Medium	Medium
Parametric models		High	High	Low	Low–High
Process-based models	Shoreline change models	Medium	Medium	Medium	High
	Cross-shore change models	High	High	Low	High
	Coastal area models	Low–Medium	Low–Medium	Medium–High	Medium
Behaviour-based models		Medium	Medium	Low	Medium
Emerging modelling techniques:		Low	Low	Medium–High	High

Notes: When the range is separated into Low–High, it covers Low–Med–High.

Legend: High | Medium | Low

4.2.4 Potential for model linking

Many studies in coastal areas involve morphodynamic modelling at some point and some use an array of models to predict the change in morphodynamics due to natural or anthropogenic causes. Sometimes these models are run independently as they answer different questions related to the same problem. More frequently, they are run linked up in some way (see Section 3.8 for an explanation of the different ways of linking models), so that results from one model are used to inform another model or so that results from one model are used as input conditions to another model.

Table 4.4 shows, in broad terms, which models are amenable to being linked to each other, and whether this linkage is uncomplicated (passing values from one to another) or requires more interpretation. These 3 categories are colour-coded whereby the darker blue represents the most straightforward linkage and the lighter blue the most difficult linkages, with the intermediate blue referring to those where linkages will tend to have some complexity or require some additional analysis to facilitate.

Table 4.4 Potential links between modelling types

Model type	**Geomorphological data analysis**	**Data-driven models**	**Parametric models**	**Process-based models**	**Behaviour based models**	**Emerging modelling techniques**
CESM						
Geomorphological data analysis						
Data-driven models						
Parametric models						
Process-based models						
Behaviour-based models						

Legend:	Uncomplicated link	Link possible but not straightforward	Difficult to link

4.3 Model types: descriptions and example applications

This section describes the model types mentioned above and gives examples of each model type. This is not meant to be an exhaustive list of all models available, but a compendium of some that are more readily available or used more frequently. The model descriptions aim to draw out the most important information that is relevant to coastal managers and decision-makers (rather than to modellers themselves).

4.3.1 Coastal and estuarine systems mapping

CESM tools consist of a repository for data and a platform for data management, analysis and visual interpretation, together with the capability for systems mapping. This mapping consists of synthesising and formalising scientific understanding of how particular areas behave via the conversion of disparate sources of information (or ‘plain data') to usable knowledge (see also Environment Agency 2009a). These tools are mostly based on GIS systems and can embed Google Earth.

Example applications

- **Coastal and Estuarine System Mapping (CESM)**. This GIS application generates a 'snapshot' of how a system is configured in terms of morphology, sediment pathways and other interactions, as constrained and influenced by human interaction (see Box 4.1). The model is freely available under GNU General Public license (GPL) and is an iCOASST-related product (www.coastalmonitoring.org/iCOASST/CESM/).
- **FUTURECOAST** (Defra 2002). This used a 'behavioural systems' approach that identified all the different elements that make up the coastal structure and developed an understanding of how these elements interact. More importantly, it presented an analysis of future shoreline evolution potential for every section of the coast of England and Wales. The model is freely available (http://coastalmonitoring.org/ccoresources/futurecoast/).

Typical outputs

The typical outputs of these tools are maps that aid understanding and conceptual modelling. As such, they are able to provide the user with morphological change information (for example, colour-coded shorelines to show erosion rates), but they mainly portray the implications of existing data rather than involving any predictive calculations.

Typical benefits

The main benefits of these tools are their simplicity, usability (once they have been applied to the area of interest) and ease of interpretation (due to their visual nature).

Typical limitations

Any future predictions will be based solely on observed past trends (assuming the processes are statistically stationary) and thus the quality/extent of understanding depends on quality/extent of input data and the validity of the underlying assumptions.

Box 4.1: Experience from the iCOASST project in applying the CESM methodology to a pilot site on the Suffolk coast

CESM was developed within the iCOASST project as an approach to the conceptualisation of connected estuary–coast–inner shelf sediment systems. CESM layers produced for the Liverpool Bay and Suffolk case study regions provided an initial high level conceptual framework within which to synthesise scientific understanding of the processes driving coastal behaviour and to provide a basis for stakeholder engagement.

CESM is based on a spatial 'ontology' – a classification and rules governing the interaction between components (see Appendix B). These link together estuary, coast and inner shelf, and nest individual landforms within larger 'landform complexes' and within broader scale coastal regions.

The main stages in the method involve:

1. Defining the purpose of the map and the parameters it will display
2. Mapping the main landform complexes and their components and structures and mapping the interactions
3. A final rationalisation of information to make the system more clear, alongside annotation with data, meta-data and/or reports and images

For more details see www.channelcoast.org/iCOASST/CESM/

Figure 4.2 shows the output from applying CESM to the Suffolk pilot site.

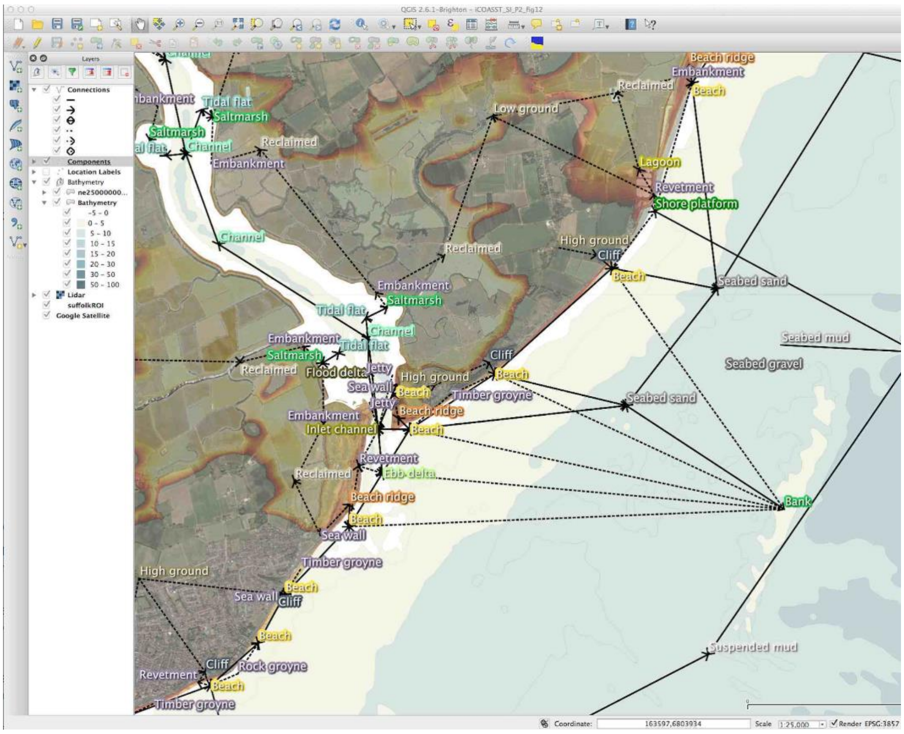

Figure 4.2 Application of CESM to the Suffolk pilot site

Source: www.channelcoast.org/iCOASST/CESM/

4.3.2 Geomorphological data analysis

Geomorphological data analysis consists of a range of techniques to study the available data from different periods in time in a meaningful and repeatable way that allows for the derivation of comparable conclusions about the nature and extent of coastal geomorphological processes.

Sub-types

Geomorphological data analysis includes techniques such as:

- **Historical trend analysis (HTA)**. This technique documents trends in coastal/estuary features from historical maps and data, and uses them as a basis for future prediction.
- **Sediment budget analysis (SBA)**. This technique involves reconciliation of sediment inputs, outputs and sources/sinks within a given coastal/estuary area. See Box 4.2 for an example application of SBA.

Box 4.2: Application of SBA to a sediment transport study

The Standing Conference on Problems Associated with the Coastline (SCOPAC) sediment transport study (SCOPAC 2004) was carried out in preparation for the second round of SMPs.

A total of 27 sediment sub-cell units were created for the study area between Start Point in Devon and Beachy Head in East Sussex. For each of these subcells, an interactive map was produced to illustrate sediment type, direction, volume, transport mechanism and reliability of information. The arrows on the map are interactive and, when clicked, take the user through to the supporting information. The supporting information is based on a review of literature up to 2012 (New Forest District Council 2017). Figure 4.3 shows an example of one of the sediment transport maps produced during the 2012 update of the study.

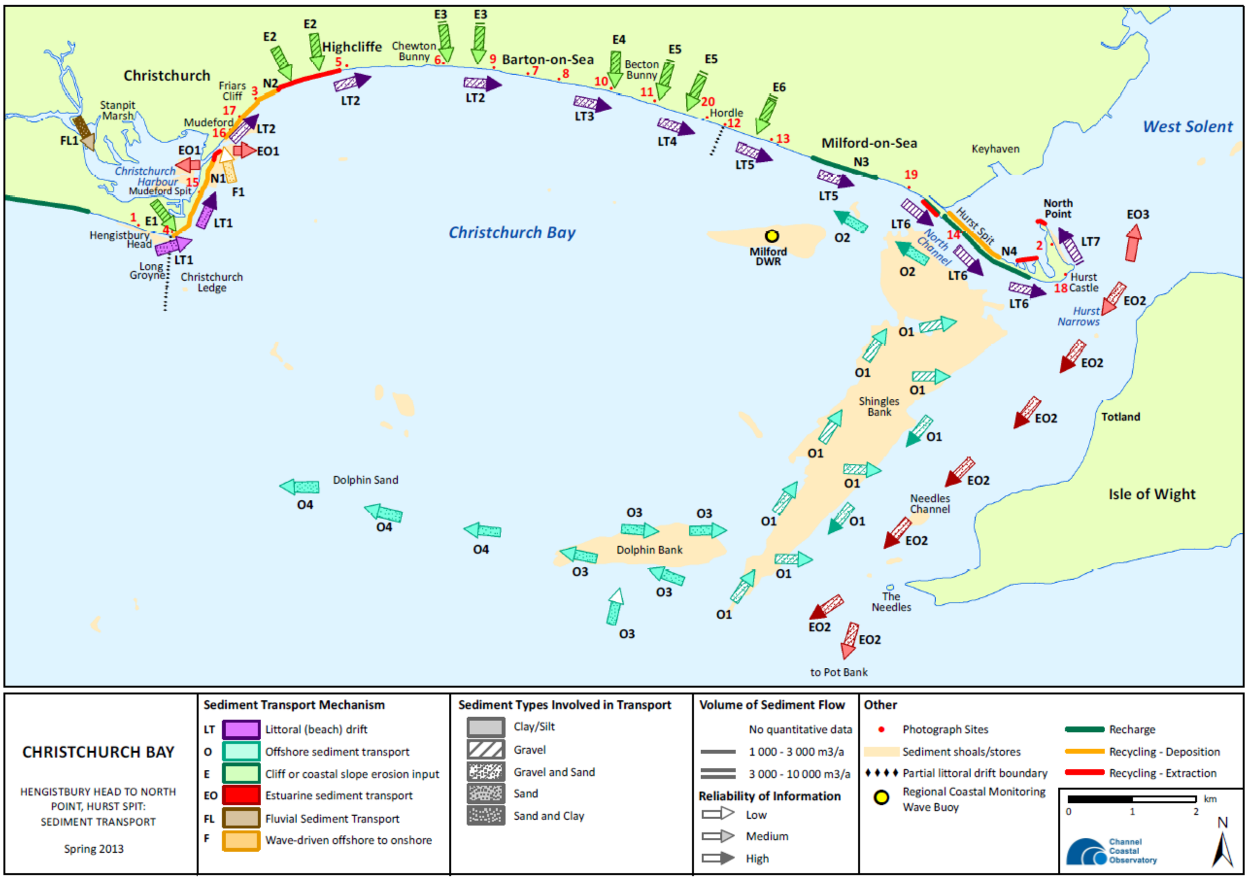

Figure 4.3 Sediment transport map for Hengistbury Head to Hurst Spit (Christchurch Bay)

Source: SCOPAC Sediment Transport Study 2012 (www.scopac.org.uk/sts/christchurch-bay.html)

Example applications

- **DSAS** (Digital Shoreline Analysis System). This is a software extension to ArcGIS that enables users to calculate shoreline rate of change statistics from multiple historic shoreline positions. The software is freely available (https://woodshole.er.usgs.gov/project-pages/DSAS/).
- **SANDS**. The SANDS Asset Management System provides data capture and analysis capability. It is a commercial package (www.sandsuser.com).
- **TrendAMaT** (Trend Analysis and Management Tool). This tool combines the time trend analysis with the spatial distribution capabilities of GIS to

show the impacts of changes of level (or any other parameter) spatially and temporally, and thus provide new information regarding coastal landform evolution (Stripling et al. 2015). It is a commercial package.

Both HTA and SBA techniques can be applied in a spreadsheet, coded or within a GIS. The Environment Agency has produced a practitioner's guide to SBA (Environment Agency 2018b).

Typical outputs

The main outputs from these tools are estimates of historical morphological changes, which can then be extrapolated into future predictions. They do not calculate sediment transport per se but can be used to infer rates. Other outputs are:

- presence, persistence of morphological features
- movement of the shoreline position
- areas of seabed erosion or deposition

These tools are not able to provide any type of quantitative prediction under different management scenarios. However, SBA can aid the prediction of impacts of different management scenarios (albeit indirectly) by indicating possible impacts to the downdrift sediment budget.

Typical benefits

The main benefit of these tools is their relative simplicity in terms of application to a given area. Learning from past historical information at a given area should not be overlooked and should always be used to support morphological assessment for coasts/estuaries.

Typical limitations

- Their validity and accuracy are strongly dependent on data quality. Although this limitation is not specific to this type of model, it is of foremost importance here as the tools are based only on historical data. Data limitations can include:
  - limited availability of historical data in some areas
  - accuracy of historical datasets can be questionable
  - different measurement techniques, specifications, datums, units and/or density of data points in successive datasets may have been used
- They identify net change between successive datasets, not the scale of variability over shorter timescales.
- Information on anthropogenic interventions can be limited.
- Past trends might not be an indicator of future behaviour.

4.3.3 Data-driven models

Data-driven methods (also called reduced physics models) rely solely on the analysis of measurements, without initial knowledge of physical processes. They involve the application of sophisticated statistical techniques to find patterns of change over space and time in selected datasets. These may then be extrapolated to form a prediction of future changes over periods of several years to a decade (Reeve et al. 2016). This complements the process-based modelling discussed in Section 4.3.5.

Sub-types

- **Empirical orthogonal function analysis (EOF) or principal component analysis (PCA)** separates the observations into patterns of spatial and temporal variation. EOF is a PCA applied to a group of time series data.
- **Canonical correlation analysis (CCA)** investigates if there are any patterns that tend to occur simultaneously in 2 different datasets and what the correlation is between associated patterns (for example, beach profiles and wave conditions). The link that this technique provides (via a regression matrix) can be used to make forecasts of beach profiles on the basis of predicted wave conditions.
- **Artificial neural networks (ANN)** are nonlinear tools used to model complex relationships between an input and an output system. The network is able to provide forecasts based on the data it has processed through a process of machine learning.

These models are categorised below as freely available, open source or commercial packages as they are techniques that can be coded or are already coded as part of programming packages such as Matlab or R.

Example applications

Statistical techniques like EOF, PCA and CCA can be applied with existing software such as Matlab, Python and R. Southgate et al. (2003) discussed the use of neural networks for coastal morphology. Pape et al. (2007, 2010) described the application of a variety of neural net algorithms to the problem of predicting the movement of a nearshore bar over a period of several years. An example application is described in Box 4.3.

Typical outputs

The main outputs are determined by the data used and are therefore mainly related to measured morphological changes and rarely to measured sediment rates (for which data are scarce). The more common outputs of these models include:

- correlations between beach profiles and wave conditions
- decadal changes in morphology of offshore sandbanks

Typical benefits

The main benefit of these techniques is the lack of pre-assumption of the physical processes involved as they rely solely on the data. The rapidly evolving field of 'big data' means that these statistical techniques will become more and more important and will play an even more essential role in decision-making as they make it easier to manipulate large datasets.

Typical limitations

- Because future predictions are based on observed past trends these models can only be used to forecast when there is **no** change of state, a new management method or a significant change in forcings.
- The quality/extent of understanding depends on the quantity/quality/extent of the input data.
- The models are not suitable for upscaling
- EOF and CCA models rely on linear methods. Although these methods are very useful for analysing and modelling coastal morphological systems, these systems often have characteristics that tend to lead to nonlinear behaviour (for example, relationships that involve power functions and have strong nonlinear interactions between the coastal forcing and the system response).

Box 4.3 Application of statistical forecasting techniques to pilot sites on the Suffolk coast as part of the iCOASST project

The statistical forecasting method developed in the iCOASST project has been applied to shorelines with a wide range of sediment types and exposures, as found along the Suffolk coastline. The method works well as a predictor over periods of several years to a decade. The data-driven, statistical approach provides an alternative forecasting method that can complement process-based modelling (Reeve et al. 2016).

In essence, the method is as follows. If records are available of beach profiles and wave conditions covering the same period, the method establishes correlations between the beach profile shape and the antecedent wave conditions. These correlations can then be used with forecasted wave conditions to provide predictions of the beach profile shape over the period for which wave forecasts are available.

Descriptions are available of the method and application to:

- the sandy beach at Duck in North Carolina on the east coast of the USA (Horrillo-Caraballo et al. 2016)
- shingle beaches (Horrillo-Caraballo and Reeve 2010)
- beaches backed by a hard defence (Horrillo-Caraballo and Reeve 2011)
- using offshore wave records to predict beach profile changes within and around a harbour entrance where wave reflection and diffraction occurs (Reeve and Horrillo-Caraballo 2014)

Even in this last case, the method was able to find useful correlations. Records covering ~20 years were split into 2 parts:

- a segment of 10–15 years to determine the correlations
- a segment of 5–10 years against which to validate ‘forecasts’ of beach profiles, based on combining the correlations found in the first segment and the wave conditions over this second segment

The main constraint is that the method requires 10–20 years of beach profile measurements and corresponding wave conditions (measured or hindcast). However, the development of co-ordinated coastal monitoring programmes and SMPs since the 1990s means this is not such a major constraint for UK sites (Horrillo-Caraballo et al. 2015, Reeve et al. 2016).

The graphs in Figure 4.4 show statistical forecasts of beach profiles using this approach at 3 sites in Suffolk as part of the iCOASST project. The forecast change in the northern and southern profiles is much greater than for the central profile, which highlights the natural variability along a stretch of coastline.

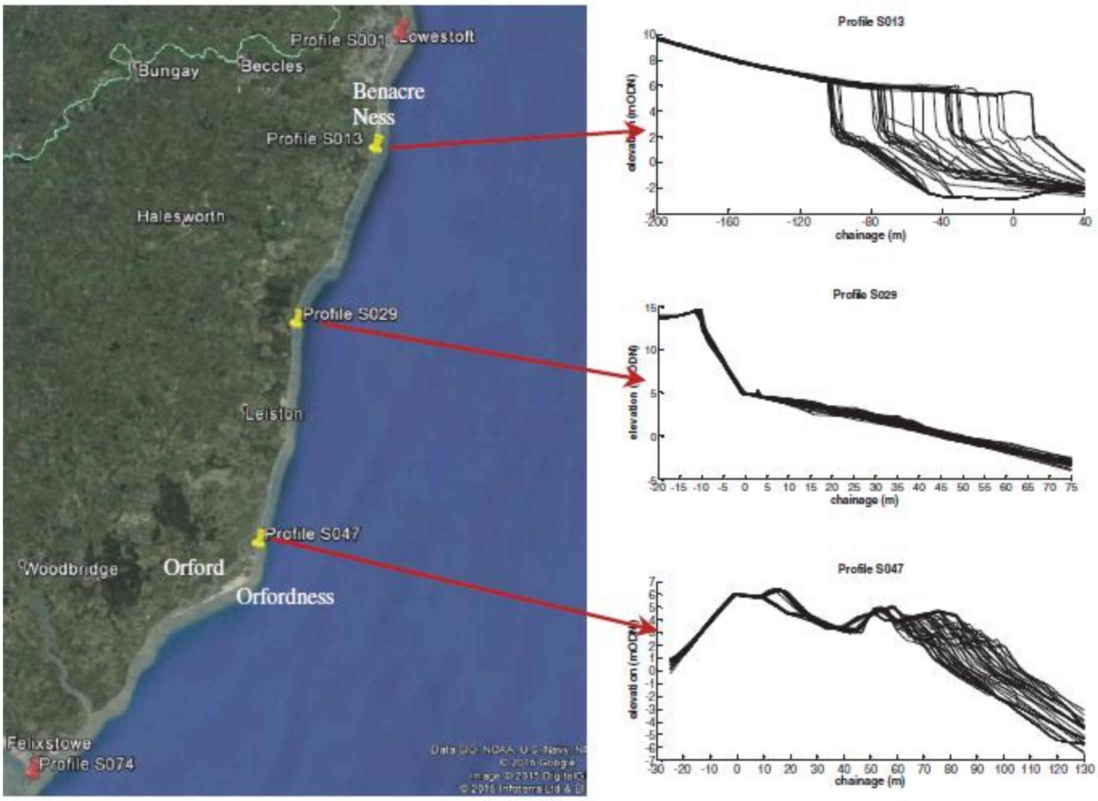

Figure 4.4 Application of statistical forecasting to 3 sites in Suffolk

4.3.4 Parametric models

These models represent the shape of the coastline and its response to forcing through simple equations derived through a mixture of hypotheses and curve fitting to empirical observations. They are simple and quick to apply.

Sub-types

Equilibrium models

- **Equilibrium cross-shore (sand) beach profiles such as Dean's profile**. Dean's profile gives the shape of the cross-shore profile in the vertical as a function of the cross-shore distance and a sediment scale parameter, which in turn can be related to the sediment size.
- **Equilibrium bay shapes**. These can be predicted using mathematical formulae that give relationships between various shoreline parameters. However, only the parabolic shape equation (PBSE) of Hsu and Evans (1989), based on a square power function, 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. This link is important because it makes the application more rigorous. An example of the use of the PBSE is given in Box 4.4.

- **Storm response cross-shore profiles for shingle beaches**. Powell (1990) provided a parametric model to estimate the dynamic equilibrium beach profile formed under a combination of wave conditions. This was recently adapted for bimodal waves (HR Wallingford 2016b) and is freely available for use.
- **Tidal inlet stability**. These are models that describe the link between hydrodynamics and estuary morphology in terms of simple empirical formulae such as the O'Brien relationship and derivatives. Environment Agency (2009a) gives a good summary of these semi-empirical techniques for estuaries.

Change of state models

- **Dune erosion**. The wave impact approach estimates the effect of high waves and water levels during a storm on coastal dunes by calculating the sediment transport from the dune and associated profile change as a result of waves directly hitting it. An example of this approach is Edelman (1972), who developed an equation to estimate dune erosion due to storm surges by employing the same basic assumption as Bruun (1954) or Dean and Maurmeyer (1983). Larson et al. (2004) provided an overview of existing empirical models to estimate dune erosion, while van Rijn (2013) gives a good compendium of the different methods available such as DUROS+ (an empirical method for dune erosion in the Netherlands), most of which are for dunes similar to those in the Netherlands.
- **Barrier inertia**. Bradbury et al. (2006) provided an empirical predictive framework to estimate the changing risk of breaching of shingle barriers. The dimensionless barrier inertia parameter identifies threshold conditions for overwashing of barrier beaches. This parameter combines the barrier crest freeboard and the supra-tidal cross-sectional area, non-dimensionalised by the wave height.
- **Sea level rise effects**. The Bruun rule (1954) addresses this issue. In its simplest form, the rule states that shoreline erosion (R) caused by sea level rise is a function of the average slope of the shoreface, which is typically the steepest part of the nearshore profile (Cooper and Pilkey 2004). The main assumption is that, over a long time period, the beach profile adjusts to an increase in sea level through a shoreward retreat, where the magnitude of the retreat is determined by translating the equilibrium profile upward and landward in such a manner that sediment is conserved.

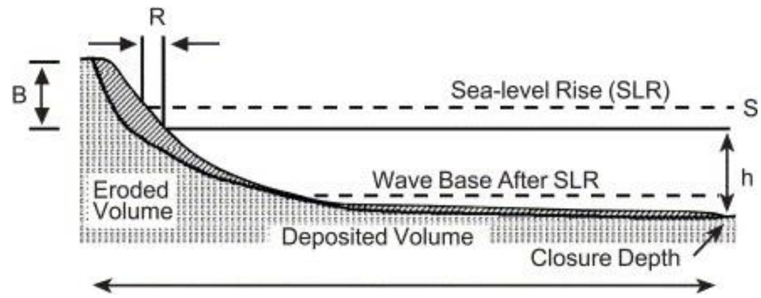

Figure 4.5 Schematic diagram explaining the Bruun Rule

Notes: Figure provided courtesy of Cooper and Pilkey (2004)

These models are not categorised as being freely available, open source or a commercial package as they are techniques that can be coded or are already coded as part of programming packages such as Matlab or R.

Example applications

These techniques are easy enough to apply in spreadsheets, GIS or with software such as Matlab.

Software packages such as BDMaT (commercial software from HR Wallingford; www.hrwallingford.com/projects/beach-design-and-management-tool) or MEPBAY (freely available; http://siaiacad17.univali.br/mepbay/?pagina=home/) have also implemented these techniques.

SHINGLE-B (https://www.channelcoast.org/shingleb/), which is free to use from the Channel Coastal Observatory website, is a parametric model for shingle beaches under bimodal wave conditions.

Typical outputs

The outputs depend on the model but in general most of the models provide an estimate of the morphological change, although they do not calculate the underlying and varying sediment transport rates. The ability to predict under different management scenarios is limited, depending on the hypothesis of the model being used. Other common outputs for this type of models are:

- the equilibrium position of the profile or planshape
- a ‘representative’ beach profile for an artificial beach to be constructed

Typical benefits

The main benefit of these formulations is that they tend to be easy to apply within a spreadsheet or simple program, providing a quick answer to a specific problem.

Typical limitations

These types of models need to be used within their range of validity, especially if they are empirical. Use outside of that range might provide an answer but one that might not be realistic. Specifically, some of the equilibrium methods cannot be used to forecast when there is a change of state, new management method or significant change in the forcing mechanisms. For example, in the equilibrium bay planshape example described in Box 4.4, the method is applied to the proposed new development of the marina. The method can only take into account the position of the new diffracting point, irrespective of the type of structure causing the diffraction, therefore a submerged breakwater will give the same results as an emerged one and user input will be required to make appropriate adjustments. In other methods, such as the dynamic equilibrium profile of shingle beaches of Powell (1990), neither the grain size of the sediment nor any human interventions are taken into account.

The concept of an ‘equilibrium profile’ is a simplified representation of the coastal conditions for example, it neither includes nor explains the occurrence of bar formations Furthermore, their underlying assumption is that such profiles represent equilibrium conditions, whereas in fact such conditions are rarely present in a dynamic coastal environment. Nonetheless, the concept of the equilibrium profile is a practical ‘tool’ for preliminary high level design.

Box 4.4 Application of the equilibrium parabolic bay planshape equation to Weymouth

The proposed development of a new marina in Weymouth will change the wave diffraction patterns arriving from the deeper waters of Weymouth Bay in Dorset. The morphology of the beaches along the seafront therefore will also change. Possible changes in the beach planform have been assessed using the parabolic bay shape model (HR Wallingford 2008). This uses the PBSE of Hsu and Evans (1989) to establish relationships between geometric parameters, arriving at a predicted equilibrium beach plan shape, shown by the red line in Figure 4.6. In this case, the marina is likely to lead to a narrowing of the beach in planform.

Figure 4.6 Output from application of the equilibrium parabolic bay planshape equation to Weymouth Bay

Source: HR Wallingford (2008)

4.3.5 Process-based models

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

- a morphology-updating module

These models require the coastal system and its governing processes to be known well enough so that the relevant and dominant processes can be included in the model. This also means that they are usually far more complex and computationally more intensive than empirical models.

In reality and in practice, pure process-based models (fully dependent on physical process formulation) are not feasible. In most process-based models, only a proportion of the physical processes are therefore simulated directly and the rest are more crudely represented or neglected.

A guide to model usage that 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, is provided by Southgate and Brampton (2001).

The main types of models based on sediment transport processes that predict changes in bed levels are described by 3 possible dimensions of analysis.

- One-line models – and the related N(multi)-line models – deal with planshape shoreline change.
- Coastal profile models deal with sediment movements in profile.
- Coastal area models deal with the sediment movements within an area.

A comprehensive review of the state-of-the-art of process-based models as well as long-term modelling strategies can be found in, for example, Roelvink and Reniers (2011) and Amoudry and Souza (2011). Other recent comprehensive reviews, which are not limited to process-based models but also cover behaviour-oriented models (see Section 4.3.6), can be found elsewhere (see, for example: de Vriend et al. 1993, EMPHASYS Consortium 2000, Hanson et al. 2003, Fagherazzi and Overeem 2007, Idier et al. 2013).

The various types of process-based models are described below.

Shoreline change (one-line or multi-line) models

These models predict changes in the shoreline position due to longshore transport induced by wave action. They are one-dimensional models. The longshore drift is normally calculated using the Coastal Engineering Research Center (CERC) formula (USACE 1984) or a variation of it.

Sub-types

- **One-line models**. The shoreline is represented by one line and the active beach is assumed to have parallel contours to this shoreline.
- **Multi-line (N-line) models**. These are an extension of a one-line model type and include the representation of more than one contour line. The cross-shore profile is schematised as a number of mutually interacting layers and the profile evolves as a result of the interactions between the layers (Hanson and Larson 1999)

Example applications

Most one-line models differ from each other in their representation of structures and their influence on the longshore drift, as well as in their required input wave conditions, as some can only consider representative annual (that is, within year) conditions and therefore miss the possible influence of year to year variations and the effects of the chronology of these variations. However, the differences in these models are of relatively minor importance compared with securing the correct data and achieving validation of the model set-up.

Information and/or model code for various shoreline change models are available on the internet as follows.

- **Beachplan**. An application example is provided by Kemp and Brampton (2014) and commercial code is available from HR Wallingford.
- **COVE** (Coastal Vector Evolution) (https://github.com/COVE-Model). COVE differs from traditional one-line models in that it uses a curved rather than straight reference baseline and the grid is adaptable over time. This is important when representing highly curved beach planshapes. The code was developed by the British Geological Survey (BGS).
- **GENESIS** (Generalised Model for Simulating Shoreline Change) and its extension to mesoscale applications, **GenCade** (Hanson et al. 2011). GenCade includes the position of the dune toe as an unknown time dependent variable linked to shoreline position. GENESIS includes a 2D hard bottom representation but not GenCade. The model is freely available (www.xmswiki.com/wiki/SMS:GENESIS), though the interface is commercial.
- **LITPACK** is part of DHI's MIKE suite products and is commercial software (www.mikepoweredbydhi.com/products/litpack).
- **SCAPE+** differs from traditional one-line models in that it also accounts for soft cliffs and shore platform morphology. In addition, with respect to the treatment of the fine sediment, a fraction of the sediment is allowed to be lost from the eroded cliff. It is freely available under GPL and is an iCOASST-related product (www.channelcoast.org/iCOASST/SCAPE/).
- **UnaLinea**. The model is freely available under GPL and is an iCOASST-related product (www.channelcoast.org/iCOASST/UNALINEA/).
- **UNIBEST-LT/CL+** (https://www.deltares.nl/en/software/unibest-cl/). The commercial code is available from Deltares in the Netherlands. UNIBEST also includes a curvilinear grid.

Typical outputs

These models calculate the sediment transport in terms of the longshore drift. Sediment transport rates and changes in shoreline position are the main outputs, the models being able to predict both under different management scenarios. The main outputs from these models are:

- minimum, maximum and average shoreline position over the simulation period
- minimum, maximum and average longshore drift over the simulation period
- shoreline position after a given amount of time during the simulation
- time series of beach level in front of a seawall or revetment

Typical benefits

These types of models play their best role when comparing different alternatives to solving a particular problem along a coastline (for example, a beach suffering erosion). The modelled time development of the shoreline positions under different alternative schemes – which can range from the construction of different structures such as breakwaters, groynes and reefs, the number of such structures and their position, or the amount of renourishment to apply – can be compared with the baseline scenario in order to come up with acceptable solutions.

Typical limitations

- The main assumption of these types of models is that they generally deal with a 'nearly straight' (that is, rectilinear) beach and so they should not be applied to curved beaches. The exceptions are the COVE model, which is specifically designed for curved beaches (Hurst et al. 2015) and UNIBEST. It is not possible to recommend a threshold of beach curvature beyond which the rectilinear models become unreliable, as this also depends on the wave climate and specific configuration of the area.
- The profile movement is restricted between the assumed berm of the beach and the depth of closure – a point along a beach profile, first described by Hallermeier (1981, 1983) where sediment transport is very small or non-existent). In one-line models the profile does not change in time, whereas in N-line models the profile is allowed to vary over time.
- These models use a sediment transport formula that relates longshore transport only to incident waves, and does not describe transport produced by tidal currents, wind or other forcing mechanisms. They therefore should not be used if breaking waves are not the dominant mechanism for transporting sediment along-shore.
- The longshore drift calculated is 'potential' (that is, assuming that there is infinite amount of sediment in the system).
- As with other process models, they can be fraught with difficulties associated with numerical stability, accumulation of rounding errors and sensitivity to small changes in boundary conditions.

Box 4.5 Application of a one-line model to planning a beach improvement scheme in Poole

The sandy beaches of Poole Bay were eroding and allowing the shoreline to retreat was impractical. A preliminary study assessed numerous options such as breakwaters, reefs and various types of groynes. These options were refined using one-line process modelling, making different assumptions about how climate change might affect future wave conditions.

The study finally recommended 5 new groynes at the eastern end. This scheme was more modest than originally envisaged, thereby reducing the costs of the scheme and reducing the impact on the amenity value and aesthetics of the beaches. Figure 4.6 shows the one-line results for an optimised groyne scheme during the fifth year of the model run, where there was a period of strong westward drift, a drift reversal from the most common eastwards drift.

For more details see Kemp and Brampton (2014).

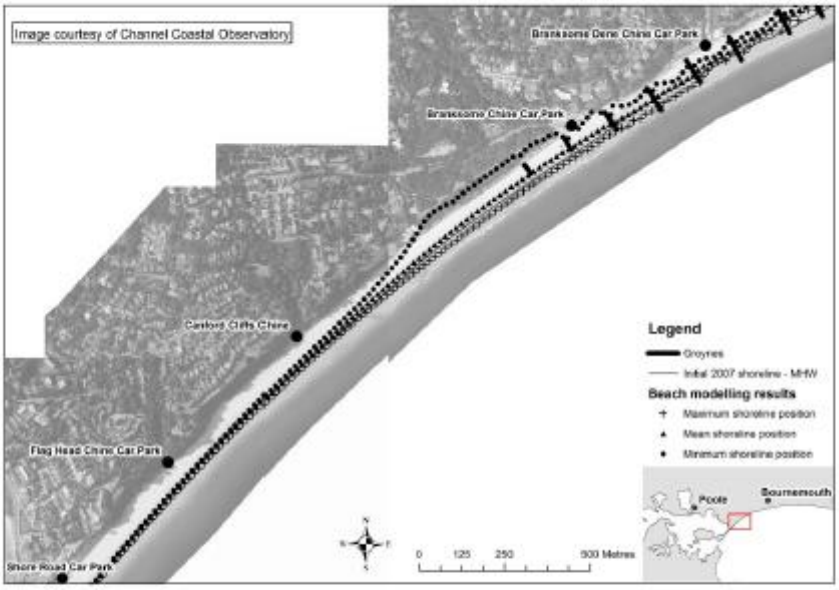

Figure 4.7 BEACHPLAN results for optimum groyne scheme at 2:1 spacing (Year 5)

Source: Kemp and Brampton (2014, Figure 6)

Coastal profile models (cross-shore change)

These one-dimensional models predict changes to a single beach profile in response to wave action over short periods of time (a storm event). The only exception is for an instance where a profile model has been specifically developed for dunes (see CS-model below).

Sub-types

There are no sub-types of this type of model, although each model within this type has a slightly different focus on different issues.

Example applications

- **C-SHORE** (https://sites.google.com/site/cshorecode/) is a time-averaged nearshore profile model for predictions of nearshore wave height, water level, wave-induced steady currents and profile evolution. The model manual gives an extensive list of papers throughout the history of its development for those seeking more information. It is available open source.
- **CS-model for dunes** (Larson et al. 2016) simulates the cross-shore exchange of sand and the resulting profile response at decadal scale to be used in regional coastal evolution models. The CS-model consists of modules for calculating dune erosion and overwash, wind-blown sand transport and bar–berm material exchange.
- **COSMOS** (Southgate and Nairn 1993) models beach profile response to wave and tidal action, and is capable of considering seawalls, non-erodible layers and sills. This is commercial code. An example application of this model is described in Box 4.6.
- **CROSMOR** (www.leovanrijn-sediment.com/page16.html) includes a probabilistic model for the propagation and transformation of individual

waves. It solves the wave energy equation for each individual wave, as well as a depth-averaged current under the trough of each wave. The sediment transport – both bed load and suspended load – is then calculated.

- **SBEACH for dune erosion** (Larson et al. 1990) is a numerical simulation model for predicting beach, berm and dune erosion due to storm waves and water levels. It has potential for many applications in the coastal environment; it has been used to determine the fate of proposed beach fill alternatives under storm conditions and to compare the performance of different beach fill cross-sectional designs. SBEACH is distributed as a component of the Coastal Engineering Design and Analysis System (CEDAS).

- **XBeach** (https://oss.deltares.nl/web/xbeach/) is an open source numerical model originally developed to simulate hydrodynamic and morphodynamic processes and impacts on sandy coasts with a domain size of kilometres and at the timescale of storms. Since then the model has been applied to other types of coasts and purposes. **XBeach-G** was developed for use on gravel beaches (https://oss.deltares.nl/web/xbeach/xbeach-og)

Schoones and Theron (1995) evaluated 10 of the most well-known mathematical cross-shore transport models. They classified the models into 3 groups depending on their theoretical basis, but noted that:

- it was vital to consider the specific purpose of a model application

- in some instances, one model may perform better while for a different purpose another one may be better

Typical outputs

These models mainly calculate the cross-shore sediment transport and, as such, the main outputs are in terms of sediment transport and associated changes in morphology. These models can predict morphological change under different management scenarios. Some of these models can also calculate the cross-shore distribution of the longshore transport.

Typical benefits

The main benefit of this type of model is that they satisfactorily predict profile changes without being too computationally expensive, especially when compared with area models. This allows for a larger range of simulations per study.

Profile models have been shown to predict the cross-shore variation in significant wave height to within 10% if properly calibrated (van Rijn et al. 2003). They have also predicted offshore and longshore current speeds in the laboratory and in the field to within 40%.

Typical limitations

- They tend to be poor at representing the rebuilding of beaches between storms (that is, during periods of net onshore transport) and so are restricted to relatively short simulations of cross-shore transport.

- As with other process models, they can be fraught with difficulties associated with numerical stability, accumulation of rounding errors and sensitivity to small changes in boundary conditions.

- They assume uniform conditions along-shore, both in the forcing and in the coastal response.

Box 4.6: Application of a coastal profile model (COSMOS) in the Netherlands

The coastal profile model COSMOS (Nairn and Southgate 1993, Southgate and Nairn 1993) was used to predict the cross-shore evolution of the barred beach at Egmond-aan-Zee during a storm from 24 to 31 October 1998 (Brady and Sutherland 2001). The prediction was tested against the Brier Skill Score, which provides an objective measure of model performance. A Brier Skill Score of 1.0 represents perfect agreement between the actual and modelled prediction. If the model prediction is further away from the final measured condition than the baseline condition, the skill score is negative.

The root mean square wave height measured at ~16m water depth during this week was 2.1m, with an average peak wave period of 8.5 seconds. Figure 4.8 shows the actual measured cross-shore profiles at the start and end of the modelling period on 24 and 31 October 1998, the profile predicted by the model on 31 October, and the Brier Skill Scores for the 3 main regions. Two lines are shown for the measured bathymetries, representing the average profile plus and minus a standard deviation. 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 predicted a lower than observed crest elevation. There was little movement of the swash bar in the measurements or the model. For more details see Brady and Sutherland (2001).

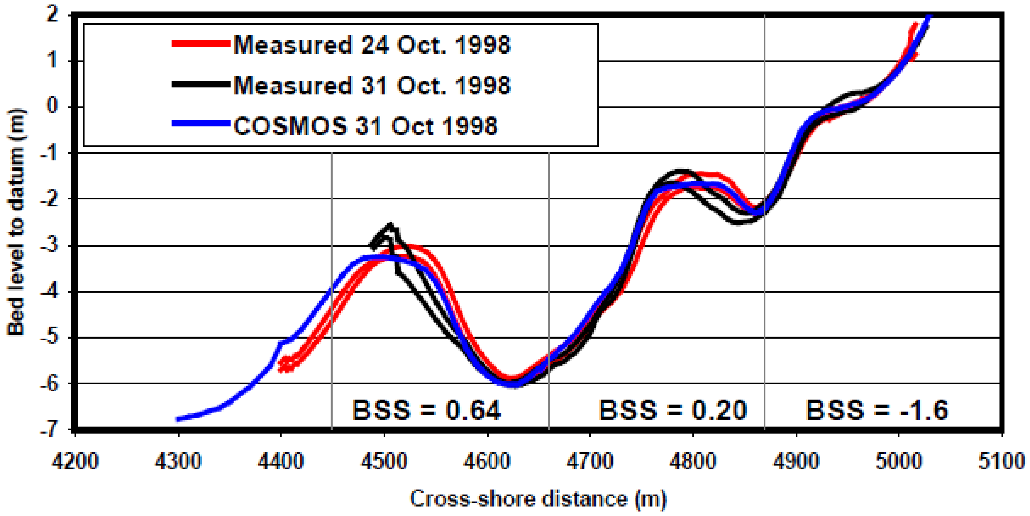

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Figure 4.8 Bathymetries and Brier Skill Scores for storm period

Source: Brady and Sutherland (2001, Figure A1.8)

Coastal area models

Coastal area models calculate sediment transport rates and associated changes in morphology in a coastal area. They are applied where a separation between longshore and cross-shore scales is not possible (for instance, in the vicinity of a tidal inlet). These models consist of hydrodynamic (wave and flow), sediment transport modules and bed morphology changes on a continuous feedback loop.

The models are usually set up in a nested manner, where the outer models have coarser resolution and the inner models nested within them have finer resolution. The hydrodynamic models are coupled to the sediment transport and bed evolution models, sometimes by dynamic internal coupling (see Section 3.8). They are much more computationally demanding than profile and one-line modelling, limiting their use for practical mesoscale applications. For more detail see the reviews by Amoudry and Souza (2011) and Roelvink and Reniers (2011).

Sub-types

The models are most commonly depth-averaged (2DH), but more recently have evolved into a quasi three-dimensional form (Q3D) and three-dimensional (3D) models, which resolve the vertical variations in flow and transport.

Example applications

Information and/or model code for various models are available on line as follows:

- **Delft3D modelling system** (https://oss.deltares.nl/web/delft3d/home) deals with mud or sand sediment in a curvilinear finite difference grid system and is available as open source.
- **2DH/3D MIKE** (www.mikepoweredbydhi.com) deals with sand or mud sediment in a rectilinear or curvilinear finite difference grid or unstructured finite volume grid, and it is available as commercial software.
- **TELEMAC** (www.opentelemac.org) can deal with sand or mud fractions of sediment in a unstructured finite element grid and is available as open source.
- **XBeach** (https://oss.deltares.nl/web/xbeach/) is a two-dimensional sand sediment model with a rectilinear finite difference grid. It focuses on extreme events such as hurricanes, for which processes like overwashing and breaching are included, but can also be applied for small coastal engineering problems (Roelvink et al. 2009). XBeach is specially designed for sediment transport studies in the nearshore area (beaches, dunes and backbarrier) and as such includes long waves. It is available as open source.

Although Delft3D, MIKE and TELEMAC are based on an area grid and the resolution of the nonlinear shallow water equations, each model has a different grid mesh types and all have now been extended to 3D. The differences between Delft3D, MIKE and TELEMAC are mainly in the way the grids are defined and the minutiae of how the processes involved are interpreted and coded.

Typical outputs

These models calculate sediment transport change across the whole area as a result of input conditions and then update the bed according to the changes. The main outputs are therefore in terms of sediment transport and morphological changes, so that areas of deposition and erosion at different times are identified, as well as sediment transport paths.

The models are computationally intensive and run times can be extremely long (almost real time, in some cases). However, there are 2 techniques that can make them more appropriate for simulation of longer timescales (Southgate et al. 2000).

- **Input time series reduction** involves the creation of a compressed input time series with an amalgamation of the most significant events.
- ‘**Speed-up’ techniques** in their simplest form multiply the calculated sediment transport with a speed-up factor to make the simulation represent more than the physically modelled time period. There are also more complicated ones. Careful calibration and validation are required when speed-up factors are applied.

Typical benefits

The main benefit of this type of model is that they can be applied where a separation between longshore and cross-shore scales is not possible as in the vicinity of a tidal inlet. In addition, they are able to model the contribution of different forcing mechanisms (for example, flows and waves) on the sediment transport, whereas the longshore and cross-shore models usually deal with one main forcing mechanism.

Typical limitations

- The combination of many multiple nonlinear process elements such as advection and bottom friction might lead to the model becoming unstable or producing non-credible results.
- The processes are highly simplified in order to keep the computational expense to a reasonable level.
- Computational time associated with this type of models is high and, depending on the grid extent, grid resolution and forcing mechanisms, the model run time could be extremely long.
- There are limitations with using any of these models (with the exception of XBeach) to represent beach evolution in front of coastal structures as surf zone processes and some wave transformation processes such as wave reflection or diffraction are not represented.

Box 4.7 Application of an area model to a megaport in Kuwait

As part of a study to support the selection and design of an alternative access channel for the Mubarak Al Kabeer Port on Boubyan Island, Kuwait, area hydrodynamic and sediment transport modelling was used to ascertain the most favourable channel.

The initial 5 potential channel routes proposed were reduced to 3 after an initial option appraisal study. The studies examined the performance of the 3 preferred options, with the preferred channel layout identified at the end of the concept design stage.

Tidal flow modelling was undertaken using the TELEMAC 3D model. Detailed wave modelling was undertaken using the SWAN wave model and non-cohesive sediment transport modelling was carried out using the Sandflow model. Cohesive sediment transport modelling was also carried out as part of this study to consider the mud fraction of the bed.

Results from the sand transport modelling for the 3 different options were presented in terms of:

- net sediment transport paths
- the predicted bed level changes over a 14 day tidal cycle
- annual infill predictions

This assessment led to a preferred option for the channel route. An example of predicted bed level changes for one of the options is shown in Figure 4.9. For more details see Baugh (no date).

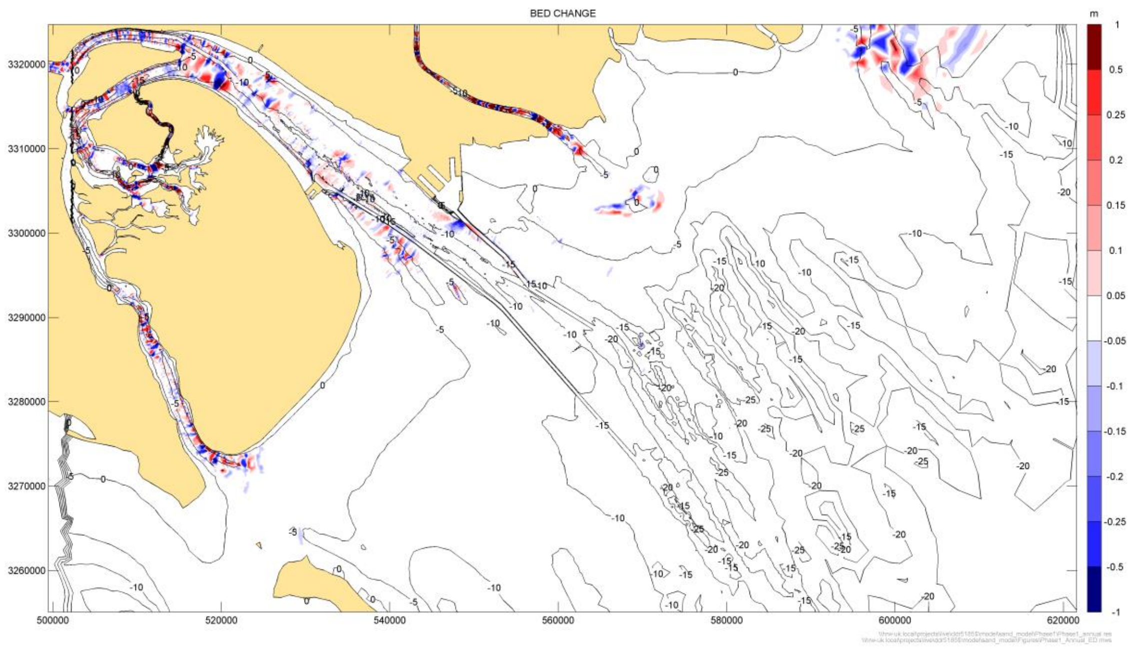

Figure 4.9 Bed level change for the one of the options channel after a 14 day tidal cycle – far field view (weighted annually)

4.3.6 Behaviour-based models

These models are also known as systems models or top-down models. They represent the overall phenomena, but simplify the processes by using empirical averaging.

This type of simplified model has been widely used in long-term morphodynamics. They have been preferred to more complex models that attempt to model all the processes due to the computing demands of such complex models and the difficulties in assessing which of the processes remain of relevance over decadal timescales.

Sub-types

There are many sub-types of behaviour-based models, depending on what morphological feature and what timescale they are trying to represent. This is because behaviour-based models represent only certain aspects of the coastal/estuarine behaviour and are less generally applicable than process-based models. The example applications below describe some of the most well-known ones.

Example applications

- **ASMITA** (Aggregated Scale Morphological Interaction between Tidal Inlets and the Adjacent Coast) is a behaviour-oriented model for predicting the large-scale evolution of estuaries over decades to centuries. Within ASMITA, the estuary has to be schematised into morphological elements such as channels, tidal flats and ebb tidal deltas, for which a morphological equilibrium is defined relating the morphology to the hydrodynamic forcing (usually the tidal prism). The volumes of the different elements are predicted through time, based on sediment exchange between elements which is driven by the difference between current volume and equilibrium volume. The model freely available under GPL and is an iCOASST-related product (www.channelcoast.org/iCOASST/ASMITA/). Box 4.8 describes the application of an ASMITA model in the Thames estuary.

- **GEOMBEST** (Geomorphic Model of Barrier, Estuarine, and Shoreface Translations) is a 2D, cross-shore, numerical morphological behaviour model that simulates the evolution of barrier island morphology and stratigraphy over timescales ranging from decades to millennia. The model is freely available (http://csdms.colorado.edu/wiki/Model:GEOMBEST).
- **MESO_i** is a landform behaviour model designed to simulate the morphodynamic evolution of a tidal inlet subject to ebb delta breaching and periodic sediment bypassing. The model is freely available under GPL and is an iCOASST-related product (www. channelcoast.org/iCOASST/MESO_i/).
- **SCAPE+** is a modelling tool that can be applied to cliff/platform coasts with or without a beach. It represents processes, but does so in abstract and behavioural terms, and is typically used to simulate change over timeframes of decades to centuries. It is also used to model the short-term rapid responses of cliffs to the removal of coast protection. This model is freely available under GPL and is an iCOASST-related product (www. channelcoast.org/iCOASST/SCAPE/).

Typical outputs

Sediment transport rates would not always be calculated within these models, but all of them do output estimates of morphological change under different management scenarios.

Typical benefits

The main benefit of these types of models is that they are more computationally efficient than process-based models, as they are based on abstractions of behavioural terms. In terms of long-term simulations of transport models for large scale, the behaviour-based models are usually more stable and robust, meaning that a beach evolution model can simulate space and timescales of up to 100km and 100years respectively.

Typical limitations

- These models are limited to modelling the aspects of the coastal/estuarine area which the model has been developed for. They therefore generally have limited ability to represent the effects of changed conditions (for example, new coastal structures). In addition, the temporal applicability is restricted to the temporal scale which the model has been developed for.

Box 4.8: Application of a behaviour-based ASMITA model to the Thames estuary

The morphological development of the Thames estuary, taking into account the effect of human intervention, was assessed using the ASMITA model (Rossington and Spearman 2009). The approach predicted the long-term evolution of the estuary into the future, assuming either historic rates of sea level rise or accelerated sea level rise.

The historical sediment budget for the Thames estuary was examined, and source and sink terms, including fluvial sediment supply and historical dredging rates were included in the ASMITA model. ASMITA predictions showed good overall agreement with the historical data (see Figure 4.10), highlighting the benefits of detailed historical review and the inclusion of anthropogenic effects in the model.

ASMITA predictions for the period 2000 to 2100 suggest that, under all scenarios, the estuary will experience accretion. However, the rate of accretion under an accelerated sea level rise scenario will be slower than sea level rise, with intertidal profiles projected to be up to 0.5m lower with respect to high water by 2100.

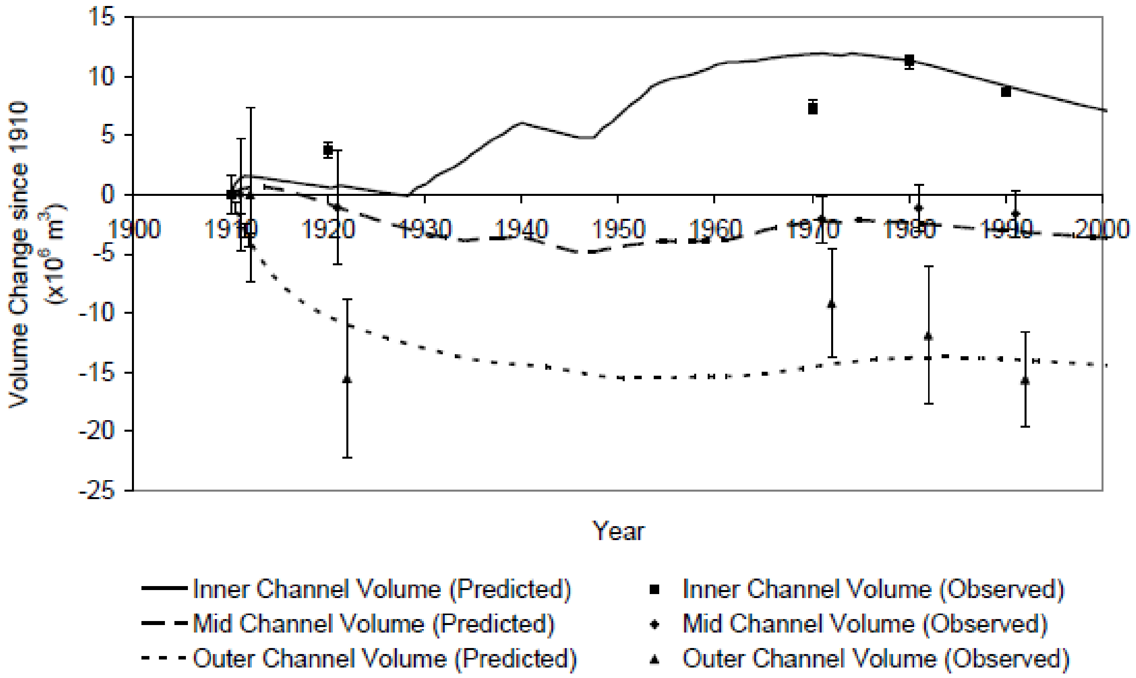

Figure 4.10 Predicted and observed changes in channel volumes for the period 1910 to 1990

Source: Rossington and Spearman (2009, Figure 3)

4.3.7 Emerging modelling techniques

This ‘catch-all’ model type covers more advanced tools and models that are currently being developed. These usually consist of hybrid models that simplify the process equations considered to govern observed morphological behaviour.

Example applications

- **CoastalME** (Coastal Modelling Environment) is a new modelling environment to simulate decadal coastal morphological changes of both open coast and estuarine geomorphological systems. CoastalME follows the complexity modelling approach described by French et al. (2016b). Morphological evolution is simulated through interacting raster and geometrical objects that follow certain user-defined behavioural rules (Payo et al. 2015). The novelty of the modelling environment is the dynamic interaction between the raster sediment accounting and the simplified geometry (lines, areas and volumes). The raster grid allows the user to represent the Q3D spatial heterogeneity of the coastal geomorphology. The shape objects provide a reduced number of shape elements at the appropriate spatial scale (that is, larger scale than individual raster cells but small enough to simulate a given coastal stretch). It is freely available under GPL and is an iCOASST-related product (www.channelcoast.org/iCOASST/COASTAL_ME/).

- **ESTEEM** (Estuary Spatial Landscape Evolution Model) simulates the morphological evolution of estuaries over timescales of the order of 10 to 100 years. The model adopts a novel 'hybrid complexity' approach (Thornhill et al. 2015, French et al. 2016b) that combines the computational efficiency and high spatial resolution of GIS-based spatial models (for example, SLAMM; Clough et al. 2010), with the more robust physical basis of morphodynamic models recently developed for tidal inlets and lagoons (Di Silvio et al. 2010). It predicts the evolution of estuary morphology, especially within the intertidal zone, and incorporates detailed representation of engineered structures. It is freely available under GPL and is an iCOASST-related product (www.channelcoast.org/iCOASST/ESTEEM/).

Typical outputs

The main outputs will depend on the model itself, but these models are developed in order to predict morphological changes under existing and new management scenarios. For example, for ESTEEM, the main output is the evolved DEM and for CoastalME, it is the coastal morphology changes.

Typical benefits

The computational cost of these models is low and they have proved effective in exploring morphodynamic trends and improving the understanding of mesoscale behaviour. Their potential is significant as they combine different types of models and behaviours, and can therefore encompass many features over long time and spatial scales. They aim to fill the gaps where other more conventional models are not that strong. For example, CoastalME includes different sediment fractions – sand, gravel and mud.

ESTEEM's computational efficiency allows whole estuary simulations at high spatial resolution (of the order 5–20m grid size) at timescales of decades to centuries. Model scenarios can include not only the effects of changing sea level, wave climate and sediment supply, but also human behaviour as articulated through flood and coastal defence policy.

Typical limitations

The main limitation of these models is that they are at embryonic states and tend to have only been applied to proof of concept exercises or realistic, but not real, scenarios.

Box 4.9: Application of ESTEEM to the intertidal evolution of the Deben estuary under partial realignment scenarios as part of the iCOASST project

Early simulations for the Deben estuary over a 200-year time interval have shown that:

- the infilling of the estuary following realignment of defences is quite strongly dependent on the assumed wind climate
- further work is needed to explore the threshold between different end states

It was also shown how ESTEEM can be used to achieve rapid computation of morphological change that can be used in conjunction with a full 2D (or even 3D) hydrodynamic scheme – such as TELEMAC, which was implemented at the estuary.

Figure 4.11 shows an indicative ESTEEM simulation of intertidal evolution under partial realignment of the outer estuary (with low wind forcing and no sea level rise).

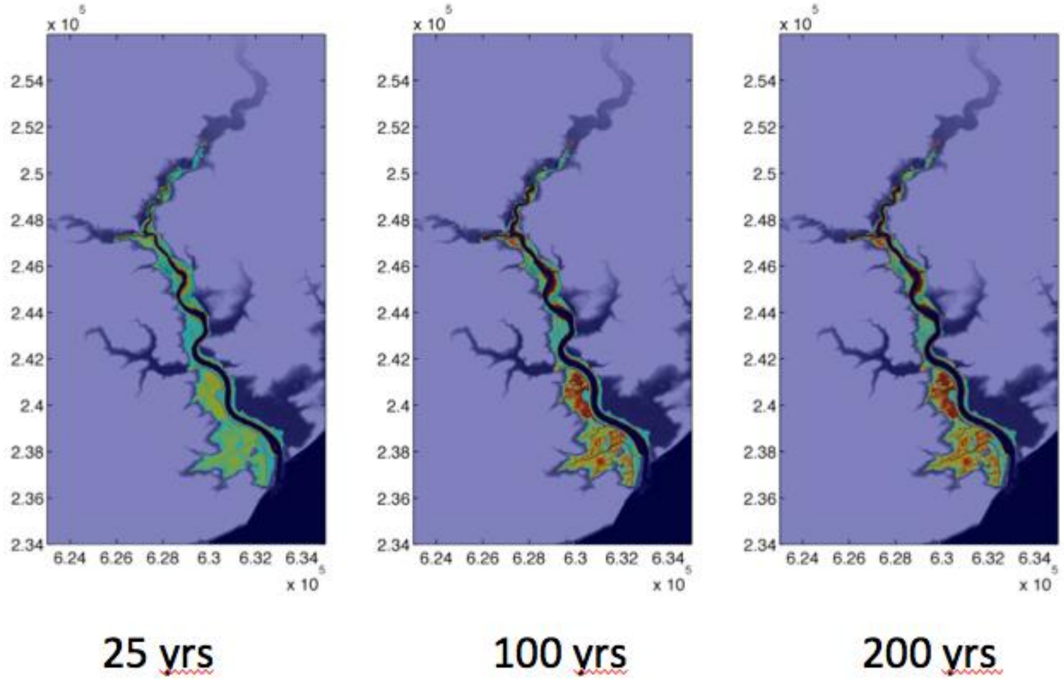

Figure 4.11 Early simulations for the Deben estuary

Source: www.coastalmonitoring.org/iCOASST/ESTEEM/

5 Using models to support coastal management decisions

This chapter explains to decision-makers the suitability and applicability of the various model types and approaches described in Chapter 4 in helping to answer a range of typical coastal management questions. These include:

- questions about the nature of temporary and permanent changes to various coastal forms – specifically beaches, cliffs, dunes and barrier beaches
- questions about the impact of climate-related changes on coastal features
- questions about the impact of estuarine change on coastal morphology
- questions about the impact of coastal morphological change on flood risk

Chapter contents

5.1 Answering the coastal management questions

To help readers, Box 5.1 repeats the typical coastal management questions posed in Box 1.1 in Chapter 1. This section draws on the model descriptions in Chapter 4 to provide guidance to end users on which models can help provide answers to those questions.

Not all of the questions can, at the moment, be answered with the aid of modelling; and some questions require alternative types of models (that is, not only morphological models). The questions that cannot currently be answered with modelling are highlighted in this section as this may help to determine the priorities for future model developments.

Box 5.1: Typical coastal management questions relevant for morphological modelling (repeat of Box 1.1)

Q1 Expected trends. What is the likely trend of change in geometry of the coastal feature (for example, beach, cliff, dune, barrier beach) and how is that likely to change naturally (that is, assuming current climatic and management conditions) in the future?

Q2 Management impacts at site. What is the likely future impact of different coastal management interventions on the feature?

Q3 Management impacts nearby. What is the likely future impact of different coastal management interventions on adjacent frontages and further afield?

Q4 Climate change impacts. What is the likely impact of climate-related changes on the feature in the future?

Q5 Storm impacts. What is the likely future short-term impact (for example, beach lowering) following an extreme storm (wave and/or tidal and/or surge event)?

Q6 Recovery after storms. To what extent might the feature recover in the short term (for example, beach rebuilding) following an extreme storm (wave and/or tidal and/or surge event)?

Q7 Estuaries. What is the likely future impact of estuarine change on coastal morphology?

Q8 Landward flood risk. What coastal morphological changes might have an impact on landward flood risk?

The predictive capabilities of the various models have been reviewed against 4 application categories. These categories can be related to the coastal management questions as follows.

- **Replicability of historical/present conditions**. This relates to the capability of replicating past behaviour and is therefore associated with Q1 in Box 5.1.
- **Prediction of future outcomes under the same conditions**. This relates to the capability of predicting future behaviour under a ‘no change’ scenario (that is, unmanaged and without the effects of climate change) and is therefore associated with Q1, Q5 and Q6 in Box 5.1.
- **Prediction of future outcomes under different management scenarios**. This relates to the capability of predicting future behaviour under different management intervention scenarios and is therefore associated with Q2, Q3, Q5 and Q6 in Box 5.1.
- **Prediction of future outcomes under climate change scenarios**. This relates to the capability of predicting future behaviour under different climate-related scenarios and is therefore associated with Q4, Q5 and Q6 in Box 5.1.

Descriptions of how different models can help answer the questions are given below.

5.2 Using models to understand beach change

Note: this section addresses Q1 to Q6 for beaches.

Estimating the change in geometry of a beach involves predicting both position and profile. Long-term processes tend to be related to the along-shore position of the beach and short-term processes to the across-shore processes. Both timescales are covered here.

Table 5.1 provides a summary of the models available to answer questions Q1 to Q6 in relation to beaches. In order to assess the consequences of interventions and help make informed decisions, it is important to understand the way the beach will evolve – both naturally and in response to alternative management decisions.

Given sufficient long-term data of suitable quality, geomorphological data analysis and data-driven models would provide historic and future trends (under the same scenario), thus tackling Q1.

Parametric models might be able to predict, in a simplistic way, the equilibrium shoreline or profile position under a different management scenario. However, their simplicity means that some may not be appropriate for application to some structures. For example, in the parabolic equilibrium planshape models, the definition of the diffraction point of a structure does not depend on whether or not it is connected to the shore and thus they are not appropriate for modelling detached breakwaters. These types of models can therefore deal with Q1, Q2 and Q3 (the latter only under certain conditions covered by the hypothesis of the models).

Only process-based or behaviour-based models can truly predict how the beach would evolve under different management (Q2 and Q3) and climate change scenarios (Q4).

Shoreline movements over medium to long-term timescales vary depending on the longshore transport that might be induced by tidal currents, breaking wave heights, wind or wave height gradients. Shoreline movements caused by breaking wave heights and wave height gradients are well reproduced with one-line and multi-line models. If the longshore transport is mainly induced by tidal currents, then an area model will be required.

Management interventions such as beach nourishment or the introduction of control structures (groynes, breakwaters and so on) or policy changes might have a considerable effect on adjacent frontages. Answering this question (Q3) will usually involve the representation of one or many morphological features, making sure that the extent of the area covers adjacent frontages. Thus the model(s) used would depend on the landforms present (cliffs, dunes and so on).

In terms of predicting the future short-term impact following an extreme storm (Q5), the beach profile response to a storm for a sandy beach is well reproduced with profile process-based models, although these cannot reproduce the beach recovery between storms (Q6). Beach profile response to a storm for gravel beaches is well reproduced with parametric models.

To ensure design resilience, these questions should be extended to understanding how the sequencing of storm events (as a climate-related change) might influence the way a beach performs. This sequencing question is usually answered with the same type of models using successive events that do not allow time for beach recovery.

Questions that cannot currently be answered with the aid of modelling include the following.

- **To what extent might the beach recover in the short term (Q6)?** Sustainable beach management requires an informed knowledge of the way beach coastlines change with time. An ability to articulate how and when a beach will recover a protective sediment buffer without human intervention following storm erosion is vital in the planning and design of beach management strategies. At present, however, the models available are not able to reproduce this recovery satisfactorily. Data-driven models (see, for example, Miller and Dean 2007, Karunarathna et al. 2012) have been able to reproduce historical recovery of beaches, but not to predict it. Depending on the severity of the storm and the coastal processes in the area, available monitoring data can often be used to assess whether a beach might recover fully or not after an extreme event

- **What is the likely impact of changes in beach material on the beach?** Although this question is not explicitly defined in the list in Box 1.1, it will be relevant when dealing with certain beaches (which have mixed sediments) and for certain management interventions that might involve placing different sediment to the one already at the beach. All current models deal either with sandy or gravel beaches, with mixed beaches falling somewhere in the middle. The variation in sediment distribution/grading is rarely acknowledged by process models, an omission which has important implications for the design of nourishment schemes, as in most cases the borrowed sediment is not the same as the native one. How recharge material will behave and be transported across and along the shoreline is therefore a question that cannot currently be answered by modelling, thus hindering decisions on sediment volumes and the required frequency of interventions.

Several researchers (see, for example, Bayram et al. 2007, van Rijn 2014) have developed longshore transport formulae that cover different sediment types (sand, gravel and shingle). This is an improvement on the CERC formulation (USACE 1984) that most one-line models are based on. However, the formulae still only deal with the sediment transport of one of the fractions at a time and not with the complicated interaction (3D) between the fractions. Area models such as Delft3D, MIKE or TELEMAC can deal with different fractions of sediment and the interaction between the gravel and sand fraction with the inclusion of hiding and exposure factors. However, the interactions covered by the models are very basic and do not cover all the different 3D interrelationships between the fractions.

Table 5.1 Using models to help understand beach morphological change

Model type	Sub-type	Limitations	Past/ present rate	Future prediction		
				Naturally	Under different management scenario	Under different climate-related changes
CESM (Section 4.3.1)		Needs long-term and well-timed beach surveys		(assuming same trend)		
Geomorphological data analysis (Section 4.3.2)	HTA	Identifies net change between successive datasets, not the scale of variability over shorter timescales.		(assuming same trend)		
	SBA			(assuming same trend)	(assuming the effect of the scenario a priori)	(assuming the effect of the scenario a priori)
Data-driven models (Section 4.3.3)	PCA	Good historical record is required (typically 10 years of 6-monthly beach surveys and time series of measured or hindcast wave conditions)		(assuming same trend)		
	CCA			(assuming same trend)		
	ANN			(assuming same trend)		
Parametric models Section 4.3.4)	Equilibrium	Constant wave conditions and single grain size Limited to validity range			(only for certain structures)	(assuming the effect of the scenario a priori)
	Change of state			ST	ST	
Process-based – shoreline change (Section 4.3.5)	One-line	Assumes straight beach and longshore transport as main cause	LT	LT	LT	LT Sea level rise by Bruun rule[(1)]
Process-based – profile models		No beach recovery; no	ST	ST	ST (different models deal with different	ST

Model type	Sub-type	Limitations	Past/ present rate	Future prediction		
				Naturally	Under different management scenario	Under different climate-related changes
(Section 4.3.5)		overwash/ breaching			structures)	
Process-based – coastal area models (Section 4.3.5)		Need techniques for LT predictions Processes at beach not well represented			(depending on the management scenario)	
Behaviour-based models (Section 4.3.6)		Limited to model the aspects of the coastal/estuarine issues for which the model has been developed				Sea level rise by Bruun rule(1)

Notes: (1) This has been challenged by several authors (see text for explanation).
HTA = historical trend analysis; LT = long- term; ST = short- term

Key:

Question can be answered with this type of model	Question can be answered up to an extent with this type of model	Question cannot be answered with this type of model

5.3 Using models to understand cliff change

This section refers to Q1 to Q6 for cliffs.

Cliff erosion is more difficult to predict than beach erosion because the mechanisms for cliff failure not only include wave action but also geotechnical cliff stability. On some UK coastlines, where cliffs comprise glacial drift deposits and have little resistance to marine action, the erosion rate can be of the order of 2 months per year. The mechanisms of instability and collapse of cliffs (apart from the marine action) include:

- weathering – due, for example, to wind, rainfall and freezing
- biological action – such as vegetation growth and burrowing animals
- variation of groundwater levels and pore pressures (very important)

Due to these complexities, techniques based only on data such as geomorphological analysis or data-driven models can still be applied but with care as the geotechnics and geology of the cliffs are not considered by such approaches. At the moment there is no parametric model dealing with cliff erosion. Although the Brunn rule[13] addresses response to sea level rise, it takes no account of geology (it assumes an infinitely deep beach) and assumes an equilibrium profile. Slope stability models from other disciplines, are not appropriate for the marine domain and are one-dimensional, and therefore do not capture the along-shore variation. Although process-based and behaviour-based models simplify the cliff processes, they should be satisfactory for most applications, especially those that involve only the position of the cliff. As such, SCAPE+ is the model that has been used most successfully.

More recently, the Environment Agency funded project, 'Cliff and Shore Sensitivity to Accelerated Sea Level Rise', extended the earlier work of SCAPE into the generic response of cliff/platform shores to accelerated relative sea level rise and to the removal of coast protection structures (Walkden et al. 2016). The project included models of the shores of:

- Holderness in Yorkshire (though unsuccessfully)
- Nash Point in Glamorgan
- the Birling Gap in Sussex
- Happisburgh in Norfolk
- Drigg in Cumbria

There is future research that could be undertaken to improve the modelling of cliff behaviour, including the interaction of cliffs with structures.

Table 5.2 provides a summary of the models available to answer questions relating to cliffs.

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[13] See Section 4.3.4 for an explanation.

Table 5.2 Using models to help understand cliff morphological change

Model type	Sub-type	Limitations	Past/ present rate	Future prediction		
				Naturally	Under different management scenario	Under different climate-related changes
CESM (Section 4.3.1)		Needs long-term and well-timed beach surveys		(assuming same trend)		
Geomorphological data analysis (Section 4.3.2)	HTA	Identifies net change between successive datasets, not the scale of variability over shorter timescales		(assuming same trend)		
	SBA			(2) (assuming same trend)	(assuming the effect of the scenario a priori)	(assuming the effect of the scenario a priori)
Data-driven models (Section 4.3.3)	PCA	Good historical record is required (typically 10 years of 6-monthly beach surveys and time series of measured or hindcast wave conditions)	(2)	(2) (assuming same trend)		
	CCA		(2)	(2) (assuming same trend)		
	ANN		(2)	(2) (assuming same trend)		
Parametric models (Section 4.3.4)	Equilibrium	Constant wave conditions and single grain size Limited to validity range				
	Change of state					
Process-based – shoreline change (Section 4.3.5)	One-line	Assumes straight beach and longshore transport as main cause	(3)	(3)	(3)	Sea level rise by Bruun rule[1]
Process-based – profile models (Section 4.3.5)		No beach recovery No overwash/breaching	(3)	(3)	(3) (different models deal with different	(3)

Model type	Sub-type	Limitations	Past/ present rate	Future prediction		
				Naturally	Under different management scenario	Under different climate-related changes
					structures)	
Process-based – coastal area models (Section 4.3.5)		Need techniques for LT predictions Processes at beach not well represented.	(3)		(3) (depending on the management scenario)	(3)
Behaviour-based models (Section 4.3.6)		Limited to model the aspects of the coastal/estuarine issues for which the model has been developed	(3)	(3)	(3)	Sea level rise by Bruun rule[1]

Notes: (1) This has been challenged by several authors (see text for explanation).
(2) This method has not been applied to cliffs, but in principle it could be.
(3) If cliffs are included in this specific model, as it is the case for SCAPE+.
LT = long- term; ST = short- term

Key:

Question can be answered with this type of model	Question can be answered up to an extent with this type of model	Question cannot be answered with this type of model

5.4 Using models to understand dune change

This section refers to Q1 to Q6 for dunes.

Compared with beaches, dunes have the added complexities of vegetation coverage, which modifies the mobility of the sediment and the impact of wind action which transports sediment when it is dry. Because of these added complexities, there are few dune models and the existing models deal mostly with the erosion of dunes due to wave action and not with dune erosion and accretion generated by wind processes.

Given sufficient long-term data of suitable quality, geomorphological data analysis and data-driven models would provide historic and future trends (under the same scenario), tackling Q1.

There are several dune erosion parametric models. They vary in complexity and are mostly based on experiments carried out in the Netherlands. Note that these models may only be valid for dunes with similar profiles to the Dutch ones. These types of models deal mainly with the short-term erosion caused by storms and therefore deal with Q5.

There is currently only one process-based cross-shore model available for dunes, the CS-model. This model simulates cross-shore sand transport for application in regional coastal evolution models that describe processes at the decadal scale. It includes dune erosion and overwash, wind-blown sand and bar–berm material exchange. This model, integrated with regional coastal evolution models, would deal with Q2 and Q3, as well as Q6.

Table 5.3 provides a summary of the models available to answer questions relating to dunes.

Questions that cannot currently be answered with the aid of modelling include the following.

- **Predictions of dune recovery** caused by Aeolian (wind-based) sediment transport into the foredunes are still difficult to make because of the heterogeneous and unsteady nature of sediment supply, especially in the along-shore position of the dune. This is one of the objectives of the BLUEcoast NERC project,[14] which involves a mixture of field campaigns and the development of numerical models.
- **What is the effectiveness of structures on dune erosion rates?** Due to the complexity of the dune erosion and accretion processes, there are currently some gaps in the modelling of dunes, especially in their interaction with structures and how these change the erosion rates and along-shore transport.

[14] Improving our Understanding of Processes Controlling the Dynamics of our Coastal Systems (http://projects.noc.ac.uk/bluecoast/)

Table 5.3 Using models to help understand dune morphological change

Model type	Sub-type	Limitations	Past/ present rate	Future prediction		
				Naturally	Under different management scenario	Under different climate-related changes
CESM (Section 4.3.1)		Needs long-term and well-timed beach surveys		(assuming same trend)		
Geomorphological data analysis (Section 4.3.2)	HTA	Identifies net change between successive datasets, not the scale of variability over shorter timescales		(assuming same trend)		
	SBA			(assuming same trend)	(assuming the effect of the scenario a priori)	(assuming the effect of the scenario a priori)
Data-driven models (Section 4.3.3)	PCA	Good historical record is required (typically 10 years of 6-monthly beach surveys and time series of measured or hindcast wave conditions)	(2)	(2) (assuming same trend)		
	CCA		(2)	(2) (assuming same trend)		
	ANN		(2)	(2) (assuming same trend)		
Parametric models (Section 4.3.4)	Equilibrium	Constant wave conditions and single grain size Limited to validity rang				
	Change of state					
Process-based – shoreline change (Section 4.3.5)	One-line	Assumes straight beach and longshore transport as main cause	(3)	(3)	(3)	(3)
Process-based – profile models (Section 4.3.5)		No beach recovery No overwash/	(3)	(3)	(3)	(3)

Model type	Sub-type	Limitations	Past/ present rate	Future prediction		
				Naturally	Under different management scenario	Under different climate-related changes
		breaching				
Process-based – coastal area models (Section 4.3.5)		Need techniques for LT predictions Processes at beach not well represented	(4)	(4)	(4)	(4)
Behaviour-based models (Section 4.3.6)		Limited to model the aspects of the coastal/estuarine issues for which the model has been developed				

Notes: (1) This has been challenged by several authors (see text for explanation).
(2) This method has not been applied to dunes but in principle it could be.
(3) If dunes are included in that specific model.
(4) Being developed by the BLUEcoast project
LT = long- term; ST = short- term

Key:

Question can be answered with this type of model	Question can be answered up to an extent with this type of model	Question cannot be answered with this type of model

5.5 Using models to understand barrier beach change

This section refers to Q1 to Q6 for barrier beaches.

This section considers barrier beaches of all grain sizes, including sandy barrier islands.

Gravel barrier beaches can respond very quickly to storm wave action, with most of the significant changes occurring in an episodic manner during major storm events. Storm surges and severe wave conditions can cause overwashing of barriers and rolling back of the whole beach. The breaching of barrier beaches has a direct effect on the flood risk and vulnerability of the hinterland assets.

Given sufficient long-term data of suitable quality, geomorphological data analysis and data-driven models would provide historic and future trends (under the same scenario), tackling Q1.

Very few models exist for barrier beaches, the most commonly applied one being the change of state model of Bradbury et al. (2006) based on a Barrier Inertia Index. This model deals with overwash, thus addressing Q5. In terms of predicting cross-shore movement, XBeach and XBeach-G can be applied to sandy and gravel barrier beaches respectively, dealing with Q1, Q2, Q3 and Q5.

Table 5.4 provides a summary of the models available to answer questions relating to barrier beaches.

The questions that cannot currently be answered with the aid of modelling include the following**.**

- **What is the along-shore change of the barrier beach?** To date, barrier beaches have been modelled to predict their potential lowering or overtopping under certain conditions at a given point. What remains unanswered with the current models is how the barrier beach may migrate under natural or managed conditions, and which factor(s) will affect it and how. Answering this question would help to design barrier beaches that are more resilient to change.

Table 5.4 Using models to help understand barrier beach morphological change

Model type	Sub-type	Limitations	Past/ present rate	Future prediction		
				Naturally	Under different management scenario	Under different climate-related changes
CESM (Section 4.3.1)		Needs long-term and well-timed beach surveys		(assuming same trend)		
Geomorphological data analysis (Section 4.3.2)	HTA	Identifies net change between successive datasets, not the scale of variability over shorter timescales		(assuming same trend)		
	SBA			(assuming same trend)	(assuming the effect of the scenario a priori)	(assuming the effect of the scenario a priori)
Data-driven models (Section 4.3.3)	PCA	Good historical record is required (typically 10 years of 6-monthly beach surveys and time series of measured or hindcast wave conditions)		(1) (assuming same trend)		
	CCA			(1) (assuming same trend)		
	ANN			(1) (assuming same trend)		
Parametric models (Section 4.3.4)	Equilibrium	Constant wave conditions and single grain size Limited to validity range				
	Change of state					
Process-based – shoreline change (Section 4.3.5)		Assumes straight beach and longshore transport as main cause				
Process-based – profile models (Section 4.3.5)		No beach recovery No overwash/ breaching	(2)	(2)		
Process-based – coastal area models		Need techniques for LT	(2)	(2)	(depending on	

Model type	Sub-type	Limitations	Past/ present rate	Future prediction		
				Naturally	Under different management scenario	Under different climate-related changes
(Section 4.3.5)		predictions Processes at beach not well represented			management scenario)	
Behaviour-based models (Section 4.3.6)		Limited to model the aspects of the coastal/estuarine issues for which the model has been developed				

Notes: (1) This method has not been applied to barrier beaches but could be.
(2) Only models developed for these type of feature
LT = long- term; ST = short- term

Key:

Question can be answered with this type of model	Question can be answered up to an extent with this type of model	Question cannot be answered with this type of model

5.6 Using models to understand climate-related changes

This section deals with the impact of climate-related changes on any of the features in the future, Q4.

The climate is changing, bringing with it a likely increase in flood and coastal erosion risk. Climate-related changes may cause accelerated change and may disturb systems that are otherwise in equilibrium.

There are a number of forcing conditions that are directly affected by climate-related changes such as air pressure, wind and waves, extreme high tide levels, storminess, rainfall and temperature (see Section 2.3.7). The implications of climate change for coastal management can often be tested through the use of scenarios within the modelling so that an understanding of the range of possible future impacts is reached.

There are different ways in which the scenario testing can be done. This will depend on the problem to be solved, the potential range of change of the climatic conditions, data availability and budgetary constraints. Below are 2 examples.

- Where only the input conditions to the feeding models (that is, offshore model, nearshore model, see Figures 3.3 and 3.4) are altered as, for example, periodically increasing the water depth in the wave propagation model to deal with the effects of sea level rise. This would create a range of plausible nearshore wave conditions for use as inputs to the morphological model.

- Where there are constraints on modelling resources, rather than altering the wind conditions in the climate models, a more simplistic approach might be chosen. For example, the sensitivity of the longshore drift to the mean wind direction might be explored by systematically changing the mean wave direction and assessing the results.

Predictions of climate change impacts for different scenarios will have different levels of associated uncertainty. Predictions based on measured long-term continuing trends (for example, sea level) will have lower uncertainty than modelled projections. Probable projections based on modelling primary climate variables (for example, wind) are inherently less uncertain than predictions based on modelling secondary variables (for example, waves). However, the range of direct and indirect impacts and their uncertainty should be considered in all decisions made.

With respect to the coastal morphological models themselves, the only formula currently available to calculate the effect of the sea level rise on the beach is the Bruun rule, which is included either implicitly or explicitly in many models and studies. However, the validity of this rule has been challenged by several researchers over the years due to its oversimplifications (Cooper and Pilkey 2004, Ranasinghe et al. 2012). A more appropriate relationship is needed that can be included in long-term shoreline models so that the sea level rise effect can be taken into account.

Relatively little work has been carried out on the relationship between sea level rise and the profiles of composite beach/rock shores. Recent results indicate that such profiles do change, becoming steeper as the rate of sea level rise increases (Walkden and Hall 2005). Recent attempts by Trenhaile (2018) to model the formation of beaches with shore platforms and their response to sea level rise are encouraging and more traditional models should look into possibly including these.

A barrier beach can respond to sea level rise and associated phenomena by landward or seaward migration, reshaping and realignment, and crest breakdown or build-up. The episodic processes of overwashing, overtopping and associated breaching are the primary phenomena behind long-term evolution. With respect to the roll-back of barrier beaches and sea level rise there are some empirical relationships (see, for example, Orford et al. 1995a, 1995b). These relate the primary factors for change (sea level rise, longshore sediment transport and changes in sediment sources and/or sinks) to modification of barrier beaches.

The suitability of the models in predicting climate-related changes in the future has been summarised in Table 5.1 to Table 5.4. When a cell in these tables says 'assuming the effect on the scenario a priori', this means that the model per se does not include any climate-related changes, but the user might somehow infer the effect of the climatic effect by modifying the input conditions into the model.

5.7 Summary of model relevance for answering questions relating to coastal features

Table 5.5 summarises the applicability of each of the different models in answering the posed coastal management questions for the different coastal features, as discussed in Sections 5.2 to 5.5 and Table 5.1 to 5.4.

Table 5.5 Summary of model type applicability in answering Q1 to Q6

Management question	Coastal feature	Model type															
		CESM		Geomorphological data analysis		Data-driven		Parametric		Process-based						Behaviour-based	
										Planshape		Profile		Area			
Q1 Expected trends. What is the likely trend of change in geometry of the coastal feature (for example, beach, cliff, dune, barrier beach) and how is that likely to change naturally (that is, assuming current climatic and management conditions) in the future? **Q2 Management impacts at site**. What is the likely future impact of different coastal management interventions on the feature? **Q4 Climate change impacts**. What is the likely impact of climate-related changes on the feature in the future?	Beach	N	F	N	F	N	F	N	F	N	F	N	F	N	F	N	F
		FD	FC	FD	FC	FD	FC	FD	FC	FD	FC	FD	FC	FD	FC	FD	FC
	Cliff	N	F	N	F	N	F	N	F	N	F	N	F	N	F	N	F
		FD	FC	FD	FC	FD	FC	FD	FC	FD	FC	FD	FC	FD	FC	FD	FC
	Dune	N	F	N	F	N	F	N	F	N	F	N	F	N	F	N	F
		FD	FC	FD	FC	FD	FC	FD	FC	FD	FC	FD	FC	FD	FC	FD	FC
	Barrier Beach	N	F	N	F	N	F	N	F	N	F	N	F	N	F	N	F
		FD	FC	FD	FC	FD	FC	FD	FC	FD	FC	FD	FC	FD	FC	FD	FC
Q5 Storm impacts. What is the likely future short-term impact (for example, beach lowering) following a storm (extreme wave and/or tidal and/or surge event)?								N, F, FD, FC				N, F, FD, FC					
Q6 Recovery after storms. To what extent might the feature recover in the short term (for example, beach rebuilding) following a storm (extreme wave and/or tidal and/or surge event)?																	

Management question	Coastal feature	Model type								
		CESM	Geomorphological data analysis	Data-driven	Parametric	Process-based			Behaviour-based	
						Planshape	Profile	Area		
Q3 Management impacts nearby. What is the likely future impact of different coastal management interventions on adjacent frontages and further afield?						N, F, FD, FC		N, F, FD, FC		

Notes: F = future no change; FC = future different climate condition; FD = figure different management scenario; N = natural

Key:

Question can be answered with this type of model	Question can be answered up to an extent with this type of model	Question cannot be answered with this type of model

5.8 Using models to understand the impact of estuarine change

This section deals with Q7.

Although the opposite question 'what is the impact of coastal change on the estuary' would also be relevant, this is outside the remit of this project. A comprehensive guide on how to identify and predict morphological change within estuaries as a basis for management is provided by 'The Estuary Guide' (www.estuary-guide.net). There are many models and techniques dealing with different aspects of estuaries from ecological modelling to socioeconomic.

To answer this question, it is vital to be able to predict sediment transport to and from estuaries, both in terms of the magnitude and timing of these exchanges, and how this interacts with sediment transport processes along the coastline. Estuaries are highly complex and dynamic ecosystems. At their simplest, estuaries can be defined in relation to their form and function. Understanding the interactions between mudflats, channels, saltmarshes and sandbanks helps support decisions on actions to maintain habitats and to meet local needs.

Geomorphological data analysis methods could be used to predict change if enough very long-term data (10–100 years) were available on the historic morphological aspects and development of the coast and estuary. However, these would not necessarily predict the influence of the estuary on the coastal morphology. In order to carry out future predictions under different management and/or climate change scenarios, parametric models could be used in the first instance. More detailed modelling could then be carried out with either area models or behaviour-based models, depending mainly on the time frame and level of assessment required. But to understand the connection and exchanges between coastal morphological change and estuarine change, the coastal and estuarine models need to be coupled. Linking of morphological models of the estuary and coast was performed as part of the iCOASST project. Box 5.2 describes this linking and the lessons learnt from it.

Box 5.2: Model linking of estuary and coast – the iCOASST experience

Two sites (Liverpool Bay and the Suffolk coast) were selected to test model linking that would improve understanding of estuary and open coast process links. These sites were chosen as representative of areas of highly mobile sediments, but also where prior knowledge, data and models would lead to more efficient research. Both sites involved compositions of different models – some of which were developed as part of the iCOASST project – tailored to open coast and estuary processes respectively.

In each trial, the different model types were linked both dynamically (that is, during model run time) and statically (offline, using model outputs). The common themes that emerged from the 2 trials will inform further efforts to link models in this way, as well as some site-specific successes and pitfalls. These are outlined below:

Liverpool Bay pilot site

At Liverpool Bay, the ASMITA behavioural model (see Section 4.3.6) was used to model estuary dynamics in the River Ribble, with the UnaLinea process-based model (see Section 4.3.5) used for stretches of open coast north (around Blackpool) and south (around Formby) of the estuary mouth. The open coast sediment feed from offshore to onshore was provided by an existing area model, POLCOMS.

The model linkages trialled by iCOASST are shown in Figure 5.1. ASMITA (A1) and UnaLinea (U1 and U2) each 'read in' POLCOMS (P1) output data to capture offshore–onshore sediment movement, that is, POLCOMS was linked statically (X2 and X3) to the open coast and estuary models. UnaLinea and ASMITA were in turn linked dynamically (X1) north and south of the estuary mouth; the approach here assumed that littoral drift plays a dominant role in sediment transport. To provide a point of comparison, the models were also run unlinked.

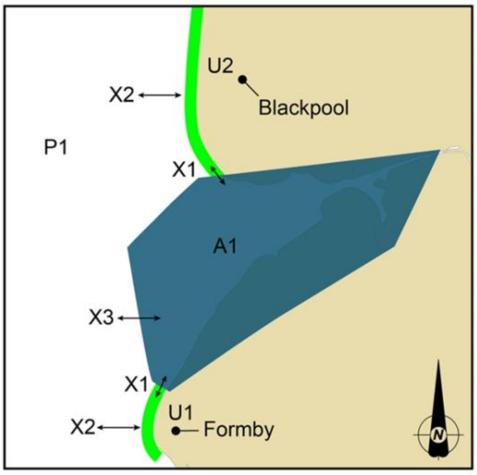

Figure 5.1 Model composition from Formby Point to Blackpool showing dynamic and static model linkages (from iCOASST)

Suffolk coast pilot site

At the Suffolk site, the ‘direction’ of the modelling is opposite to the Liverpool Bay pilot. Instead of reading outputs from an offshore model to onshore, the static link came from the inner estuary to the estuary mouth and open coast (see Figure 5.2).

The mouth of the Deben estuary was modelled using the behaviour-based models (see Section 4.3.6) MESO_i and SCAPE+ to dynamically represent the open coast north-east (around Bawdsey) and south-west (around Felixstowe) of the estuary mouth. The emerging model (see Section 4.3.7) ESTEEM (developed as part of iCOASST) provided a time series of sediment coming into the beach system. This was then read statically by the already linked SCAPE+ program.

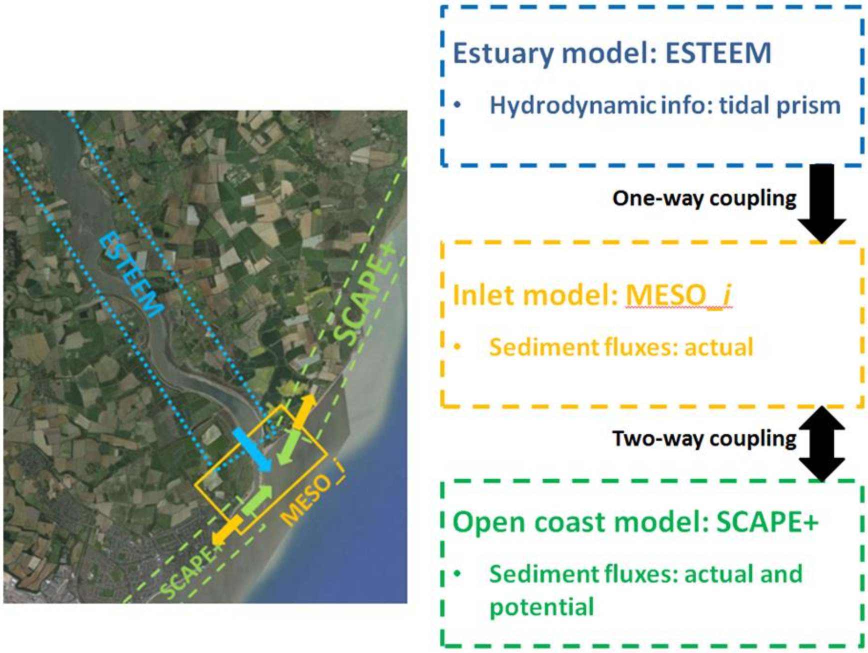

Figure 5.2 Model composition for Suffolk coast pilot site (from iCOASST)

As with Liverpool Bay, key components of the coastal–estuarine system were better represented by model linkage, notably the complex connectivity between open coast and estuary mouth on the Bawdsey side, and the very large random periodicity in the volume of the uplift shoal there.

The Suffolk coast pilot also illustrated the benefits of end user engagement in developing model linkages and calibrating their outputs iteratively (see Section 3.5). In this case, the greater importance of inlet–estuary connectivity relative to inlet–open coast connectivity became increasingly apparent. This has important implications both for the way this complex system is understood to behave and for how its future modelling might be approached. Importantly, there is now an interconnected set of models that can be adapted to reflect this knowledge.

Main lessons from linking models in iCOASST

As scientists get better at linking models in this way, system linkages such as those described above should be portrayed by model outputs more reliably. However, there are caveats. At the Liverpool pilot site, while those involved agreed a better model calibration and general reflection of reality was achieved through model linkage, the same result might have been achieved without the linkage by varying other parameters within ASMITA in the Ribble estuary; hence, assumptions about the added value of model linkage should be treated cautiously. Care also needs to be taken when coupling beach and estuary models to note that sediment types may be different and that sediment exchange, while numerically possible, may be impossible on grounds of sediment type incompatibility.

At the Suffolk coast pilot site, calibration could not be finalised within the project timescales and so the use of non-linked model to compare parameters such as flood hazard and long-term recession was not possible. Despite the composition outputs recognisably reflecting the Deben area, the representation was not yet considered by end users to be realistic enough to infer long-term coastal development trends – or therefore reliably inform management approaches. Although not a systematic problem with the approach, this does illustrate the potential effort required to develop reliable model linkage results in complex systems.

5.9 Using models to understand changes to flood risk

This section deals with the impact of coastal morphological changes on landward flood risk, Q8.

Coastal morphology models will need to be linked to coastal flood inundation models in order to understand what impact any changes in topography/bathymetry might have on the probability of coastal inundation and associated flood volumes. Note that morphological change can both increase and decrease flood risk (for example, letting cliffs erode may deliver sediment to adjacent areas that then provide flood inundation protection).

Flooding might occur as a consequence of the overtopping of a defence (including beaches) or of its failure. The latter would result in more significant flooding (orders of magnitude greater). Historically, flood inundation risk modelling has been performed with a static bathymetry. In order to incorporate morphological changes into flood inundation risk modelling, it is necessary to consider how changes in the bathymetry/ topography might have an impact on flood inundation risk.

Morphological influences on flood inundation risk might include (Whitehouse et al. 2009):

- changes in the bathymetry that lead to changes in the waves and water levels driving these models
- changes in the level of a beach at the toe of a structure that affect the local water depth at the structure, and hence the overtopping rate and the stability of the structure toe itself
- changes in the cross-sectional area of a beach that affect its ability to protect a shore platform and the base of a cliff from erosion, which in turn affects the probability of cliff failure
- changes in the cross-sectional area and beach profile shape of a barrier beach that affect the ability of this single barrier to withstand breaching
- changes in the cross-sectional area of a dune that affect its ability to survive a storm without breaching

Morphological models can be used to provide input datasets for coastal flood risk models. However, morphological models may not output in a form that provides sufficiently detailed bathymetry/topography and additional work may be needed to establish suitable input datasets for the flood inundation risk model.

Flood risk models answer questions relating to the likelihood and magnitude of extreme events (assessed through the transformation of offshore conditions) and the consequences of flooding associated with those events. This is achieved mainly through consideration of the overtopping and breaching of defences and subsequent flood inundation.

Both morphological models and coastal flood risk models are informed by a common understanding of the offshore conditions, as demonstrated in Figure 5.3.

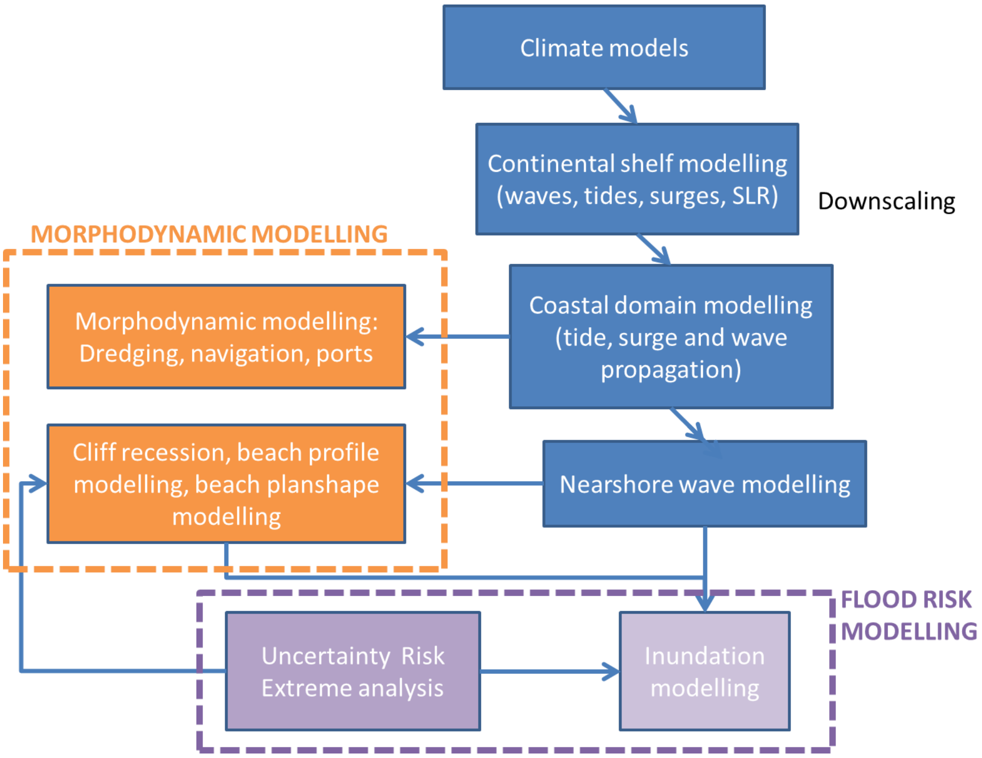

Figure 5.3 Links between coastal morphological and flood risk modelling: morphological modelling (in orange) and flood risk modelling (in lilac)

It may not be cost-effective to invest significant resources in assessing the morphological change, at least initially. It may simply be necessary to determine:

- whether substantive change is likely to occur (for example, by understanding what has occurred in the past – both in response to short-term events and over a long period, or by understanding whether the present day system is in dynamic equilibrium or is adjusting to a new morphology that will be realised in the future)
- whether the impact of such change is likely to be significant in terms of consequence and/or risk

Scenario testing using likely maximum ranges of potential bathymetric change should indicate whether the use of more detailed morphological model outputs may be of value to decision-makers. The impact on flood inundation risk of the probable extent of bathymetric change should be assessed in relation to the impact of long-term relative sea level rise, as this may overwhelm the overall impact levels.

Figure 5.4 presents a recommended framework for assessing the impact of morphological change on flood inundation risk.

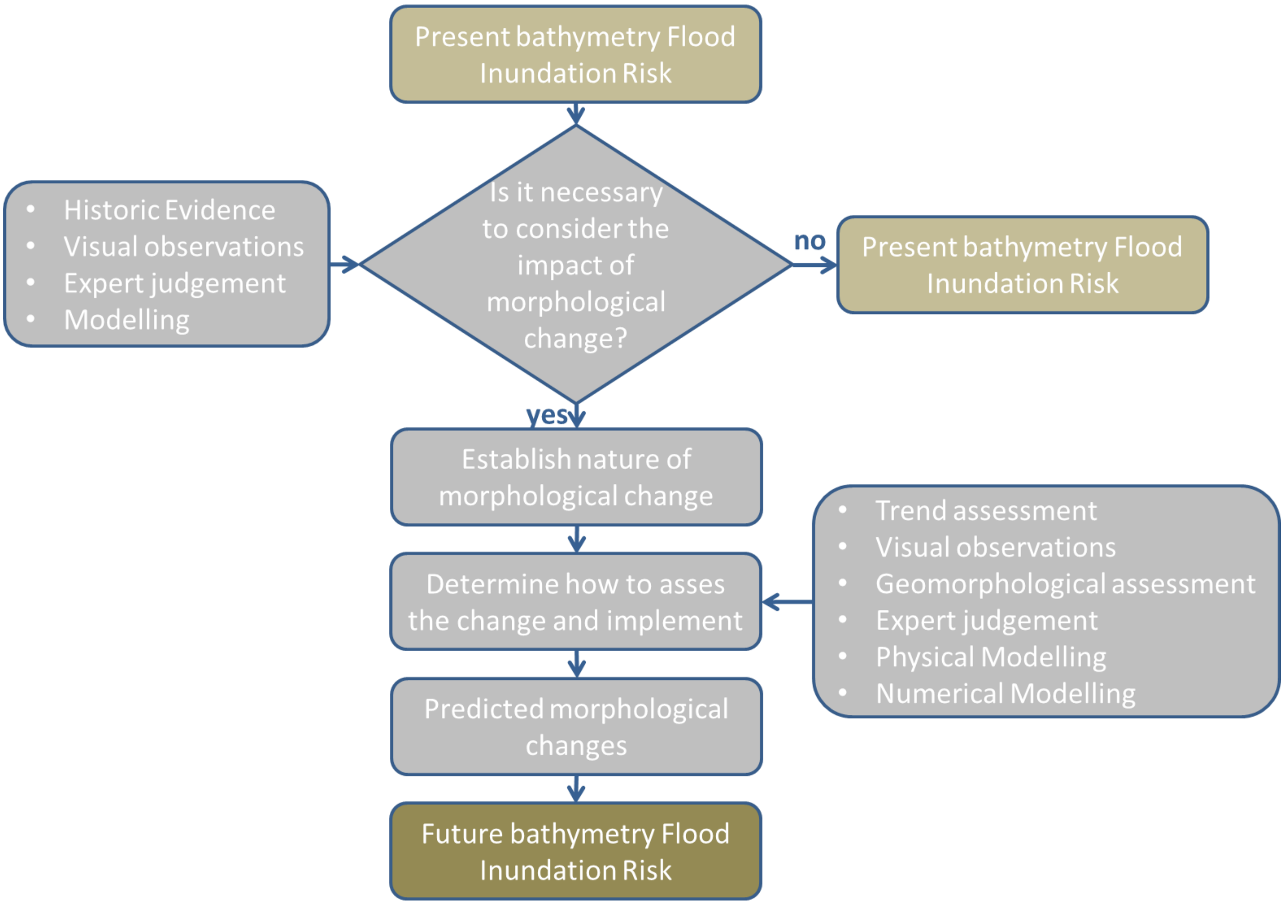

Figure 5.4 Framework for assessing the impacts of morphological changes on flood risk

Notes: Modified from Reeve (2007).

Examples of the outcomes of 2 studies that have investigated the impact of morphological change on flood risk are provided in Boxes 5.3 and 5.4.

Box 5.3: Tyndall Centre cliff erosion and flood risk study

The Tyndall Centre for Climate Change Research developed an integrated assessment of flood and erosion risk by linking the results of a SCAPE model of coastal erosion to a flood risk assessment model. This study demonstrated the role of sediments released from cliff erosion in protecting neighbouring low-lying land from flooding. The following conclusions were drawn from the study.

- Analysis of climate risks and long-term coastal management may need to be implemented at a broader scale that accounts for morphological interdependence.
- The main drivers for flood risk over the 21st century (in the study area) are a combination of:
  - rising sea levels
  - local- and broad-scale natural and anthropogenically driven morphological change that may lower or raise beach levels
  - changes in exposure to flooding (and erosion) due to socioeconomic change
- A rapidly increasing sensitivity to sea level is predicted for rates of mean sea level rise greater than about 4.5 mm per year.
- Over the 21st century, significant benefits in terms of mitigating flood risk could potentially be obtained by allowing previously defended cliffs to erode naturally. These benefits are greatest under high sea level rise scenarios.
- Given the uncertainties involved, adaptive strategies were recommended.

Source: Dawson et al. (2007)

Box 5.4: Using iCOASST pilot study model outputs to investigate the potential impact of long-term morphological change on flood risk at the iCOASST Suffolk coast pilot site

This investigation was undertaken to evaluate whether, by using pilot study model outputs from the iCOASST project as inputs to the State of the Nation flood risk models, an improved assessment of future flood risk (taking account of long-term coastal morphological change, including change resulting from management interventions) could be achieved. Figures 5.5 to 5.7 show the change in annual probability of inundation through time for different modelled scenarios. The following conclusions were drawn from the study.

- For the Suffolk coast pilot site, the change in flood hazard through time (represented as annual probability of inundation) was dominated by sea level rise (specifically where this was >4.5 mm per year) and that any influence of morphological change driven by that sea level rise was limited.
- For the Suffolk coast pilot site, managed realignment in the estuary provided significant mitigation to increasing flood hazard resulting from sea level rise across the entire study site. This demonstrates the strong influence of estuarine water levels on flood inundation behind defences along this stretch of coastline.
- It would be reasonable to assume that different conclusions could arise should the same analysis be conducted at different sites. In particular sites with different exposure, wave climate and topography, and defence asset characteristics may

yield significantly different results.

- The complexity and uncertainties associated with morphological modelling demonstrated in this study point to the need for a pragmatic approach whereby appropriate sensitivity testing of flood hazard to shoreline evolution is conducted before embarking on more complex studies.

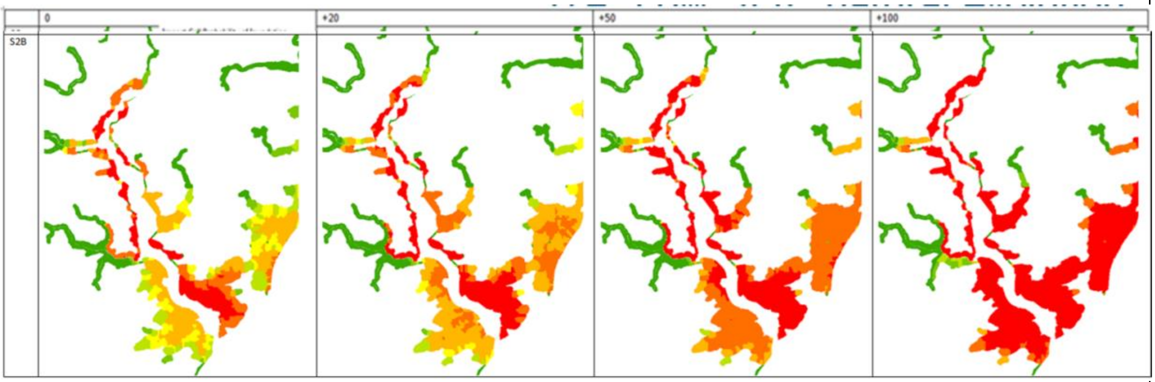

Figure 5.5 Annual probability of inundation through time (Scenario Baseline B – no morphological change, medium rate of sea level rise)

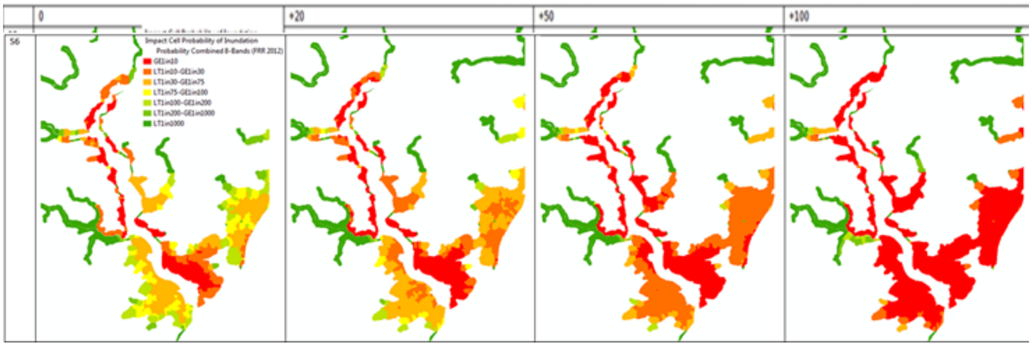

Figure 5.6 Annual probability of inundation through time (Scenario S6 – full morphological change in response to sea level rise, medium rate of sea level rise)

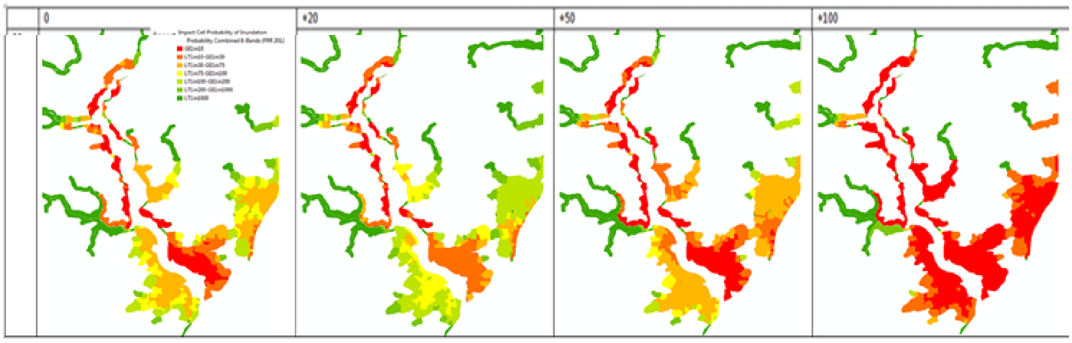

Figure 5.7 Annual probability of inundation through time (Scenario S7 – full morphological change in response to coastal management interventions and sea level rise, medium rate of sea level rise)

Source: Environment Agency

6 Using morphological modelling to help set performance indicators and thresholds

Coastal State Indicators (CSIs) are performance indicators of coastal morphological behaviour (for example, the position of the high water line) that can be monitored. This chapter describes what these indicators are, how modelling can support their selection and use in coastal management, how modelling can help identify critical or trigger thresholds, and how CSIs may be visualised and levels of associated uncertainty evaluated.

Chapter contents

6.1 Introduction

Coastal features such as beaches perform a number of important functions with respect to coastal management and FCERM. The Beach Management Manual (CIRIA 2010) introduces the importance of monitoring and performance assessment of beaches as part of the beach management cycle. The manual identifies a range of functions of the beach and suggests the establishment of performance indicators and the corresponding thresholds or triggers beyond which these functions can be compromised.

Every beach is subject to specific morphology and processes, and so performance assessment may be a complex task. The guidance for beach triggers (Environment Agency 2018b) supplements the Beach Management Manual by providing a framework to make this process more accessible, with a step-by-step methodology and sketches that illustrate the background concepts and science.

This chapter describes how morphological modelling can help in identifying the most appropriate performance indicators (for monitoring) and in establishing critical thresholds.

6.2 What are CSIs?

'Indicators' are parameters that can be measured (or calculated from measurements). They are used in a wide range of fields to assess changes in the state of systems and/or to review the progress of management strategies against stated objectives.

CSIs are defined as a:

> 'reduced set of parameters that can simply, adequately and quantitatively describe the dynamic state and evolutionary trends of a coastal system (that is, that can relay a complex message in a simple and useful manner)' (Jiménez and van Koningsveld 2002).

CSIs can be used to:

- assess the condition of the coastal environment
- monitor trends in conditions over time
- provide an early warning signal of important or critical changes in the coastal environment
- help diagnose the cause of an environmental problem
- anticipate future conditions and trends
- help inform timely management interventions (that is, anticipate and respond to problems before they emerge)

CSIs can therefore be used as a proxy for a larger suite of measurements or modelling outputs, potentially assisting coastal managers in:

- short-term decision-making
- long-term policy implementation
- assessing how effective an implementation/strategy has been (that is, performance evaluation)

CSIs can be used to support a wide range of functions at the coast including:

- ecological management
- health and safety risk management
- flood and erosion risk management

Indicator monitoring and evaluation can be a core part of planning and measuring the performance of coastal management and adaptation programmes in terms of the relevance, effectiveness, efficiency and sustainability of outcomes. They can help to determine whether specific objectives have been achieved, or if a threshold or trigger for action has been reached. Their application specifically to FCERM is described in Section 6.4. A range of existing CSI applications are described in Payo et al. (2018).

6.3 How are CSIs selected?

The selection of CSIs is dependent on:

- the policy or aim to be achieved (for example, manage the rate of beach erosion or maintain a minimum standard of coastal protection from flood risk)

- the monitored or modelled data that can be collected or accessed
- the coastal processes operating in the area of interest

CSIs can be established to monitor and evaluate processes occurring over different timescales. They can be linked to their impact on different outcomes (for example, recreation, biodiversity, flood risk management). For example, in the Costa Brava in Spain, the selected CSI was beach width, defining its value at 100m intervals along the beach. The minimum acceptable beach width (prior to management actions being triggered) was defined based on 2 tactical objectives (Valdemoro and Jiménez 2006):

- maintaining public safety during storm events (mainly in the winter)
- providing a minimum summer width for recreation

Key characteristics of CSIs are set out in Box 6.1.

Box 6.1: Key CSI characteristics

CSIs should be:

- relevant for understanding the problem/process
- measurable taking account of repeatability, necessary precision and available resources
- responsive to disturbances/stresses in ways that are understood and predictable
- indicative of future changes in the system
- timely that is, time sensitive to change
- cost-effective at the desired frequency of evaluation
- integrative combining measured data and process knowledge to assist in implementing a policy most efficiently
- understandable and communicable

Two different types of CSI can be adopted, depending on the timescales associated with the coastal change at the site, and the management drivers and needs:

- **Long-term CSIs (LT-CSIs)**. These are focused on risk management at decadal to centuries timescales, and tend to be driven by model predictions. Changes from desired paths of LT-CSIs may trigger re-evaluation of the management philosophy (for example, hold the line, managed realignment, withdraw intervention, land use planning).
- **Short-term CSIs (ST-CSIs)**. These are mostly used to guide day-to-day coastal management at a given location, and usually depend on the analysis of monitored data and extrapolation techniques. Changes from the desired status of ST-CSIs may trigger localised human interventions (for example, beach nourishment, seawall construction, reinforcement).

CSIs are often selected in a negotiation between stakeholders in a three-step process:

1. **Define the 'coastal problem'**. Stakeholders involved in actively managing the local coast present 'problem-driven' coastal management issues and identify a set of relevant provisional CSIs from this perspective.

2. **Define the 'scientific problem'**. Stakeholders with more detailed knowledge (including conceptual and/or process models) present their 'process-based' view of the system (the conceptual model – see Section 3.4) and identify a set of interesting and feasible provisional CSIs (related to the problem) from a more scientific perspective.
3. **'Integration'**. The 2 sets of provisional CSIs are integrated into a single optimised set of operational CSIs, the monitoring of which is most likely to deliver maximum benefits to decision-making.

A CSI is considered appropriate only if stakeholders can readily understand and use it in relation to their problem. Stakeholders need to agree the acceptable resolution (spatial and temporal), accuracy and critical threshold values.

Spatial and temporal resolution is understood as the minimum distance between consecutive CSIs in space and time respectively. CSIs are understood as proxies for the actual quantity of interest and therefore CSIs measured below certain minimum levels of accuracy might be of little use. For example, when assessing long-term changes in cliff position where the cliff is eroding at a rate of 1m per year, the uncertainty associated with a historic map may not be important; in contrast, when assessing the short-term evolution of a granite cliff, even terrestrial laser scanner surveys may not be sufficient to measure cliff retreat accurately.

6.4 Using CSIs in coastal management

CSIs (and associated trigger thresholds, which are used to determine when a particular threshold is met and are discussed in Section 6.5) can be used to support and improve the coastal management process for end users. They can be used to help structure:

- the system of establishing and reviewing both short-term and long-term objectives for the site
- the monitoring and data collection strategy at the site
- the integration of modelling outputs with decision-making
- the definition and evaluation of short-term and long-term coastal management strategies

The flow chart presented in Figure 6.1 shows how CSIs can be used in a simplified coastal management procedure.

The strategic objective may, for example, be 'sustainable risk management' of the coast. The operational objective would then be to 'hold the line'. The selected CSIs may be beach volume/beach width/dune toe position and a short-term action may be to nourish, recycle or re-profile at specific points.

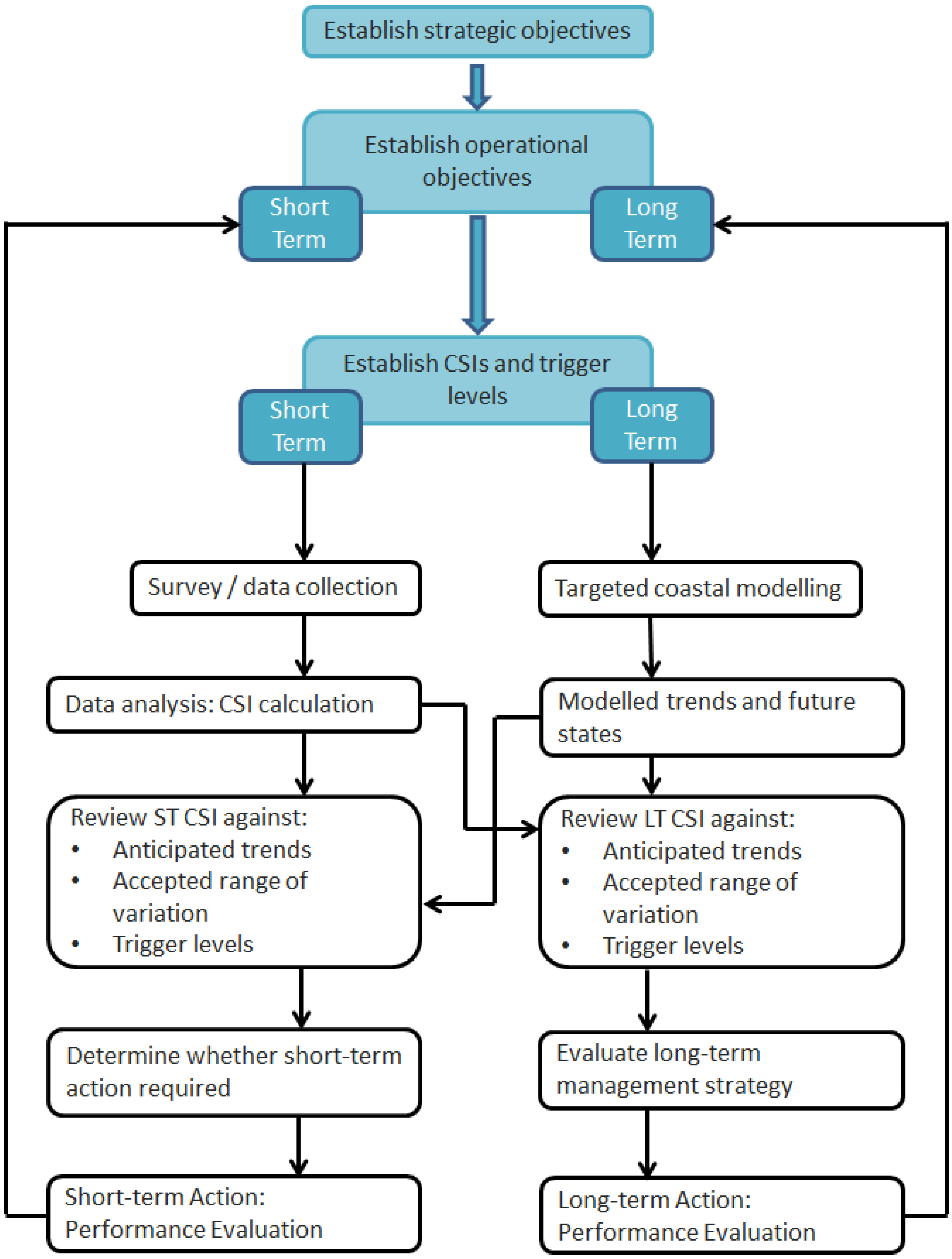

Figure 6.1 Simplified coastal management procedure with the use of CSIs

FCERM CSIs are often framed within the source–pathway–receptor or similar risk analysis framework (see, for example, Sayers et al. 2002, Zanuttigh 2011). Coastal geomorphology is a crucial component, representing the pathway that modifies the severity of marine hazards such as surges and extreme waves as they are experienced by 'receptors' on the coast. Coastal geomorphology is subject to change at all scales and hence affects flood/erosion consequences and risks. However, it is relatively unusual to see any long-term changes in geomorphology represented in these flood risk frameworks (see Section 5.9).

Systematic, frequent and broad-scale monitoring of coastal morphology change is therefore a fundamental planning task. Merging monitoring with coastal simulation knowledge can support analysis of how selected CSIs might evolve in the future and potentially allow responses to problems before they emerge.

The iCOASST project collected a list of potentially valuable coastal FCERM CSIs and defined them according to whether they were associated with a source–pathway–receptor framework element. These CSIs are listed in Table 6.1. However, only a small subset of those listed will be relevant to decision-making at any individual site.

Table 6.1 Examples of CSIs characterised using their risk framework element

Type	CSI description
S	Relative sea level rise (subsidence + sea level rise)
S	Highest water level (wave, surge, tide)
S	River sediment supply
S	Number of stormy days
S	Duration of storms
S	Change of temperature/evaporation
S	Change of precipitation (mm per year) or river discharge (m^3 per second)
S	Number of floods or flooding days per year
S	Number of droughts or drought days per year/% of delta with salinity problems
S	Frequency of storms (storm surge)/frequency of extreme river discharge, flood hazard
S	River discharge (peak/low and variability)
P	Shoreline evolution trend status (stable, eroding, accreting)
P	Vertical elevation relative to mean sea level
P	Geological coastal type (likely erodible versus non-likely erodible)
P	Areas of high ecological value within flood and coastal erosion risk areas (biodiversity index)
P	Length of defended coastline and % of coastal defence at target condition grade
P	Area and volume of sand nourishment
P	Dune strength
P	Barrier width
P	Total barrier volume
P	Backshore width
P	Dune zone width
P	Dune zone height
P	Beach width
P	Barrier crest position
P	Shoreline position
P	Intertidal habitat area including mudflat and saltmarsh

Type	CSI description
R	Coastal land use change
R	Coastal development
R	Coastal population
R	% area vulnerable for flooding/number of vulnerable people/value of vulnerable assets

Notes: S = source; P = pathway; R = receptor
Adapted for the UK from Payo et al. (2018, Table 11)

A suite of long-term indicators developed for the Thames Estuary 2100 project are described in Box 6.2.

Box 6.2: Thames Estuary 2100 (TE2100) project

The TE2100 project created a long-term flood risk management strategy for London and the tidal Thames. The project looked at the impacts of sea level rise and the need to adapt the Thames estuary flood defences to a changing climate. Since the TE2100 Plan has to be adaptable and remain fit for purpose throughout its 100-year life, 10 key indicators were identified – changes to which will suggest changes to flood risk. These indicators are:

- mean sea level
- peak surge tide level
- peak fluvial flood flows
- condition of estuary flood defences
- frequency of closure of the Thames Barrier (and other barriers)
- developed area and value of property at risk
- extent of erosional/depositional areas in the estuary
- intertidal habitat areas (including mudflats and salt marsh)
- land use planning and development activities
- public/institutional attitudes to flood risk

These indicators are therefore ‘triggers for change’ and will be monitored throughout the life of the TE2100 Plan. The outputs from this monitoring programme will inform the regular reviews and reappraisal of the Plan. Importantly, they will also trigger action if rapid change occurs in any of the indicators.

Source: adapted from Payo et al. (2018)

6.5 Trigger thresholds

6.5.1 Definition of trigger thresholds

Relative changes in CSIs provide potentially useful information about trends in coastal change. To be used as prompts for management interventions, however, trigger levels need to be defined.

Trigger thresholds are used to determine when a particular criterion is met and there has been a specific level of irreversible change. Trigger levels usually identify when the ongoing management activities are no longer achieving their intended objectives and further action is required. Triggers should be set at levels that allow sufficient time for the appropriate planning, stakeholder engagement and funding to be achieved for the next action in the management plan. Depending on the nature of the plan, trigger indicators can be physical, social or biophysical in nature.

Trigger thresholds should be developed in conjunction with stakeholders to ensure that they are accepted and understood, and reflect local knowledge. Working with stakeholders can help to ensure that triggers consider social impacts in addition to just physical and biophysical impacts (Barnett et al. 2014).

Typically, 2 trigger levels are defined: an alarm level and a crisis level. These are defined in Box 6.3.

Box 6.3: Definition of alarm and crisis levels

In simple terms, trigger values represent a value of a particular beach parameter (say average beach level) beyond which some form of intervention is required.

Alarm or action level/threshold

This is the level before crisis level/threshold. This is usually a predetermined value where the monitored beach parameter falls to within range of the crisis level, but has not resulted in systematic failure of the function being monitored. An example would be recession of a beach crest eroding to within 10 m of an asset where it has been predetermined that an extreme storm event could result in recession of 5m. The alarm level in this example is therefore a 5m buffer.

Increased monitoring would be required when an alarm level is compromised and intervention undertaken if deemed necessary. Managing alarm levels can be planned in advance.

Crisis or emergency level/threshold

This is the level at which the function being monitored, such as the stability of the beach and/or any backing structures (seawall/promenade), could be compromised and emergency remedial action becomes necessary. For example, as in the case described above, the beach crest recedes to within 4m of an asset that requires protection, where it has been predetermined that an extreme event could result in 5m of recession.

Source: CIRIA (2010)

6.5.2 Framework for determining trigger values

The guide on triggers for beach management (Environment Agency 2018b) sets out a three-step process of determining trigger values (Figure 6.2). This process assumes that the beach type and the functions of the beach with regard to flood risk management have been confirmed, before determining the actual trigger thresholds and developing a response plan.

Three types of beach are considered in the guide on triggers for beach management:

- beach with a structure behind
- beach with a cliff behind
- standalone barrier beach

The guidance does not include triggers for supporting structures such as groynes and other physical features. Although these can significantly influence the characteristics of the beach, active management of groynes may enable the beach to be led towards a preferred geometry. Groynes, similar to other management initiatives such as beach renourishment, offshore breakwaters and so on, are a way in which beach levels, volumes or other measurable parameters can be managed to remain within trigger values as part of a range of management methods. The choice of intervention type was beyond the scope of the guidance.

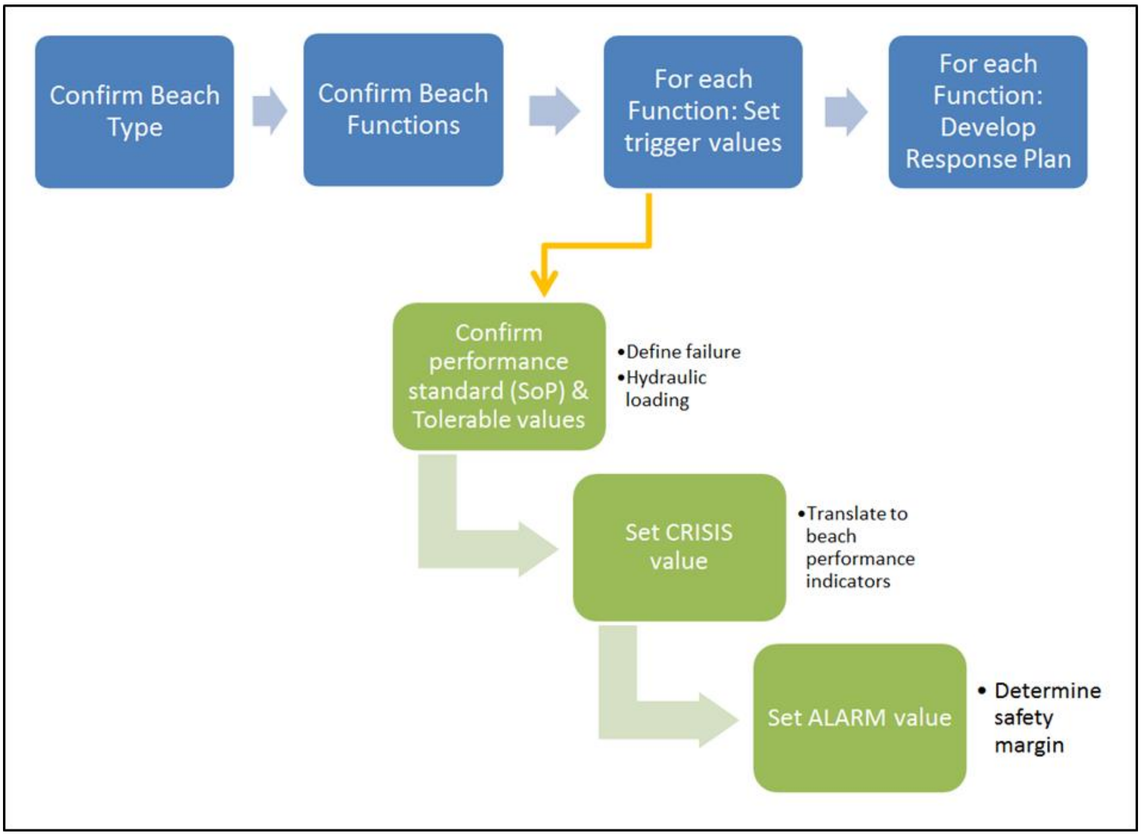

Figure 6.2 Stepwise process of determining triggers

Source: Environment Agency (2018b, Figure 2.1)

6.5.3 Determining trigger values

Trigger levels can be defined in several ways. The guidance for beach triggers (Environment Agency 2018b) describes the process of setting trigger thresholds for a pre-planned approach for the 3 types of beaches defined.

Establishing a limiting system state (for example, beach width, building setback width and so on) beyond which is considered unacceptable from a policy perspective

A minimum beach width may be specified based on a beach width in a particular year that was considered to be acceptable, or a functional width that is required (for example, for amenity, biodiversity or safety reasons). A stated setback line is normally defined as the required distance of a building from a spatial limit or feature. A setback line for the coastal zone is therefore determined by a buffer applied to the coastline, with the required width of this buffer depending on environmental and socioeconomic criteria. The monitored indicator will be the actual buffer width and any established trigger point will need to take account of the time required to implement appropriate management actions.

Establishing a level of variance from, for example, an average measured value that is considered acceptable (taking into account the historic observed variability, and the risk associated with that variability)

Where CSI values vary around some sort of average value, a simple and effective way of defining trigger values for CSIs (mainly short-term) is by evaluating the mean and standard deviation (σ) of the data, and using these to establish a number of different ranges. Given a CSI (for example, beach volume or beach width), the temporal variation of the CSI value is plotted based on available survey data, together with the calculated mean and different ranges of mean ± a value of standard deviation. This figure would immediately show the variability of the CSI. The mean and standard deviation ranges can be mean ± σ, mean ± 2σ, mean ± 3σ, as shown in Figure 6.3.

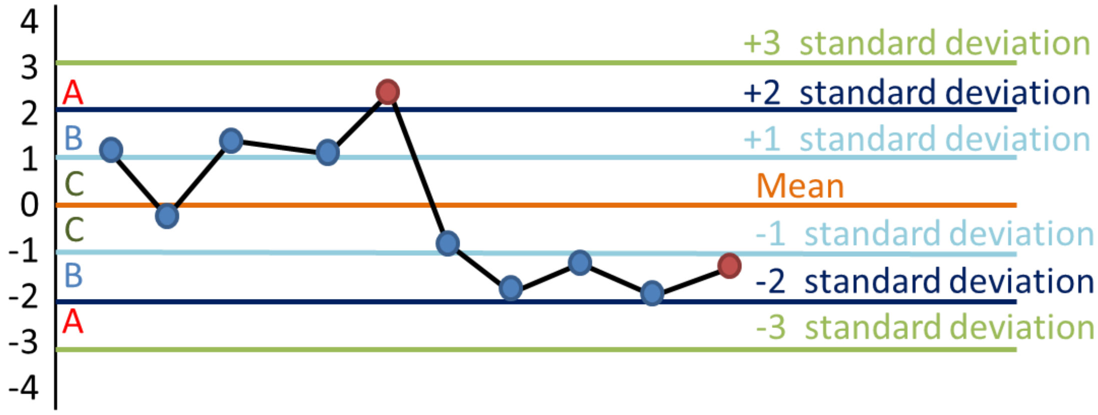

Figure 6.3 Schematic representation of time evolution for a CSI value and when a trigger (red dot) would be achieved

Trigger situations can then be defined depending on potential future values of the CSI, for example, when:

- any point goes beyond Zone A (mean ± 3σ)
- 2 out of 3 consecutive points fall within Zone A (mean ± 3σ) or beyond
- 4 out of 5 consecutive points fall within Zone B (mean ± 2σ)or beyond
- 8 consecutive points on the same side of the mean – this would indicate that the mean needs to be recalculated

In Figure 6.3, the trigger (the second red dot) is achieved after 4 consecutive measurements of the CSI falling within Zone B.

Using calculations, numerical or conceptual modelling to establish the link between the indicator and a level of risk – a threshold can then be set in order to manage risk to acceptable levels

An example may be the definition (via modelling) of a minimum beach width below which the risk of inundation of properties inland increases significantly (for example, width B in Figure 6.4). Monitoring indicates a temporal variation in beach width (W). A combination of the trend in W, together with modelled trends and the necessary lead in time for planning and implementing beach nourishment, allows a likely time before intervention planning may be triggered. This would be reviewed in the intervening years while further monitoring takes place.

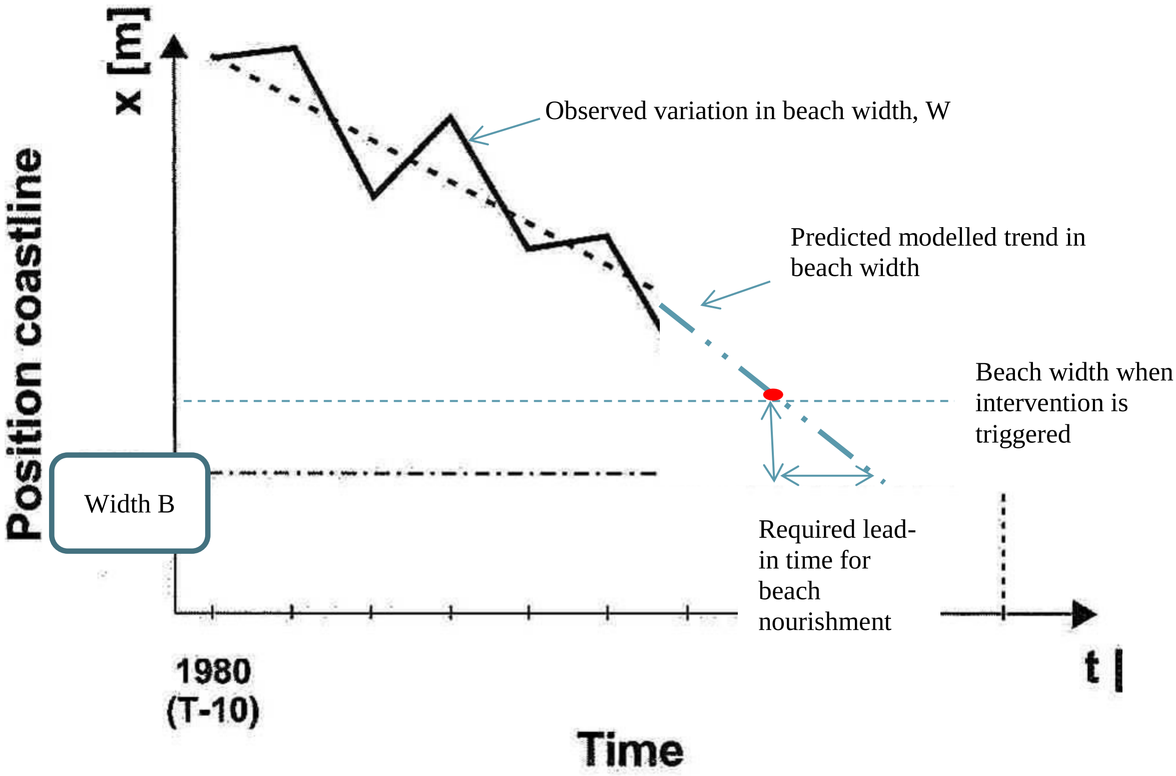

Figure 6.4 Use of a combination of monitored and modelled data to set a management intervention trigger point in order to manage risk to acceptable levels

6.6 Visualising CSIs, thresholds and uncertainty

Good quality data interpretation tools and graphical output are essential for effective support for beach managers and effective stakeholder engagement. It is important to condense large quantities of information into a format that can be readily digested and understood.

The guidance for beach triggers (Environment Agency 2018b) summarises current and historic beach levels for a single beach profile in the context of alarm and crisis triggers (Figure 6.5). By summarising information in this way, an entire coastal frontage can be presented and evaluated within a single graph (Figure 6.6). This output allows problem areas to be easily identified, assisting with the prioritisation of interventions.

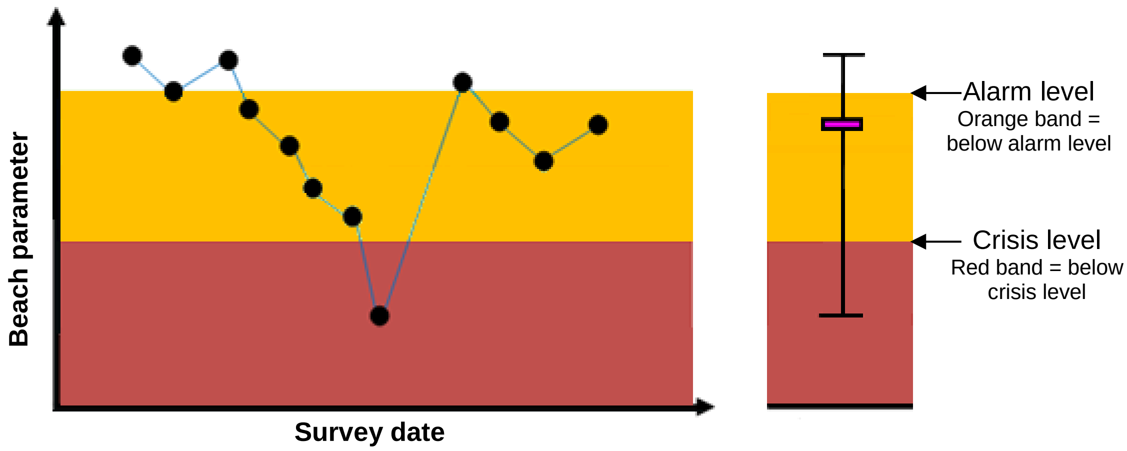

Figure 6.5 Example presentation of a beach parameter (for example beach level or cross-sectional area) in the context of alarm and crisis triggers

Notes: In this example, the beach parameter used for setting beach triggers is summarised as a pink bar showing current state. Black bars show the historic high and low (right).
Source: Environment Agency (2018b, Figure 4.3)

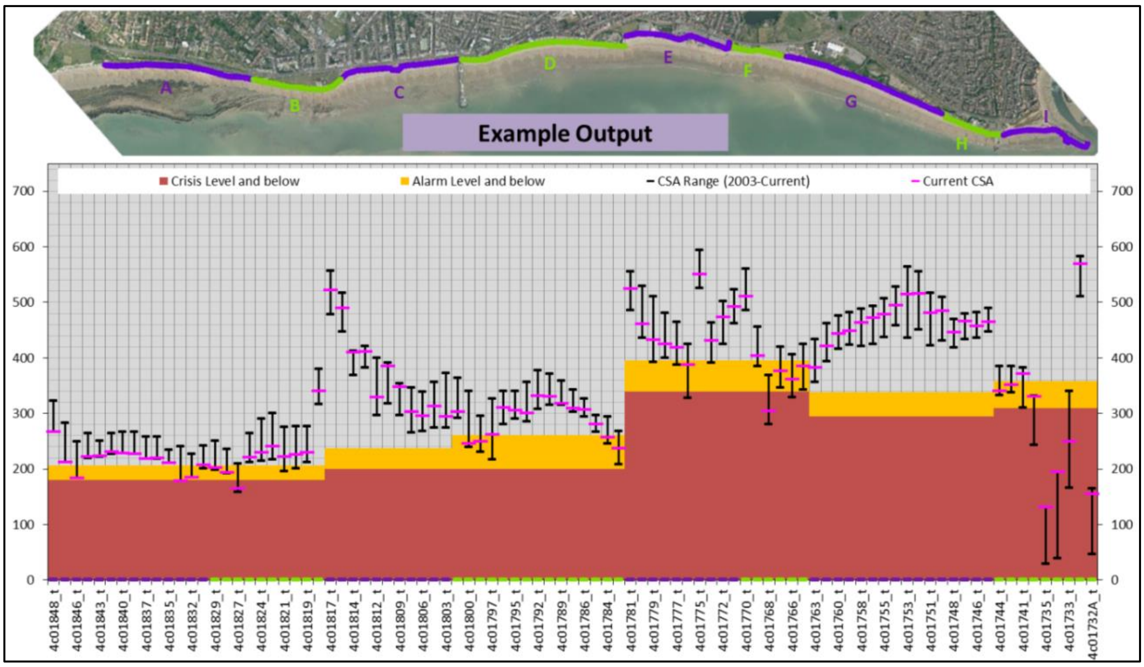

Figure 6.6 Recommended output which maps trigger level against current and historic beach cross-sectional areas (using data from the Regional Coastal Monitoring Programme)

Source: Environment Agency (2018b, Figure 4.4)

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List of abbreviations

2DH	two-dimensional spatially averaged over water depth (hence ‘H’ for horizontal plane)
AEP	annual exceedance probability
ANN	artificial neural network
CCA	canonical correlation analysis
CERC	Coastal Engineering Research Center [US Army Corps of Engineers]
CESM	Coastal and Estuarine System Mapping
CoaEST	Coastal and Estuarine Systems Tools
CoastalME	Coastal Modelling Environment
CONSCIENCE	CONcepts and Science for Coastal Erosion Management
CSI	Coastal State Indicator
DEM	digital elevation model
DTM	digital terrain model
EOF	empirical orthogonal function analysis
FCERM	flood and coastal erosion risk management
GIS	geographical information system
GPL	General Public License
HTA	historical trend analysis
iCOASST	Integrating Coastal Sediment Systems
LIDAR	light detection and ranging
LT-CSI	Long-term Coastal State Indicator
NERC	Natural Environment Research Council
OpenMI	Open Modelling Interface
PBSE	parabolic shape equation
PCA	principal component analysis
Q3D	quasi three-dimensional
SBA	Sediment Budget Analysis
SCOPAC	Standing Conference on Problems Associated with the Coastline
SMP	Shoreline Management Plan
ST-CSI	Short-term Coastal State Indicator

Glossary

Accretion	Accumulation of sediment due to the natural action of waves, currents and wind
Aeolian transport	The erosion, transport and deposition of material due to the action of wind at or near the Earth's surface
Alarm level/threshold	The level before crisis level/threshold. This is usually a predetermined value where the monitored beach parameter falls to within range of the crisis level, but has not resulted in systematic failure of the function being monitored, for example, recession of a beach crest eroding to within 10m of an asset, where it has been predetermined that an extreme storm event could result in recession of 5m. The alarm level in this example is therefore a 5m buffer. Increased monitoring would be required when an alarm level is compromised and intervention undertaken if deemed necessary. Managing alarm levels can be planned in advance.
Along-shore	Direction parallel to the shore
Backshore	The upper part of the active beach above high water extending to the limit of the beach
Barrier beach	A sand or shingle bar above high tide, parallel to the coastline and separated from it by a lagoon
Baseline	Condition that would prevail if no actions were taken or forcing mechanisms changed
Beach	A deposit of non-cohesive material (for example, sand, gravel) situated on the interface between dry land and the sea (or other large expanse of water) and actively 'worked' by present day hydrodynamic processes (that is, waves, tides and currents) and sometimes by winds
Beach management	The process of managing a beach, whether by monitoring, simple intervention, recycling, recharge, the construction or maintenance of beach control structures or by some combination of these techniques in a way that reflects an acceptable compromise in the light of available finance, between the various coastal defence, nature conservation, public amenity and industrial objectives
Beach Management Plan (BMP)	A BMP takes into account the prevailing coastal processes and provides a basis for the management of a beach primarily for coastal defence purposes, but while recognising the other uses of the beach.
Beach planshape	The horizontal alignment of the beach; usually shown as a contour line, combination of contour lines or recognisable features such as beach crest and/or the still water line
Beach profile	Cross-section perpendicular to the shoreline. The profile

	can extend seawards from any selected point on the landward side or top of the beach into the nearshore.
Beach recharge (nourishment)	Artificial process of replenishing a beach with material from another source
Beach recycling	Process by which sediment is collected from one part of a beach and deposited further 'updrift'
Beach re-profiling	Shaping the beach profile to have a desired crest height, width and slope
Berm	A ridge located to the rear of a beach, just above mean high water. It is marked by a break of slope at the seaward edge.
Bimodal wave period	Related to frequency distribution of waves – for each bimodal wave periods, 2 wave peaks are observed.
Breaching	Failure of the beach crest or other coastal protection structure allowing flooding of the hinterland by tidal action
Breakwater	A structure projecting into the sea that shelters vessels from waves and currents, prevents siltation of navigation channel, protects a shore area or prevents thermal mixing (for example, cooling water intakes). In beach management, breakwaters are generally structures protecting areas from the full effect of breaking waves. Breakwaters may be shore attached and extended seawards from the beach, or may be detached and sited offshore, generally parallel to the beach, to provide sheltered conditions.
Bypassing	Mechanical collection of beach sediment from one area where it has accumulated and redistribution of it to another where beach widths have reduced
Cliff	Vertical, or nearly vertical, rock or sediment exposure. Cliffs are formed as erosion landforms by the processes of weathering and erosion. Cliffs are common on coasts, in mountainous areas, escarpments and along rivers.
Climate change	This term as commonly used implies long-term changes rather than short-term changes in climate. Furthermore, the term is generally used for changes resulting from human intervention in atmospheric processes through, for example, the release of greenhouse gases to the atmosphere from burning fossil fuels, the results of which may lead to increased rainfall and sea level rise.
Climate model	Climate models are based on well-documented physical processes to simulate the transfer of energy and materials through the climate system including atmosphere, oceans, land surface and ice.
Climate-related changes	Variation of climate, not necessarily due to human intervention
Coastal cell	Coastline unit within which sediment movement is self-

	contained.
Coastal flood risk models	Models that assess the risk of flooding by determining the likelihood and magnitude of extreme events (assessed through the transformation of offshore conditions) combined with an assessment of the consequences of flooding associated with those events
Coastal morphological models	Models that predict the evolution of beaches and/or the nearshore bed
Coastal State Indicator (CSI)	Reduced set of parameters that can simply, adequately and quantitatively describe the dynamic state and evolutionary trends of a coastal system
Cohesive sediment	Sediment containing significant proportion of clays, the electromagnetic properties of which cause the sediment to bind together
Conceptual model	Representation of a system using general descriptive rules, concepts and relationships
Continental shelf model	Numerical model covering a given area of continental shelf (for example, North-west European, Scottish) to simulate the forcing conditions, including meteorological and tidal forcings
Coupled models	Combination of models together so that data are transferred from one to another, or exchanged in some way
Crest	Highest point on a beach face, breakwater or seawall
Crest level/height	Vertical level of the beach relative to metres Ordnance Datum (mOD)
Crisis level/threshold	The level at which the function being monitored such as the stability of the beach and/or any backing structures (seawall/promenade) could be compromised and emergency remedial action becomes necessary, for example, as in the case described under alarm level/threshold above, the beach crest recedes to within 4m of an asset that requires protection, where it has been predetermined that an extreme event could result in 5m of recession.
Cross-shore transport	Movement of material perpendicular to the shore
Depth of closure	The ‘seaward limit of significant depth change’ – it does not refer to an absolute boundary across which there is no cross-shore sediment transport
Downscaling	Procedure to infer high-resolution information from low-resolution variables
Drift	Sediment transport in the direction along the coastline Also referred as longshore drift or littoral drift
Drift-aligned	A coastline that is oriented obliquely to prevailing incident wave fronts

Drift reversal	A switch of an indigenous direction of littoral transport
Dune	Ridges, mounds and depressions of loose sand built by Aeolian processes (wind) or the flow of water
Dynamic linking	Linkage of models such that they exchange data in computer memory at run time with no requirement for writing into files that then need to be re-read
Engineered coastline	Coastal zones that have consciously been modified by humans from their natural state
Erosion	Wearing away of the land, usually by the action of natural forces
Estuarine models	Numerical models that represent the different elements of an estuary and simulate the morphological evolution of these elements
Estuaries	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
Forcing factors (coastal forcing)	The natural processes that activate coastal hydrodynamics and morphodynamics (for example, winds, waves, tides)
Forecast	Prediction or estimation of a future event or trend
Foreshore	Part of the shore/beach, which is wet due to the varying tide and wave run-up under normal conditions
Fully data-oriented model	Sophisticated statistical methods that rely solely on the analysis of historic measurements, without prior knowledge of physical processes.
Fully process-oriented model	Numerical models that are based on physical laws with the aim of reproducing changes in bathymetry via temporal and spatial integration
Geomorphology/ morphology	The branch of physical geography/geology which deals with the form of the Earth, the general configuration of its surface, the distribution of the land, water and so on
Groyne	Narrow, roughly shore-perpendicular structure built to reduce longshore currents and/or to trap and retain beach material. Most groynes are of timber or rock, and extend from a seawall, or the backshore, well onto the foreshore and rarely even further offshore.
Hard defence	General term applied to impermeable coastal defence structures of concrete, timber, steel, masonry and so on which reflect a high proportion of incident wave energy
Joint probability	The probability of ≥2 conditions occurring together
Linked models	Combination of models together so that data are transferred from one to another, or exchanged in some way
Littoral drift	Sediment transport in the direction along the coastline Also referred as longshore drift or drift

Longshore transport	Movement of material parallel to the shore – also referred to as longshore drift.
Long term	Occurring over or relating to a long period of time (months to decades)
Managed realignment	A policy decision to allow the shoreline to move backwards or forwards, with management to control or limit movement (such as reducing erosion or building new defences on the landward side of the original defences)
Mean high water	The average of all high waters observed over a sufficiently long period
Mean low water	The average of all low waters observed over a sufficiently long period
Mean sea level	Average height of the sea surface over a 19-year period
Mixed beach	Continuum where a diverse range of different beaches can be found, with different along-shore, across-shore, in depth and in time variation of the sediment sizes present on it
Model	Graphical, mathematical (symbolic), physical or verbal representation or simplified version of a concept, phenomenon, relationship, structure, system or an aspect of the real world
Model calibration	Process of making changes to a model to improve the fit with observed data
Model run	Term used for one complete calculation of a given model
Model validation	Process of testing a model to see if it can simulate other sets of observations not previously used for calibration to confirm that the model is likely to have some predictive ability
Monte Carlo	Computational algorithm that relies on repeated random sampling to obtain numerical results
Multivariate analysis	Involves the study of more than one variable at a time, taking into account their dependencies
Nearshore	The zone that extends from the swash zone to the position marking the start of the offshore zone, typically to water depths of about 20m
Nearshore model (system)	Model (or system of models) used to determine the time-varying water levels and wave conditions at the coastal boundary of a morphological model
Nested models	Combination of the same type of models to cover a broad area at different resolutions and sub-area coverings, exchanging results among them
Non-cohesive sediment	This term covers sediments from fine sands to gravels and boulders.
Non-engineered coastline	Coastal zones that have not been modified by humans

	from their natural state
Numerical modelling	Mathematical model that uses some sort of numerical time-stepping procedure to obtain the model behaviour over time
Offshore	The zone beyond the nearshore zone where sediment motion induced by waves alone effectively ceases and where the influence of the seabed on wave action has become small in comparison with the effect of wind
Offshore breakwater	Structure built parallel or nearly parallel to the shore. Some are part of a harbour. These structures have similar effects to rocky islands or outcrops on the nearshore seabed.
Offshore model (system)	Model (or system of models), typically a large-scale regional model used to predict forcing conditions over large areas
Overtopping	Water carried over the top of a coastal defence due to wave run-up exceeding the crest height
Overwash	The effect of waves overtopping a coastal defence, often carrying sediment landwards which is then lost to the beach system
Particle size distribution	Distribution defining the relative amount, typically by mass, of particles present according to their size
Permeability	Measure of the ability of a porous material (for example a rock or an unconsolidated material) to allow fluids to pass through it
Physical model	Scaled 2D or 3D copy of an object. In coastal and estuarine engineering, the models are always smaller and they are created to allow the investigation of coastal/ estuarine processes.
Pocket beach	A beach, usually small, between 2 fixed headlands
Reef	A ridge of rock or other material lying just below the surface of the sea
Return period	A statistical measurement denoting the average probability of occurrence of a given event over time
Revetment	A sloping surface of stone, concrete or other material used to protect an embankment, natural coast or shoreline against erosion
Rock armour	Wide-graded quarry stone normally bulk-placed as a protective layer to prevent erosion of the seabed and or other slopes by current and/or wave action
Sand beach	Beach with sediment particles, mainly quartz, with a diameter of between 0.062mm and 2mm
Scenario evaluation	Possible consequences of proposed management developments in system are assessed and compared with the baseline condition.

Scour	Removal of underwater material by waves or currents, especially at the toe of a shore protection structure
Sea level rise	The rise of sea levels throughout time in response to global climate and local tectonic changes
Seawall	Structure built along the shore to prevent erosion and damage by wave action
Sediment	Particulate matter derived from rock, minerals or bioclastic debris
Sediment transport	The movement of a mass of sedimentary material by the forces of currents and waves. This can be either perpendicular to the shoreline (cross-shore) or parallel to the shoreline (longshore).
Sediment transport model	Mathematical model that simulates sediment transport
Sediment transport rate	Mass of sedimentary material that passes across a given flow-transverse cross-section of a given flow in unit time. Sometimes the sediment transport rate is expressed in terms of weight or in terms of volume rather than in terms of mass.
Sensitivity test/analysis	Systematic testing of the model output behaviour in response to changes in the inputs, the initial conditions, model parameters and future climatic assumptions
Shingle beach	Beaches containing a majority of coarse beach material, a mixture of gravel, pebbles and larger material. In places, such beaches may also contain up to 30% of interstitial sand.
Shoaling	Wave transformation process that occurs when waves enter shallower water. The wave speed and wave length decrease in shallow water; hence the energy per unit area of the wave has to increase and so the wave height increases.
Shore platform	Horizontal or gently sloping surfaces, backed by a cliff, eroded in bedrock at the shore
Shoreface or littoral zone	The active littoral zone off the low water line; this zone extends seaward from the foreshore to some distance beyond the breaker zone.
Shoreline position	The intersection between the mean high water line and the shore. The line delineating the shoreline on nautical charts (sea maps) approximates this mean high water line.
Short term	Occurring over or relating to a short period of time (days to weeks)
Skill score	Generic term referring to the accuracy and/or degree of association of prediction to an observation or estimate of the actual value of what is being predicted
Stakeholder engagement	Process by which different people or groups become involved in decision-making and action. Such

stakeholders include both those who influence the decisions and those who are affected by them.

Static linking	Simplistic form of combining models whereby one model takes the output from another model as an input. It is mostly only one way and there is no feedback between the models as they are run independently.
Statistical model	These rely solely on the statistical analysis of measurements, without initial knowledge of physical processes to find patterns of change over space and time in selected indicators.
Still water level	The level that the sea surface would assume in the absence of wind and waves
Storm surge	A rise in the sea surface on an open coast, resulting from a storm
Structure toe level	The level of the lowest part of a structure, generally forming the transition to the underlying ground
Swash	The area onshore of the surf zone where the breaking waves are projected up the foreshore
Swash-aligned	A coastline that is oriented parallel to prevailing incident wave fronts
Tidal current	The movement of water associated with the rise and fall of the tides
Tidal range	Vertical difference in high and low water level once decoupled from the water level residuals
Tide	Periodic rising and falling of large bodies of water resulting from the gravitational attraction of the Moon and Sun acting on the rotating Earth
Trigger threshold	Value of a certain parameter when a particular criterion is met.
Uncertainty	The lack of certainty, a state of limited knowledge where it is impossible to exactly describe the existing state, a future outcome or more than one possible outcome
Univariate analysis	Used to determine extreme values from a given individual historical set of data (typically a time series) for a single variable
Vegetated marsh	Wetland that is dominated by herbaceous plant species. Marshes can often be found at the edges of lakes and streams, where they form a transition between the aquatic and terrestrial ecosystems.
Wave breaking	Reduction in wave energy and height in the surf zone due to limited water depth.
Wave chronology	This refers to the effects on the final model morphology of differences in the sequencing of input data, in which the actual sequencing is not known, but the probability distribution can be determined reasonably accurately.

Wave climate	Average condition of the waves at a given place over a period of years, as shown by height, period, direction and so on
Wave direction	Direction from which a wave approaches
Wave dissipation	Process by which the waves loses energy, for example by wave breaking or bottom friction
Wave generation	Process by which the waves are creating
Wave height	The vertical distance between the crest and the trough
Wave hindcast	In wave prediction, the retrospective forecasting of waves using measured wind information
Wave hindcasting	Modelling that is carried out retrospectively to estimate past wave conditions using measured or derived historical wind information
Wave-induced currents	The movement of water driven by breaking waves that create a current travelling in an along-shore direction
Wave period	The time it takes for 2 successive crests (or troughs) to pass a given point
Wave reflection	The part of an incident wave that is returned (reflected) seaward when a wave impinges on a beach, seawall or other reflecting surface
Wave refraction	Process by which the direction of approach of a wave changes as it moves into shallow water
Wave run-up/run-down	The upper and lower levels reached by a wave on a beach or coastal structure, relative to still water level
Wave transformation	Changes in wave characteristics during its propagation from deep to shallow water, such as shoaling, breaking and so on

Appendix A: Coastal morphological features

A.1 Beaches

A beach is defined in the first edition of the Beach Management Manual (CIRIA 1996) as:

> 'a deposit of non-cohesive material situated on the interface between dry land and the sea (or other large expanses of water) and actively 'worked' by present day hydrodynamic processes (such as waves, tides and currents) and sometimes by winds'.

All natural beaches have a variety of sizes of sediment within their surface and through their depth. Beaches can be categorised by the sediment from which they are formed so that there are 4 different types:

- sandy
- shingle
- shingle/sand mixed
- shingle upper and sand lower

These different types of beaches behave differently under the same hydraulic conditions. Discussion of non-cohesive sediment such as mud, on or in proximity to beaches, is outside the remit of this guidance (see also the discussion of estuaries in Section A.5).

Beaches normally extend from the backshore (only occasionally affected by wave action) to the seaward limit. This is given by the limit of sediment mobility under wave action, and will vary from site to site and (at a particular location) from season to season.

The shoreline may be defined as the position of a given contour, usually mean high water. By tracking the shoreline position in time, an assessment of the status of the shoreline (that is, whether it is eroding or accreting) can be obtained. This definition limits the understanding of erosion or accretion to this feature and provides no information about what may be happening elsewhere such as below this contour.

There are a number of morphological features associated with beaches. These are described below and in Figure 2.2.

A.1.1 Linear beaches

These are beaches in their simplest form, either straight or gently curving in planshape, with a seabed normally with parallel contours.

A.1.2 Pocket beaches, headlands and bays

These occur due to the geology of the area; marine action erodes the coastal land mass, removing the softer rock and leaving the less easily eroded outcrops. Bays develop between these hard features or headlands, often trapping sediment. Sediment often moves from one end of the bay to the other depending on the incident wave direction, although in smaller bays, the planshape might not change much even if the wave direction changes significantly.

A.1.3 Salients and tombolos

An island situated offshore causes wave diffraction and refraction (see Section 3.4.5) creating smaller wave heights in the lee, which causes breaking wave height gradients to transport sediment behind it. The seaward bulge is commonly known as a salient. When the sediment deposits connecting the island to the beach, this creates a tombolo.

A.1.4 Cuspate forelands or nesses

These are marked shoreline reorientation features similar to salients which are created without the offshore feature and without a full explanation of their origin. Some of these features have moved along the coast in the past, slowly, such as Dungeness or Orford Ness, whereas smaller ones like Benacre Ness seem to have moved along-shore more rapidly. These features seem to be common in areas with a strong wave direction bimodality, with opposing wave directions.

A.1.5 Spits

Sediments eroded from cliffs and transported into the sea by rivers can be worked into a variety of landforms. One such feature is a spit, which consists of a beach and associated backshore and dunes that are tied to the coast at the landward end. Spits are formed when a longshore current reaches a cove or headland, where the change in orientation is greater than 30°. 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 estuaries. The majority of these features grow in the direction of predominant longshore sediment transport. Other examples are known to align themselves almost at right angles to the prevailing wave direction during periods of abundant sediment supply.

A.2 Shore platforms

Shore platforms are horizontal or gently sloping surfaces, backed by a cliff, eroded in bedrock at the shore. These platforms can be of many different types of rock, ranging from hard to easily erodible. The 2 most common profile forms are the sloping platform (commonly 1–5° slope) and the horizontal platform. It is not unusual to find that a gently sloping rocky shore platform occupies much of the nearshore and sometimes the lower part of the intertidal foreshore as well. When shore platforms have sand or shingle on top of them, their slope is noticeably shallower than that of the overlying beach.

The size and development of beaches on shore platforms is constrained by the underlying geology, the slope of the substrate and the sediment supply.

A.3 Natural backshore features

There are a number of different types of backshore features that occupy the active beach above high water and are affected by waves occurring at high water during extreme astronomic tides and severe storm surges. These features are important because they can influence the amount of beach sediment present, as well as the behaviour of the beaches in front of them.

A.3.1 Cliffs

These are vertical or near vertical rock exposures. Direct wave action at the base of the cliffs leading to their collapse is a dramatic form of erosion. However, the processes involved in the collapse of cliffs are complex including both erosion (driven by storm seas and governed by the cycle of beach growth and loss), together with a range of other factors such as the flow of groundwater or geotechnical processes. Cliffs can be formed of hard or soft material, which will affect their rate of erosion (and thus the amount of sediment the cliffs provide to the beach) as well as the longshore drift in front of them.

A.3.2 Dunes

These are systems of ridges, mounds and depressions of loose sand created by the accumulation of wind-blown sand transported landward from the backshore and the higher portion of the intertidal foreshore. The size and shape of the dune will depend on:

- the amount of sand available from the beach
- the size of the sand particles
- the prevailing wind directions and strength

Dunes create a temporary sand store and there will be a strong relationship between the changes in beach and dune volumes and profiles.

A.4 Barrier beaches

These are narrow, low-lying strips of beach and dunes that are roughly parallel to the coastline and are separated from the mainland by a body of water (sea). The essential feature of a barrier beach is that it has a distinct crest separating the seaward beach face and a well-developed back-slope, with an area of water on their landward side (Defra 2008). The low-lying hinterland may not be permanently wet, but there would originally have been water behind the barrier beach, such as at the Pevensey levels.

There are some specific processes that contribute to the development of barrier beaches in addition to erosion and accretion – overwashing of sediments, overtopping, seepage or through flow. These processes can lead to barrier beach retreat or barrier breaching.

A.5 Estuaries

An estuary is a partially enclosed coastal body of brackish water with one or more rivers or streams flowing into it, and with a free connection to the open sea. Estuaries are important to coastal processes as they form a transition zone between river and coastal environments. They are subject to:

- marine influences —such as tides, waves and the influx of saline water
- riverine influences such as flows of fresh water and sediment

Estuaries are therefore subject to the same or similar processes as the open coast, but with modifications resulting from the interaction with and addition of fluvial processes. In particular, the sediment load of the river will become a source of sediment to the adjacent coastline and any changes to that load (for example, damming of the river for irrigation purposes) will have a direct effect on sediment transport and deposition in the estuary and thus have an indirect effect on the coast.

A comprehensive guide (EMPHASYS Consortium 2000) for the prediction of morphological change within estuarine systems was produced by the then Ministry of Agriculture, Fisheries and Food (MAFF) in 2000 under Phase 1 of the Estuaries Research Programme (MAFF project FD1401). This appendix therefore deals only with estuaries in terms of their interaction with adjacent coastal systems.

Appendix B: Spatial classification and linkages of estuary–coast–inner shelf systems

As part of the development of CESM within the iCOASST project (see Section 4.3.1), a conceptual framework for classifying and setting the interactions among the components within the estuary–coast–inner shelf was produced (French et al. 2016a). An idealised spatial ontology – or formal specification of a conceptualisation – to provide the basis for mapping the configuration of coastal systems was devised (Figure B.1). Estuarine, open coastal and inner shelf complexes were also outlined as part of the classification (Figure B.2).

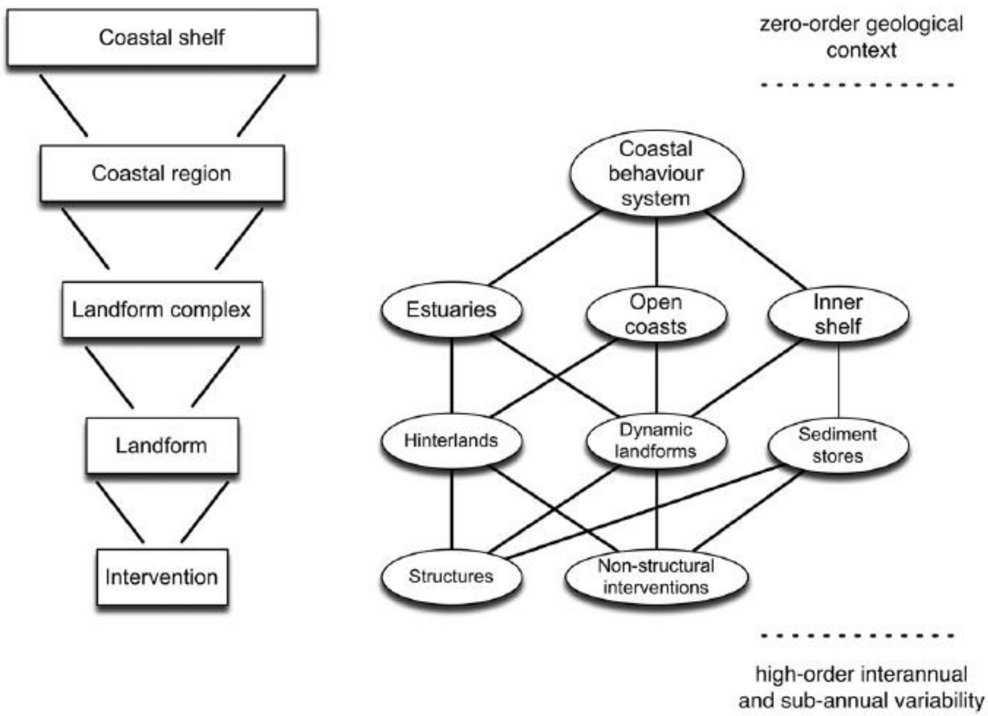


Figure B.1 Overview of spatial ontology of estuary–coast–inner shelf geomorphic systems

Source: French et al. (2016a, Fig. 2)

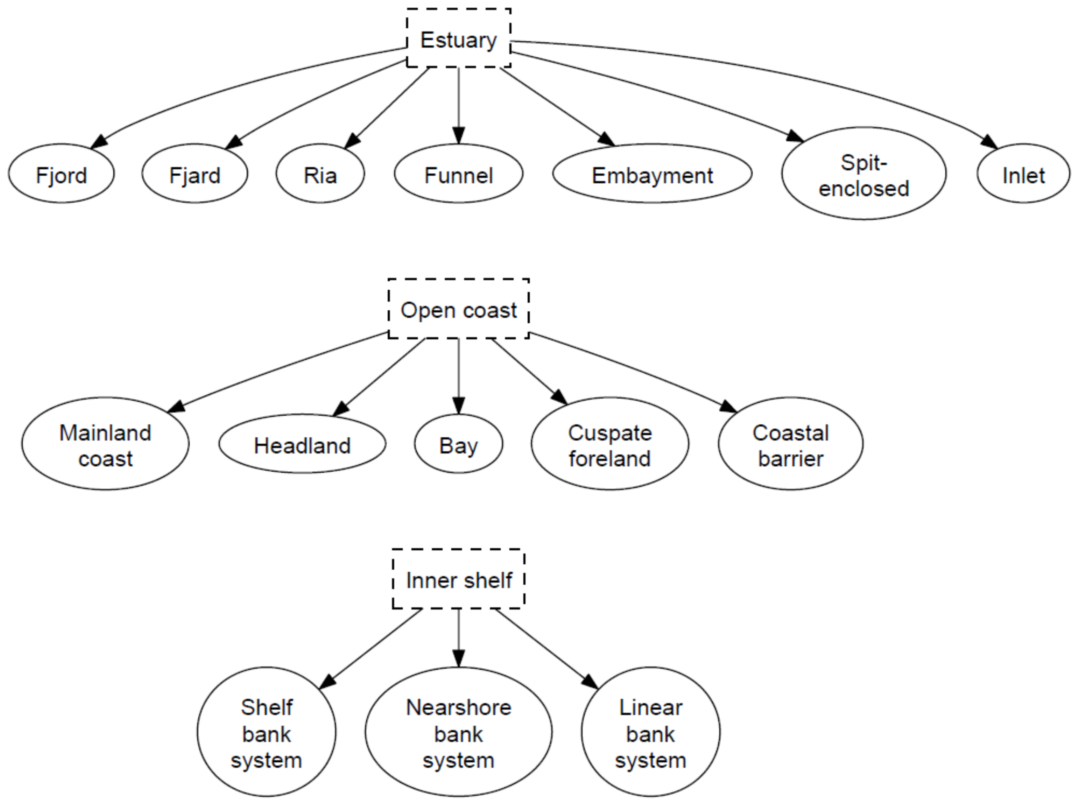


Figure B.2 Illustrative classification of estuary, coast and inner shelf landform complexes

Source: French et al. (2016a, Fig. 3)

The estuarine, open coastal and inner shelf complexes outlined in Figure B.2 represent aggregations of landforms. Table B.1 summarises a provisional set of landforms which includes features such as cliffs and beaches covered in this report.

Table B.1 Shared set of landform components common to open coast, estuarine and inner shelf complexes

Landform		Hinterland	Sediment store
Cliff	Inlet channel	High ground	Seabed gravel
Shore platform	Ebb delta	Low ground	Seabed sand
Beach	Flood delta	Reclaimed	Seabed mud
Beach ridge	Bank		Suspended mud
Tombolo	Channel		
Dune	Tidal flat		
Spit	Saltmarsh		
Rock outcrop	Brackish marsh		
Lagoon	River		

Source: French et al. (2016a, Table 1)

The ontology was then finalised by defining the interactions between the different components. Three essential types of interaction were considered:

- **None –** paired components exert no influence on each other
- **Influence –** where there is a process interaction such as wave sheltering, but no direct sediment exchange
- **Sediment pathway** – a direct exchange of sediment between components

Table B.2 represents an illustrative portion of an interaction matrix.

Table B.2 Illustrative paired examples of system interaction rules for landforms and interventions

From	To	Interaction	Logic (literature source)
Cliff	Beach	Sediment pathway (sand, gravel)	Cliff sources beach-grade sediment (mud typically lost offshore)
Beach	Cliff	Influence	Presence and morphology of beach feeds back into cliff recession rate (see, for example, Walkden and Hall 2011)
Seawall	Beach	Influence	Presence of seawall may cause lowering of beach (see, for example, Basco 2006)
Beach	Seawall	Influence	Beach protected toe of seawall and reduces wave energy on face
Jetty	Inlet channel	Influence	Jetty exerts stabilising influence on channel position and constrains width adjustment
Inlet channel	Jetty	None	No direct causal relation in this direction

Source: French et al. (2016a, Table 3)

Appendix C: Hydrodynamic processes important in morphological modelling

C.1 Waves

Most waves affecting coastlines are generated by the action of wind over the sea surface. Waves usually grow larger as each of the following increase:

- the distance over which the wind can act (**fetch length**) (Figure C.1)
- the time over which the wind is able to act on the same water of area (**duration**)
- the wind strength (**speed**)

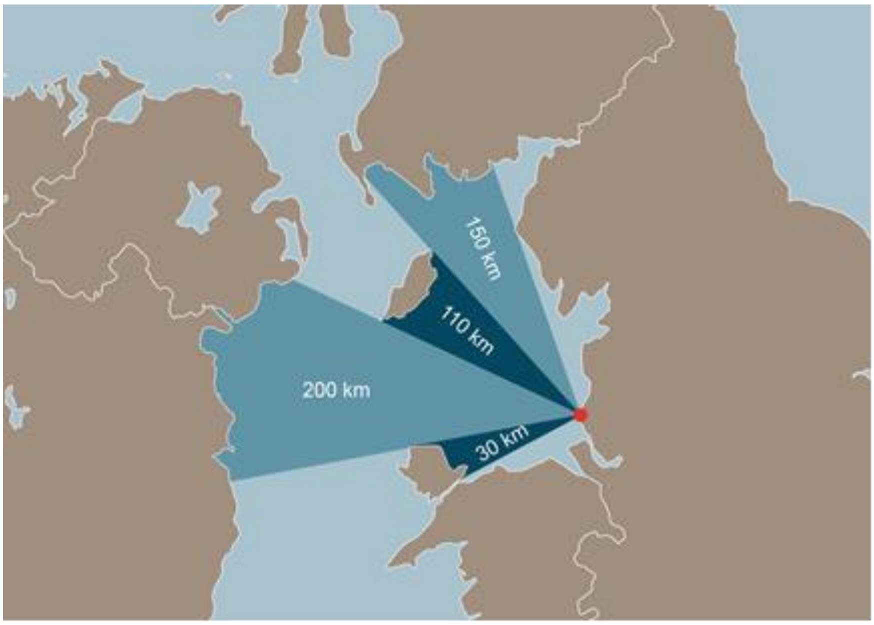


Figure C.1 Fetch lengths from different wind directions affecting the wave generation at a given point (shown as a red dot)

In most cases, the wave condition is influenced to the greatest extent by the wind speed together with either the fetch length or duration. Only in open seas, when fetch and duration might be very large, will the sea then reach a 'fully developed' state (that is, when the wave heights depend only on the wind speed).

Waves are characterised by:

- their height – the distance between the trough (lowest part) and crest (highest part) of the wave
- their length – the distance between wave crests
- their period – the time for 2 consecutive crests to pass a point (Figure C.2)

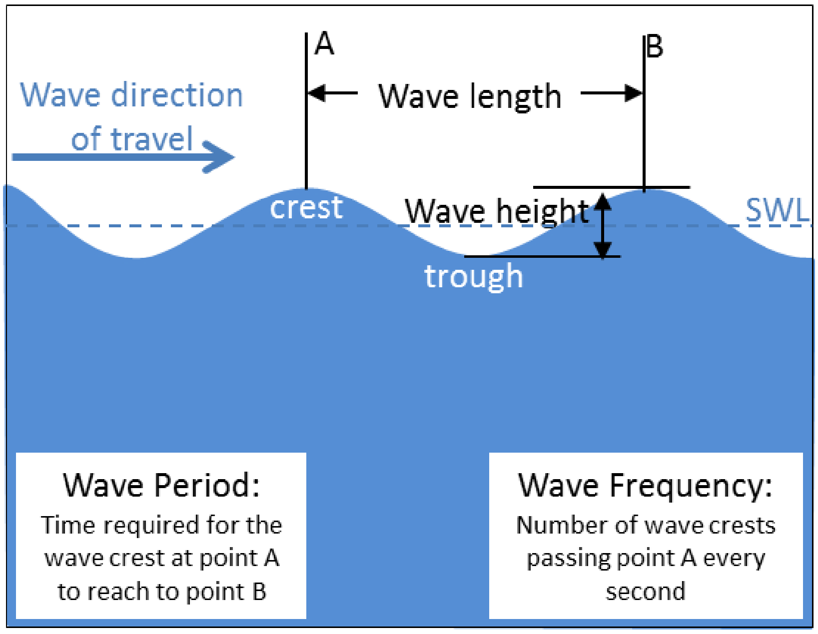


Figure C.2 Wave characteristics

The ratio of the wave height to the wavelength is known as wave steepness. If the water depth is less than half the wavelength, then the wave is considered to be in shallow water. At most sites, it is convenient to consider 'wave generation' in deep water separately from 'wave transformation' in shallow water.

Wave transformation refers to changes in the wave's characteristics during its propagation from deep to shallow water. As waves travel towards the shoreline, they are affected by the seabed through processes such as refraction, shoaling, energy dissipation (as a result of bottom friction and wave breaking), diffraction and reflection (when they meet an obstacle). Once they approach the beach and after breaking, waves are further transformed (for example, as a result of wave run-up, wave set-up and wave overtopping). The wave transformation processes described below dictate the nearshore wave conditions that influence the rate and direction of sediment transport.

C.1.1 Shoaling

Shoaling occurs as the waves enter shallower water (Figure C.3). The wave speed and wave length decrease in shallow water, and so the energy per unit area of the wave has to increase leading to an increase in the wave height. This process does not involve any (significant) loss of energy and is potentially reversible if the wave travels into deeper water again. Long period waves shoal more than short ones.

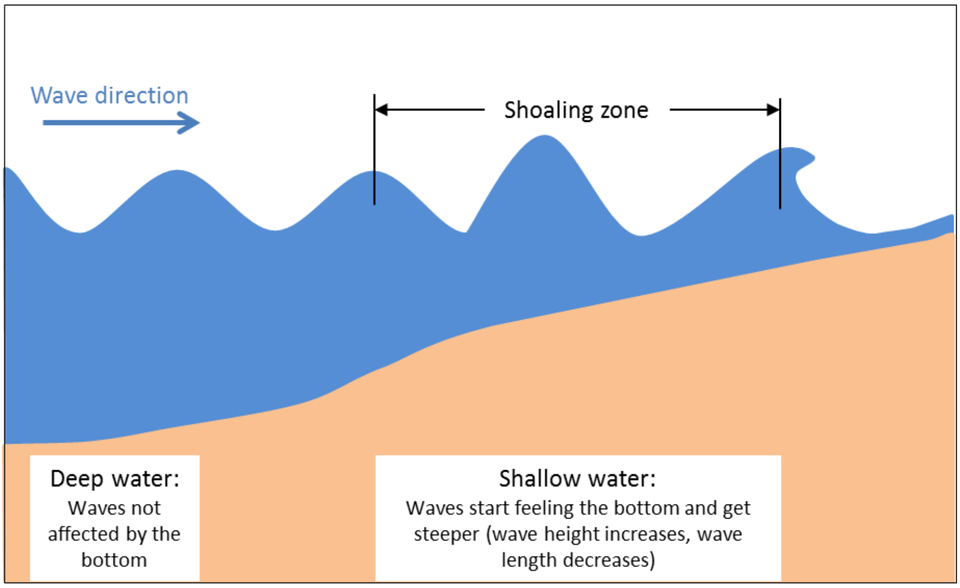


Figure C.3 Wave shoaling

C.1.2 Refraction

Refraction is the bending of waves due to varying water depths underneath. The part of the wave in shallower water moves more slowly than the part of the wave in deeper water. So when the depth under a wave crest varies along the crest, the wave bends (Figure C.4).

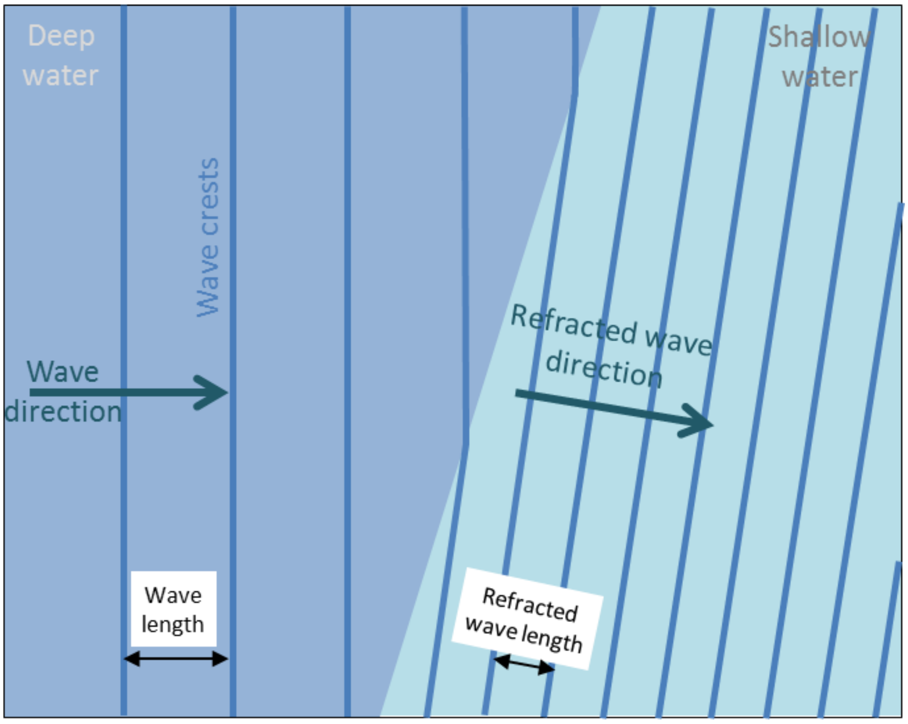


Figure C.4 Wave refraction

C.1.3 Energy dissipation (due to bottom friction)

As waves propagate from deep to intermediate water, the orbits of the water particles start feeling the bottom and become elliptical (Figure C.5). Bottom friction causes energy dissipation (by reducing the wave height) as the water depth becomes shallower. Friction is of special importance over large areas with shallow water.

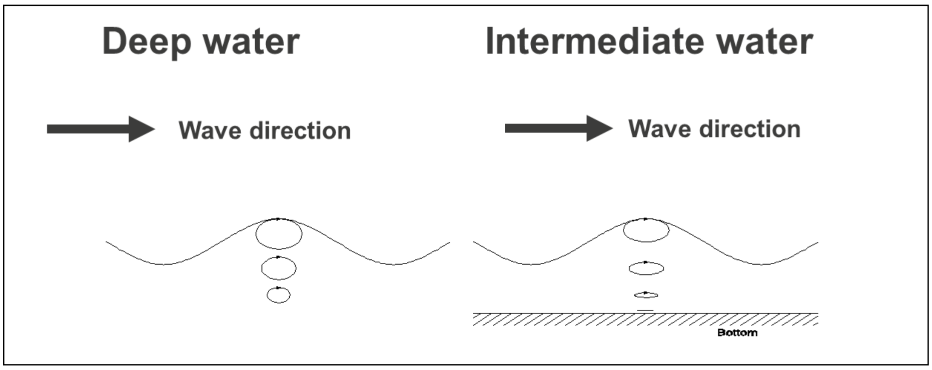


Figure C.5 Wave dissipation due to bottom friction

C.1.5 Energy dissipation (due to depth-induced breaking)

There is a limit to the steepness of a wave beyond which it starts to collapse or break. Wave breaking involves a loss of energy from the wave and a reduction in local wave heights, and so this process is not reversible. Wave breaking is a complex process. The height of the waves and the type of breaking depend on many factors including bed slope, water depth, wave steepness and wind.

C.1.6 Diffraction

At an obstacle such as a breakwater or an island, some wave energy will bend around behind the obstacle into the ‘shadow zone’ (Figure C.6). Wave energy diffracted into this zone spreads out, reducing in intensity further away from the obstacle tip and further away from the shadow line.

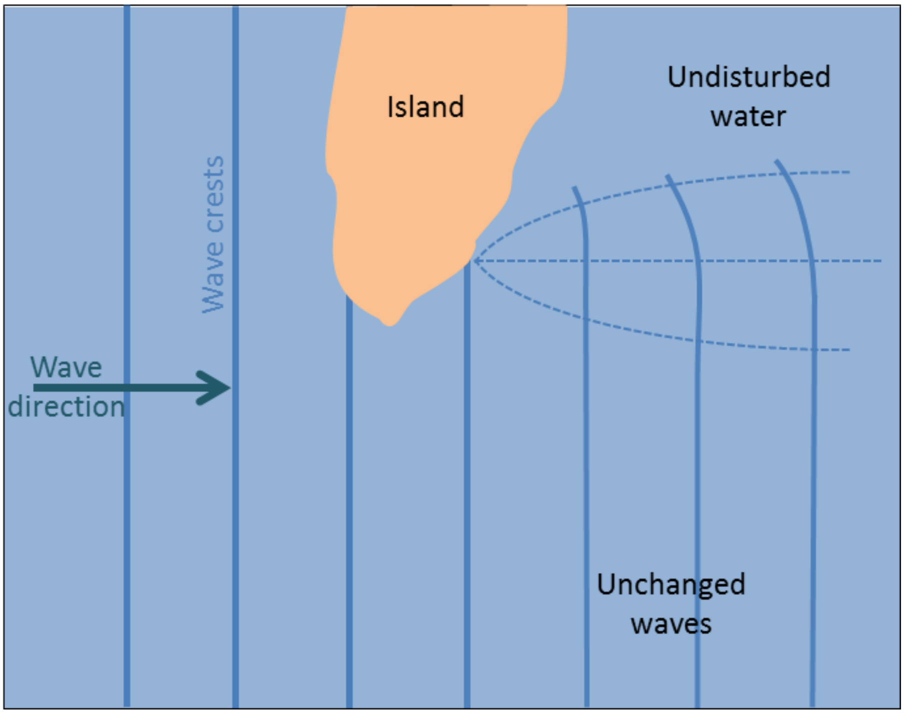


Figure C.6 Wave diffraction as caused by an island

C.1.7 Reflection

Obstacles such as breakwaters, sea defences and harbour walls reflect waves incident upon them (Figure C.7) and are often designed to absorb some wave energy (particularly rock armour or concrete armour units). The reflection properties of a structure are characterised by a reflection coefficient; for a vertical wall it will be close to 1, whereas for a gently sloping beach or coastal revetment system it can be as little as 0.1. The degree of wave reflection depends on the wave period and the characteristics of the structure.

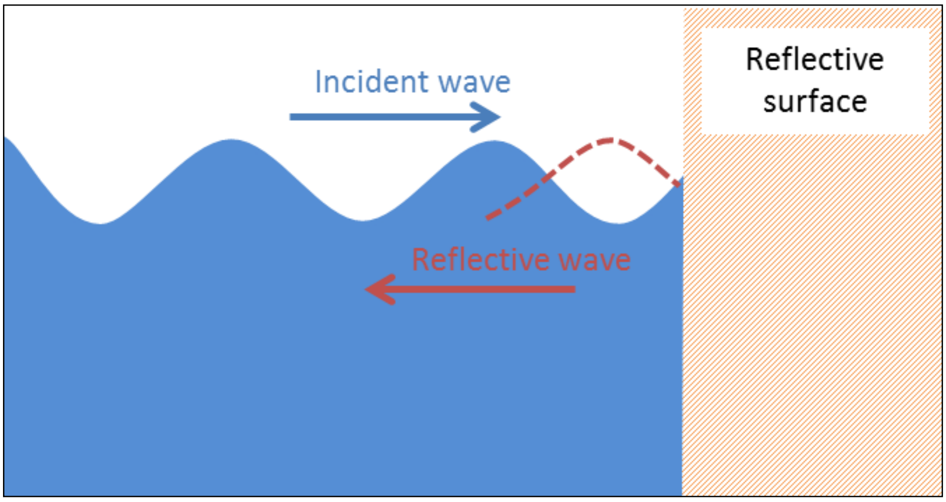


Figure C.7 Wave reflection

C.1.8 Wave overtopping

Wave overtopping takes place when waves meet a submerged reef or structure, but also when waves meet an emerged reef or structure lower than the wave height (Figure C.8).

Two processes take place during overtopping:

- wave transmission (where the structure has a degree of permeability)
- the passing of water over the structure

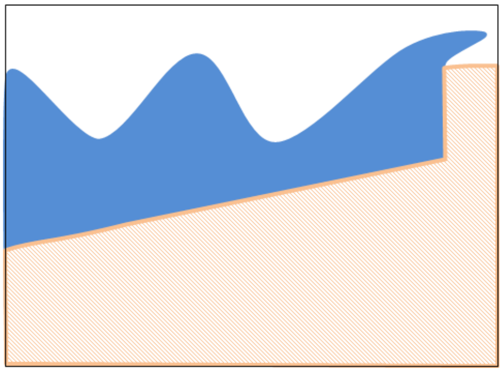


Figure C.8 Wave overtopping

C1.9 Wave set-up, swash and wave run-up

Wave set-up is a local elevation in the mean water level on the foreshore. It is caused by energy dissipation due to depth-induced breaking of the waves and it is preceded by a slight lowering of the sea level or set-down (which is caused when the wave shoaling reaches a minimum in the outer part of the surf zone). The wave set-up is proportional to the wave height at breaking. Gradients in wave set-up (for example, in partly sheltered areas near port entrances) will generate local circulation in the surf zone towards the sheltered area (that is, longshore).

Wave swash or uprush is the propagation of the waves onto the beach slope. The swash consists of an onshore phase with decelerating upwards flow (uprush or swash) and an offshore phase with accelerating downwards flow (downrush or backwash).

Wave run-up is the sum of the wave set-up and the wave swash (Figure C.9). The wave run-up is thus the maximum level the waves reach on the beach relative to the still water level. Wave run-up depends primarily on the beach slope angle, and the incident wave steepness.

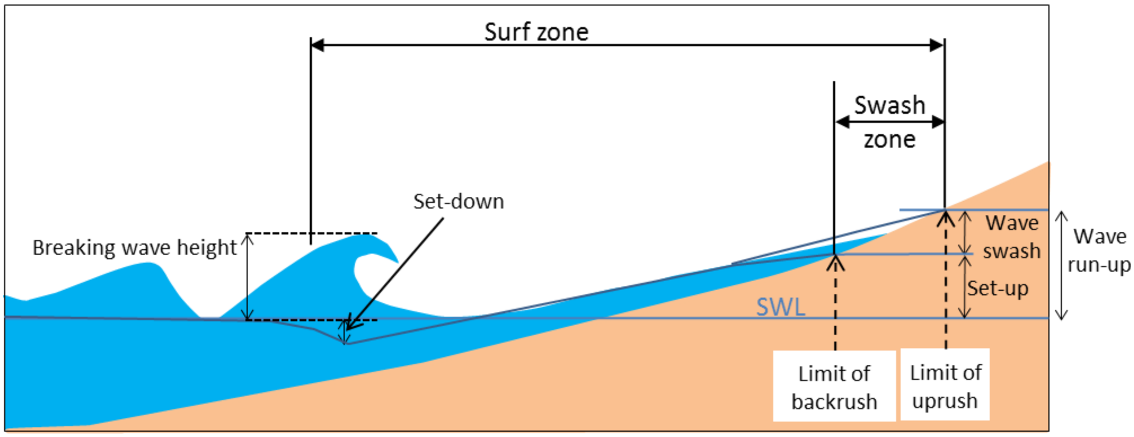


Figure C.9 Wave set-up, swash and wave run-up

C.2 Water levels

Periodic variations in mean water levels are mainly caused by the astronomical tide – the influence of which can be relatively easily predicted (see Box C.1). However, there are additional temporary sources of variation in water levels that are less certain:

- **Meteorological effects** – from changes in air pressure, wind or wave set-up (for example, storm surges)
- **Geological effects** – from earthquake disturbances (for example, tsunamis) (not discussed in this report)

There are also the permanent changes in mean water level resulting from climate change and sea level rise (discussed separately in this report).

Water levels will not only influence the wave generation and transformation processes but also have a direct influence on the rate and direction of sediment transport.

Box C.1 Astronomical effects on water levels

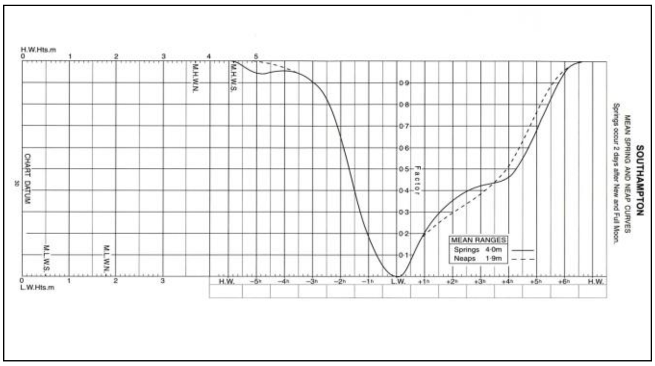
The astronomical tide is the periodic rise and fall in the mean level of water in oceans and seas resulting from the gravitational attraction of the Sun and Moon. The tides of our planet display extremely complex and varied behaviour. In some places such as in the Mediterranean, the tidal range is very small (<1m) and in others (for example, the Bay of Fundy in Canada) the shape of the bay augments the tidal range to >15m. In Europe, the biggest tides can be found in the Severn estuary (12m) in the UK and near Mont Saint-Michel in France where the tide goes out for 9km.

The importance of tides for coastal processes is often in the currents they generate, which can reach speeds of up to 5m per second (Bay of Fundy). The rising tide is usually referred to as the ‘flood’, whereas the falling tide is called the ‘ebb’. The tidal currents of the ebb and flood play a major part in shaping our coasts, transporting large volumes of sediment and moulding estuary environments.

In contrast to the majority of coastal processes, the tides can be predicted with very good accuracy, for as many as 200 years into the future. However, there is sometimes a difference between the observed and predicted tide due to weather-induced effects such as the storm surge.

The most obvious timescale of tidal variation is that of the semi-diurnal (occurring twice a day) and diurnal tides (once a day). In addition, the equilibrium theory predicts the variation in tidal range of the spring–neap cycle, which has a period of 14.7 days. There is also a seasonal (yearly) cycle, governed by the rotation of the Earth about the Sun with a period of 365.25 days. Even longer period cycles are also evident, resulting from longer period astronomical effects.

In the UK, most coastlines have a semi-diurnal component. Details of tidal levels around the UK can be found in Admiralty Manual of Tides (NP120) (Figure C.10 shows an example) and tide gauge data can be found in the UK National Tide Gauge Network (www.ntslf.org/data/uk-network-real-time).



ENGLAND — SOUTHAMPTON

LAT 50°54'N LONG 1°24'W

TIME ZONE UT(GMT) TIMES AND HEIGHTS OF HIGH AND LOW WATERS YEAR 2002

JANUARY						FEBRUARY						MARCH						APRIL					
	Time	m		Time	m		Time	m		Time	m		Time	m		Time	m		Time	m		Time	m
1 TU	0528 1150 1755	0.8 4.7 0.6	16 W	0013 0606 1224 1824	4.4 1.0 4.4 0.8	1 F	0053 0650 1310 1915	4.7 0.5 4.7 0.3	16 SA	0055 0648 1307 1859	4.3 0.9 4.2 0.8	1 F	0552 1206 1815	0.2 4.9 0.0	16 SA	0555 1208 1808	0.6 4.3 0.6	1 M	0052 0653 1311 1912	4.8 0.2 4.7 0.3	16 TU	0025 0619 1243 1832	4.3 0.7 4.3 0.9
2 W	0018 0613 1236 1840	4.6 0.8 4.7 0.6	17 TH	0048 0641 1259 1855	4.3 1.0 4.3 0.9	2 SA	0139 0735 1356 1959	4.7 0.6 4.6 0.5	17 SU	0127 0714 1339 1925	4.2 1.0 4.1 1.0	2 SA	0033 0634 1250 1856	4.9 0.2 4.8 0.1	17 SU	0025 0621 1238 1832	4.3 0.7 4.3 0.7	2 TU	0134 0731 1354 1950	4.6 0.5 4.4 0.8	17 W	0057 0648 1317 1902	4.3 0.9 4.2 1.1
3 TH	0105 0700 1324 1927	4.6 0.9 4.6 0.7	18 F	0123 0713 1335 1925	4.3 1.2 4.2 1.1	3 SU	0226 0821 1445 2045	4.5 0.8 4.4 0.8	18 M	0159 0742 1412 1955	4.1 1.2 4.0 1.2	3 SU	0117 0715 1334 1936	4.8 0.3 4.7 0.3	18 M	0055 0645 1309 1856	4.3 0.8 4.2 0.9	3 W	0217 0811 1440 2033	4.3 0.9 4.1 1.2	18 TH	0132 0722 1355 1940	4.2 1.1 4.1 1.3
4 F	0155 0750 1415 2017	4.5 1.0 4.4 0.9	19 SA	0159 0745 1411 1957	4.2 1.3 4.1 1.2	4 M	0317 0911 1537 2136	4.3 1.1 4.1 1.1	19 TU	0233 0816 1448 2032	4.0 1.4 3.9 1.4	4 M	0200 0756 1418 2017	4.6 0.6 4.4 0.7	19 TU	0125 0711 1340 1924	4.2 0.9 4.1 1.1	4 TH	0304 0857 1536 2127	4.0 1.4 3.8 1.7	19 F	0212 0805 1443 2031	4.0 1.3 3.9 1.6
5 SA	0249 0844 1510 2111	4.4 1.2 4.3 1.1	20 SU	0237 0820 1450 2034	4.1 1.5 3.9 1.5	5 TU	0413 1008 1638 2237	4.1 1.4 3.9 1.5	20 W	0313 0900 1534 2121	3.9 1.6 3.7 1.7	5 TU	0245 0839 1506 2101	4.3 0.9 4.1 1.1	20 W	0157 0743 1415 1959	4.1 1.2 4.0 1.3	5 F	0403 1001 1653 2251	3.7 1.7 3.6 2.0	20 SA	0304 0904 1550 2144	3.9 1.6 3.8 1.9
6 SU	0348 0944 1612 2212	4.2 1.4 4.1 1.3	21 M	0319 0903 1534 2120	3.9 1.7 3.8 1.7	6 W	0519 1119 1753 2353	3.9 1.6 3.7 1.7	21 TH	0407 1002 1640 2235	3.7 1.8 3.6 1.9	6 W	0335 0929 1602 2158	4.0 1.3 3.8 1.6	21 TH	0234 0824 1458 2046	4.0 1.4 3.8 1.6	6 SA	0529 1137 1836	3.5 1.9 3.6	21 SU	0420 1029 1719 2323	3.7 1.7 3.8 1.9
7 M	0453 1050 1720 2320	4.1 1.5 4.0 1.4	22 TU	0409 0958 1630 2221	3.8 1.9 3.6 1.8	7 TH	0637 1239 1918	3.8 1.7 3.7	22 F	0522 1130 1809	3.7 1.9 3.6	7 TH	0438 1038 1719 2320	3.7 1.7 3.6 1.9	22 F	0324 0921 1603 2156	3.8 1.7 3.7 1.9	7 SU	0035 0708 1308 1956	2.1 3.6 1.8 3.8	22 M	0553 1205 1847	3.7 1.6 3.9
8 TU	0602 1200 1831	4.1 1.5 3.9	23 W	0511 1109 1740 2337	3.8 1.9 3.6 1.9	8 F	0113 0753 1352 2031	1.7 3.9 1.6 3.9	23 SA	0011 0649 1300 1935	1.9 3.7 1.7 3.8	8 F	0604 1211 1900	3.6 1.8 3.6	23 SA	0439 1048 1735 2341	3.6 1.8 3.6 2.0	8 M	0148 0817 1407 2049	1.8 3.8 1.6 4.0	23 TU	0050 0715 1322 1955	1.6 3.9 1.3 4.2

Figure C.10 Example of tide tables information

Source: Tide Tables

A **storm surge** is an abnormal rise of water (over and above the predicted astronomical tide) caused by the effects of the wind and low atmospheric pressures happening during storms (Figure C.11). They propagate over the continental shelf, resulting in large increases in water levels. For example, Stansby et al. (2013) stated that a storm surge in the North Sea can raise the still water level by up to 2m above the predicted tidal level.

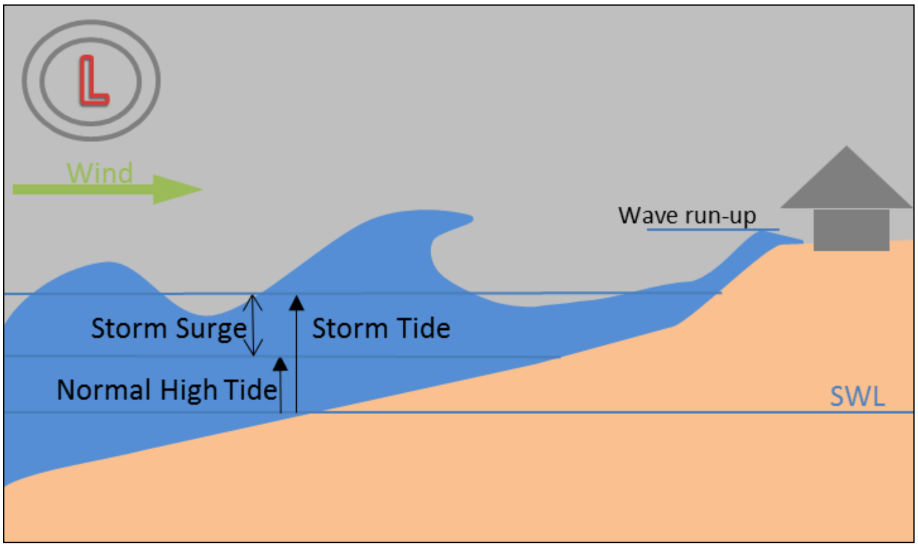


Figure C.11 Storm surges

C.3 Currents

Currents are the continuous, directed movement of seawater generated by forces acting on the mean flow. Currents are the mechanisms for sediment transport and so various types of currents in the sea may be important to coastal processes.

Currents in the open sea are typically generated by tidal or wind effects. Tidal currents are strongest in large water depths away from the coastline and in straits where the current is forced into a narrow area. Along many parts of the UK coastline, there are significant variations in tidal levels but the associated tidal currents are weak close inshore. Wind-generated currents are caused by the direct action of the wind shear stress on the surface of the water. Wind-generated currents are normally located in the upper layer of the water body and are therefore not very important from a morphological perspective.

Nearshore currents are usually separated into cross-shore and longshore components: Undertows and rip currents have their principal axes oriented perpendicular to the beach, while longshore currents act parallel to the beach.

Longshore drift is the main method of transport of material along a beach. As waves do not (usually) approach the shore at right angles, this leads to the creation of a longshore or 'littoral' drift, which runs parallel to the coast.

While incoming and outgoing tides produce currents in opposite directions on a daily basis, the current in one direction is usually stronger than the other resulting in a net one-way transport of sediment. Longshore drift, longshore currents and tidal currents in combination determine the net direction of sediment transport.

C.4 Wind climate

Wind is an important forcing consideration in the following situations:

- as an independent mechanism for sediment transport
- as a mechanism for amplification of overtopping volumes
- as input to wave prediction models where wave data are not available or fit for purpose

Winds may erode, transport and deposit materials independently of waves. They are effective transport agents in areas with sparse vegetation, a lack of soil moisture and a large supply of unconsolidated sediments, as for example in dune systems. Although water is a much more powerful eroding force than wind, Aeolian processes for some beach and dune systems are important. Over long timescales, beach losses can occur because of offshore sediment transport by wind-induced currents or because of wind transport to backshore dune systems.

In the short term, few beaches maintain a constant alignment but are continually adjusting their planshape to the changing weather conditions, mainly the wind conditions and wave directions.

The UK Met Office Wavewatch III model provides synthesised wind and wave time series on about a 12km grid for the past 35 years. This can be then used as offshore input data to regional wave models to provide required inshore wave data.

Appendix D: Model evaluation for end users proforma

This appendix contains the evaluation proforma used in the Environment Agency project ‘Embedding iCOASST into Practice’ for independently evaluating the accessibility and usability of the models produced by the iCOASST project.

Each of the models was downloaded from the Channel Coastal Observatory’s iCOASST website (https://www.channelcoast.org/iCOASST/introduction/), compiled and run using the documentation and the site-specific datasets on which they had been developed.[15]

The outcome of this evaluation for each of the models can be found in the model’s webpage under the Channel Coastal Observatory iCOASST website and should be referenced by anyone interested in using or developing the model further.

[15] Also provided on the website through the Models and Mapping Tools dropdown menu available from the ICOASST button in the top navigation bar.

Model name: xx					
	Evaluation question	**Score (0 / 0.5 / 1)**			**Comment**
		For User Type 1: End user (coastal manager)	**For User Type 2: Basic modeller (simple input changes only)**	**For User Type 3: Advanced modeller/ model coder (application to entirely new systems/ model development)**	
A Website model introduction www.channelcoast.org/iCOASST/introduction/	1. Is the model description on the website adequate to understand what the model is for?				
	2. Are relevant applications of the model explained?				
	3. Are the key model assumptions and limits to the model use explained?				
	4. Is the level of expertise required to use the model and/or use the results specified?				

Model name: xx

	Evaluation question	Score (0 / 0.5 / 1)			Comment
		For User Type 1: End user (coastal manager)	For User Type 2: Basic modeller (simple input changes only)	For User Type 3: Advanced modeller/ model coder (application to entirely new systems/ model development)	
B Model download www.channelcoast.org/iCOASST/introduction/	1. Can you download the source code and/or executable/dll?				
	2. Are there simple instructions on how to install, with images if needed?				
	3. Are the model boundary conditions explained?				

Model name: xx					
	Evaluation question	**Score (0 / 0.5 / 1)** For User Type 1: End user (coastal manager)	**For User Type 2: Basic modeller (simple input changes only)**	**For User Type 3: Advanced modeller/ model coder (application to entirely new systems/ model development)**	**Comment**
C Model user manual	1. Is the user manual easy to read, user friendly and comprehensive?				
	2. Is there sufficient information provided on what the model is doing and how it works?				
D Model Inputs	1. Are example model input data available to download and enough information provided to understand what the data represent?				

Model name: xx					
	Evaluation question	**Score (0 / 0.5 / 1)**			**Comment**
		For User Type 1: End user (coastal manager)	**For User Type 2: Basic modeller (simple input changes only)**	**For User Type 3: Advanced modeller/ model coder (application to entirely new systems/ model development)**	
	2. Are all input parameters expanded/explained? Are ranges of values to be used indicated? Are required units provided?				
	3. Are timescales and date stamp inputs explained?				
	4. Are there any errors when you enter the compiled example data/input parameters?				

Model name: xx					
	Evaluation question	**Score (0 / 0.5 / 1)**			**Comment**
		For User Type 1: End user (coastal manager)	**For User Type 2: Basic modeller (simple input changes only)**	**For User Type 3: Advanced modeller/ model coder (application to entirely new systems/ model development)**	
E Model runs	1. Does the model run successfully with the data provided?				
	2. Is information provided in the manual on the operation system required and prerequisites in terms of software?				
	3. Is model calibration/validation discussed in the manual?				

Model name: xx					
	Evaluation question	**Score (0 / 0.5 / 1)** For User Type 1: End user (coastal manager)	**For User Type 2: Basic modeller (simple input changes only)**	**For User Type 3: Advanced modeller/ model coder (application to entirely new systems/ model development)**	**Comment**
	4. Have you been able to successfully run another example that is different to the one provided?				
	5. Are potential errors and bugs dealt with in the manual?				
F Model outputs	1. Are the output file headings explained in the manual?				

Model name: xx					
	Evaluation question	**Score (0 / 0.5 / 1)** For User Type 1: End user (coastal manager)	**For User Type 2: Basic modeller (simple input changes only)**	**For User Type 3: Advanced modeller/ model coder (application to entirely new systems/ model development)**	**Comment**
	2. Is the meaning of each of the output variables explained in the manual?				
	3. Is there a description of how to process (tabulate and display) the output data?				
G Other	1. Does the manual make further recommendations for reading and supply references?				

Model name: xx					
	Evaluation question	**Score (0 / 0.5 / 1)**			**Comment**
		For User Type 1: End user (coastal manager)	**For User Type 2: Basic modeller (simple input changes only)**	**For User Type 3: Advanced modeller/ model coder (application to entirely new systems/ model development)**	
	2. Is the contact information completed?				
	3. Is the email address valid?				
Total score					

Recommendations table for model developer

Recommendation	Action completed (sign)

Appendix E: Coastal morphodynamic models: generic guidelines for model developers

This appendix reproduces guidance produced for the 'Embedding ICOASST into Practice' project in January 2017.[16]

Outline

The document aims to provide a useful guide for model developers when writing a user manual for coastal morphodynamic models. It is based on lessons learnt from the evaluation of a suite of 6 models and 2 model compositions. It includes a generic model user manual structure together with recommendations of valuable content that should be included. The appendix includes recommendations based on the composition evaluations, summarising the risk associated with model composition development.

The document has been written with the proposed structure for the user manual, so that the headings and subheadings are the ones proposed to be followed. This is just a suggested contents table, which the developer might decide to structure differently; however it is recommended that the issues described in each of the sections are taken into account in order to aid potential users in how to use their model appropriately.

E.1 Introduction

This section should be used to deliver a clear but detailed model description, as well as information regarding its typical application.

E.1.1 Model description

The model description is suggested to outline how the model works, the type of model, and its main assumptions and limitations. It is suggested to include a basic diagram in the form of an image depicting the model elements and/or processes.

E.1.1.1 Key features

A list of key features of the model and definitions should be included in this section, with any relevant formula (for example: equilibrium, exchange of sediment between the elements, drivers and so on).

[16] Available from: www.channelcoast.org/iCOASST/icoasstforendusers/iCOASST%20Model%20User%20Manual%20Generic%20GuidelinesV5%20(1).pdf

E.1.1.2 History

A brief history of the model or description of predecessor versions with references may be useful to a user or developer who would like to understand more about the models evolution or requires technical detail.

E.1.2 Typical application

The models typical application provides detail of its use and why it was built, in particular what are its objectives within coastal morphology. Other suggested applications are valuable but not always necessary.

E.2 Naming convention

This is a useful section to include if the model has a set naming convention for the input/output files and steering files.

E.3 Model basics

This section can be used to expand on the basic model description in the introduction (Section E.1).

E.3.1 Technical detail

Include some technical detail and extra formula the model is based on. Diagrams, if not included already, are useful within this section to add an extra level of understanding of the processes within the model. If the model has been adapted or developed especially for a particular use, this section should include detail of what has been changed and why.

E.3.2 Boundary conditions

List and describe the boundary conditions, including how they are calculated or estimated.

E.3.3 Assumptions and limitations

E.3.3.1 Assumptions

List and describe all assumptions within the model, in order of importance.

E.3.3.2 Limitations

List and describe all known limitations, in order of importance.

E.3.3.3 Known instabilities

Use this section to highlight if the user could configure the model in a way that causes an instability.

E.4 Running model

To run the model the user needs to understand all the inputs files, input variables and how they are changed. If there is more than one input file, there should be a description for each of them, including all the variables used for each. Therefore, it is necessary for the user manual to contain a full list of inputs names, definitions, range of values and units per input file.

E.4.1 How to run the model

Specify the code language, compilers, versions and requirements to run the model.

E.4.2 Input files

Specify the amount of compulsory files needed to run the model, together with any optional files that can also be used and when to use them. A description of the different input files, their format and their variables will then follow in each subsection.

E.4.3 Steering file

The steering file format would be described here, together with all the variables in it, which should be fully defined (ideally within a table, see Table E.1 for example), along with their range of values and units

Table E.1 Example of a table containing definition of variables in a given file

Variable name (units)	**Description**	**Default value and range of values**
D50(m)	Value for the sediment D50, which represents the main sediment size in the area applied.	The default value is 0.0002m. D50 needs to be between 0.1mm and 1.5mm for the applied formulation to be valid.
…		

It is recommended that there is an example steering file in the form of an image (Figure E.1).

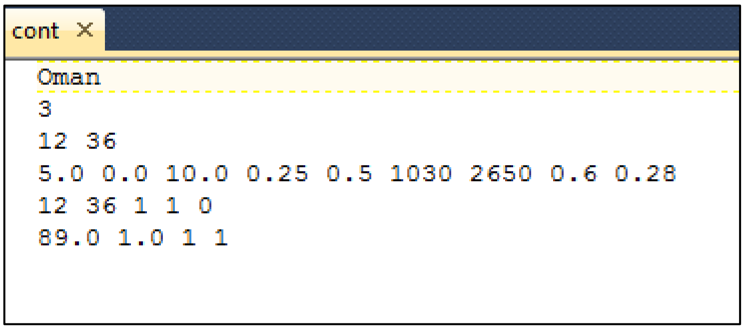


Figure E.1 Example of a control file image

E.4.4 Other file

A similar description to the steering file above is recommended for each of the files (optional or compulsory) used within the model. Ideally, each will include a table describing the variables used and an image so that the format is easily understood.

E.4.5 Errors

Within this section or the next typical errors should be dealt with. For example, it is suggested to include typical error messages and what problem they refer to. Sometimes this is not so simple and providing a contact email will suffice.

E.5 Running model with supplied input

This section can be merged with Section E.4, although it is suggested that these are separate to avoid confusion. The information supplied in this section should make it simple for a user to download and run the model using the supplied inputs.

E.5.1 Downloading and running

E.5.1.1 Prerequisites

List all prerequisites that are needed to run the model, for example, the computing system, programmes and their version.

E.5.1.2 Download

Tell the user where the model and example inputs can be downloaded from.

E.5.1.3 File structure

It is recommended to include the file structure of the download to check that all the components have been downloaded and any supporting documents are defined.

E.1.5.4 Running with example files

From previous user manual evaluations, it is seen to be beneficial for the model user to have a step-by-step guide to follow when running the example with the supplied inputs and steering file. This should be accompanied by an image depicting a successful run (see screen output example in Figure E.2) or text describing how a user can tell if the run was successful.

```
 Timeframe:
 From year  1015 output every     1 years
 Until year  2015
 Run duration:  706706 tides

 Assigning wave point numbers
 Structure control files loaded
 look-up tables loaded
C:\workshop\28_UserManualExample Year:  1015
```

Figure E.2 Example of successful model run screen output

E.6 Output files

All output options, files and variables are listed in this section. The variables should be defined and units given. An image of what the output file looks like is necessary; see Figure E.3 for an example. It is recommended to include an example of how to process the output data along with an example plot.

```
Results for time:
SECTION          X
1           0.0000
2         100.0000
3         200.0000
4         300.0000
```

Figure E.3 Example of data in output file

E.7 References

List the references cited in the manual.

Annex: Model composition development

The guidelines in this document were drawn from the review of the models and models' user manuals on the Coastal Channel Observatory iCOASST webpage. Additionally, the compositions were also reviewed, and some conclusions on the development are summarised here, emphasising the risks associated with model composition development.

Model composition development is specific to the models being linked and the software these models rely on. This makes it difficult to write general recommendations on the development of model compositions. There are, however, 2 major issues that should be borne in mind when developing a composition.

It is understood that model linking can be quite an onerous task, especially if the models were developed a long time ago and therefore their structure was not designed for model linking. The models will tend to required extensive code development to get the right structure and expose the right variables to be ready for the other models.

Another difficulty comes from the software requirements of the different components and possible incompatibilities from the different models to be linked. Thirdly, there might be proprietary software dependencies which are difficult to overcome when such compositions need to be made public.

The problems encountered within both the Liverpool site and the Suffolk site compositions all emanate from these difficulties when linking models. Moving forwards, it will be advisable when writing new software to design it with a structure that would make it easy to link to other models in the future. Moreover, there are 2 fundamental issues to be borne in mind when linking models:

- **Portability**. It is recommended that the model compositions are tested on a different environment PC to try and assure portability of the composition. The need for full paths in OpenMI does not help with this issue, although it should be considered as much as possible.
- **Software compatibility**. When the models are dependent on software it is difficult to foresee possible updates to the software that might make the composition to fail when these updates are carried out in the future. However, it is desirable if possible to reduce the software dependencies and try and write the linkages in a generic form to try and overcome this problem.

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