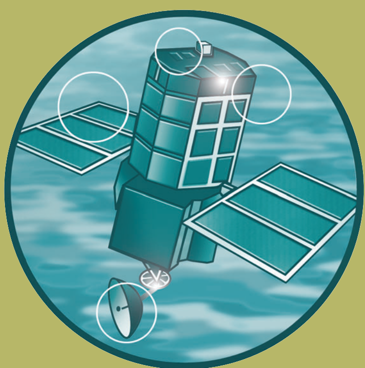
Joint Defra/EA Flood and Coastal Erosion
Risk Management R&D Programme

Development and Demonstration of Systems-Based Estuary Simulators

R&D Technical Report FD2117/TR



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Food and Rural Affairs

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

Development and Demonstration of Systems-Based Estuary Simulators

R&D Technical Report FD2117/TR

Final Report

Produced: March 2008

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For document control this report also constitutes ABPmer Report No. R.1429

Statement of use:
This document provides information for the Department for Environment Food and Rural Affairs (Defra) and Environment Agency Staff (EA), researchers and consultants about the research project Development and Demonstration of Systems Based Estuary Simulators (EstSim) and constitutes an R&D output from the Joint Defra/Environment Agency Flood and Coastal Defence R&D Programme (Estuaries Research Programme Phase 2).

Dissemination status:
Internal: Released internally
Externally: Released to public domain

Keywords:
Estuary, Geomorphology, Qualitative Modelling, Systems Approach, Behaviour, Morphology.

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www.defra.gov.uk/environ/fcd

Published by the Department for Environment, Food and Rural Affairs
June 2009.

Executive Summary

This report describes the outcomes of project FD2117 'Development and Demonstration of Systems-Based Estuary Simulators' (EstSim), which has provided research into the application of a systems-based approach to estuary environments as an alternative, yet complementary, approach to understanding morphological behaviour in estuaries. The project has been completed as part of the joint Defra/Environment Agency R&D Programme.

The rationale for applying a more formalised systems-based approach derives from the inherent complexity of interactions between physical processes, sediment transport and geomorphological form. With incomplete knowledge of these relationships, there is a benefit in developing and applying qualitative models and descriptions that do not solely rely on having precise knowledge of the physical laws governing 'bottom up' approaches.

The report documents the provision of a qualitative framework to assist in understanding:

- Presence and behaviour of geomorphological features within an estuary;
- Linkages that exist between them; and
- Their response to change.

Formal definition has been provided for UK estuaries in systems based terms. This includes the development and application of a typology to classify all UK estuaries according to the presence of constituent geomorphological elements. Seven estuary behavioural types were identified, as follows:

- Fjord;
- Fjard;
- Ria;
- Spit-enclosed;
- Funnel-shaped;
- Embayment; and
- Tidal inlet.

Behavioural statements and systems diagrams are provided for each behavioural type and also for each of the constituent geomorphological elements. These are used to map a set of influences between the morphological and process components within an estuary.

This definition of estuary systems has then been formalised mathematically to develop a qualitative, or behavioural, model. This consists of a series of Boolean variables and functions (i.e. essentially a rule-based approach). The behaviour of each system component (variable) in response to combined inputs from other components is defined using the Boolean functions. Application and development of this framework has produced a Prototype Simulator. The Prototype Simulator therefore allows a user to investigate the response of the

different system components that make up a given estuary to natural and anthropogenic change.

A review of existing legislation and previous work, combined with end user consultation, has been used to compile an up-to-date and relevant list of management questions for estuaries. The outputs from this exercise steered the compiling of a series of scenarios which were subsequently applied within a pilot testing exercise. The Prototype Simulator has been tested against these scenarios on the Thames and Teign estuaries in order to evaluate the capabilities and limitation of the approach.

The study has developed a web-based interface that provides a visualisation tool for the Prototype Simulator and additionally hosts a number of other key outputs from the project. The interface therefore provides a means to disseminate the research and promote knowledge and understanding of the systems-based approach.

EstSim has been successful in providing exploratory level research into the systems-based approach and its application to develop qualitative or behavioural models to simulate estuary response to change. The research has been formalised and the resulting Prototype Simulator has revealed considerable potential in this field, although it must be emphasised that at this stage this is still primarily an R&D tool.

At its present level of development, the Prototype Simulator is capable of capturing characteristic morphological behaviour and provides a framework for formalising qualitative geomorphological knowledge. However, at its present level of development, this predictive systems-based tool in isolation is not intended as a means to evaluate estuary management options. The model can be used to explore geomorphological behaviour, as a resource to guide the conceptual development of studies and as an educational tool, in terms of disseminating systems based understanding and principles.

It is recommended that the detailed consideration of the capabilities and limitations of the Prototype Simulator presented in Section 6 of this report be understood prior to any application of the approach.

This report includes the following:

- Definition of UK estuary systems;
- Development of a behaviour, or qualitative, model in the form of the Prototype Simulator;
- Testing of the Simulator using two case studies;
- Assessment of its capabilities and limitation;
- Development of the web-based interface;
- A model summary providing a description of the key aspects of the Prototype Simulator;
- Recommendations for further work; and
- Details of the accessibility of the research outputs (including the web-based interface, the Matlab research code and further project outputs).

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1. Introduction

1.1 Background to the Research

This report presents the results of research project FD2117 titled ‘Development and Demonstration of Systems-Based Estuary Simulators’ (hereafter EstSim). This research forms one of three contracts awarded under Phase 2 of the Estuary Research Programme (ERP). The two other contracts under the umbrella of ERP Phase 2 are (i) FD2107: Development of Estuary Morphological Models, and (ii) FD2116: Review and Formalisation of Geomorphological Concepts and Approaches.

The three phases of the ERP seek to improve our understanding and prediction of estuarine morphological change over the medium to long-term, thereby facilitating strategic and sustainable decisions regarding flood and coastal defence.

The EMPHASYS Consortium undertook Phase 1 of this programme by evaluating existing morphological modelling approaches (EMPHASYS, 2000a; 2000b). Phase 2 includes the three projects described above with the purpose of developing the most promising approaches examined in Phase 1. It is anticipated that Phase 3 will seek to incorporate prior ERP research into an ‘Integrated Estuary Management System’. This is currently being scoped within another project under ERP Phase 2, namely FD2119 ‘Development and Dissemination of the Estuary Research Programme’.

1.1.1 Research Objectives

The overall aim of EstSim is to extend our ability to simulate estuarine response to change. This has been achieved through the delivery of research into the systems-based approach as an alternative, yet complementary, methodology to those research lines being undertaken within the other ERP Phase 2 projects (morphological concepts, bottom-up, top-down and hybrid methods). EstSim has explored the simulation process in order to facilitate knowledge exchange between the systems-based tools and estuary managers.

Additionally, this project has sought opportunities to support, link and integrate with the projects FD2107 and FD2116. In particular, a number of joint meetings have been held between EstSim and FD2107 where the research ongoing within each project has been presented and researchers given the opportunity to feedback into their respective projects. EstSim and FD2107 also undertook a joint dissemination programme. The research developed within EstSim has also provided a qualitative framework for capturing the knowledge and understanding developed within the allied ERP2 projects.

1.2 Purpose and Scope of Research

1.2.1 Purpose

The effects of natural change and anthropogenic interventions on an estuarine environment requires consideration over a range of space and time scales, and robust and justified decisions can only be made with an understanding of morphological change and the ability to predict future change.

Supporting scientific investigations must consider the complexity of the whole system and its many functional attributes, and the adoption of an 'estuarine management' approach attempts to meet the diverse aims of estuary users by considering the interlinking relationships within the estuary. Once provided, such a management system would provide a coherent and consistent framework to be applied in exploring questions regarding the effects of change, policy planning and sustainability, and hence inform balanced estuary management decisions.

The overarching objective of the Estuary Research Programme (ERP) is to develop an Estuary Management System and a fundamental requirement will be to understand and predict estuarine morphological change over the medium to long-term. The EMPHASYS Consortium undertook Phase 1 of this programme by evaluating existing morphological modelling approaches and the most promising of these approaches are being developed as part of ERP Phase 2.

On their own, numerical modelling approaches provide quantitative outputs that can inform on trends and directionality of an estuarine system response, and the parallel ERP2 projects, FD2107 and FD2116, have taken forward recommendations from ERP1 to further develop and research these methods. However, a need to capture knowledge of estuary response with other complementary, morphological tools and expert knowledge within a qualitative framework has been identified.

A systems-based approach is appropriate for the qualitative assessment of the behaviour of estuarine systems and in the context of flood and coastal defence issues, which are part of, and influence, the wider estuarine environment. A change or action in one compartment or location of the system can have much wider-scale impacts, for example a change in flow conditions altering a sediment budget and the stability of engineering or defence works.

1.2.2 Scientific Context

The rationale for applying a more formalised systems-based approach derives from the inherent complexity of interactions between physical processes, sediment transport and geomorphological form. With incomplete knowledge of these relationships, there is a benefit in developing and applying qualitative models and descriptions that do not solely rely on having precise knowledge of the physical laws governing 'bottom-up' approaches. Such methods do not preclude the use of more quantitative approaches, but are more likely to use the knowledge gained from these methods in the development of the behavioural knowledge of systems. The requirement for estuarine research in these fields has been discussed by Townend (2002) and Van Koningsveld *et al*. (2003).

The development of behavioural models that combine the physical elements (geomorphological features) and the dynamics of the interactions between elements provides a pathway to explore and populate the systems approach and this has been examined by Cowell & Thom (1994), Capobianco *et al*. (1999) and through the development of ASMITA by Stive *et al*. (1998).

1.2.3 Scope

As previously noted, the overall study objective is to provide research into the application of a systems-based approach to estuary environments as an alternative, yet complementary, approach to understanding morphological behaviour in estuaries.

This has involved the provision of a qualitative framework to assist in understanding the following:

- Presence and behaviour of geomorphological features in an estuary;
- Linkages that exist between them; and
- Their response to change.

The project has been structured into a series of scientific objectives in order to deliver the required research and dissemination. The first Objective (Objective 1, '**System Conceptualisation'**) provided detailed scoping and confirmation of the Objectives to focus subsequent effort.

Following this, Objective 3 (**'Behavioural Statements'**) provided formal definition of UK estuaries in systems-based terms. This included the development and application of a typology to classify all UK estuaries according to the presence of constituent geomorphological elements. A methodology was evolved to provide formal definition of UK estuaries, in generic terms, based on typology for each of the seven identified behavioural types and each component geomorphological element. This was achieved using systems diagrams and behavioural statements.

Objective 4 (**'Mathematical Formalisation'**) developed a mathematical framework to capture the formal definition from Objective 3. A Boolean network approach was implemented and initial proof of concept testing undertaken. This approach was expanded to incorporate a broader set of morphological and process components within Objective 5 (**'System Simulation'**). Simulation of the seven generic estuary behavioural types and development testing on two estuaries was also undertaken within Objective 5.

Objective 6 (**'Manager-System Interface'**) developed a web-based interface as a visualisation tool. The interface provides access to the prototype simulator and disseminates supporting information from the study regarding the system approach as applied to estuaries.

Objective 2 (**'Management Questions'**) identified an up-to-date and relevant list of management drivers based on a review of previous work, updating of a review on the legislative context and an end-user consultation. The outputs from this Objective were used to derive a series of scenarios applied within Objective 7 (**'Pilot Testing'**). Objective 7 undertook testing of the prototype simulator on two UK estuaries using these scenarios to provide an assessment of the capabilities and limitations of the approach.

Dissemination activities (Objective 8) included the holding of a 1-day workshop at the University of York (2nd July, 2007) at which the results of the study were presented to estuary managers, practitioners and researchers.

As part of the research, 'translation workshops' were held during each Objective to allow discussion amongst the project team regarding the ongoing work and the focussing of subsequent stages.

1.2 Report Structure

The report is presented in the following sections:

- Section 2 provides an overview of the systems-based approach, its application to estuaries and qualitative modelling.

- Section 3 then provides a definition of UK estuary systems, including a typology of UK estuaries and formal definition of estuarine systems in terms of the systems approach.

- Section 4 is concerned with the technical development of a prototype estuary simulator through the application of a Boolean network approach.

- Section 5 documents a series of pilot tests undertaken on two UK estuaries to provide an independent evaluation of the prototype simulator.

- Section 6 provides an assessment of the capabilities and limitations of both the Boolean Network approach and the Prototype simulator.

- Section 7 outlines the development of a web-based interface as a visualisation tool to support the prototype simulator. In addition details are provided of the 'Research Code web page' providing open access to the underlying MATLAB code.

- Finally, conclusions and recommendations are made within Section 8. Included within this summary is a 'model summary'. This provides a description of the key aspects of the Prototype Simulator, in terms of purpose, background, inputs, outputs, scales and range of applicability. In addition details are provided of how to access both the web-based interface and the MATLAB research code.

- Appendices: A series of appendices provide supporting information as appropriate:
  - Appendix A provides behavioural descriptions of the geomorphic elements referred to in Section 3;
  - Appendix B Management Questions, provides a summary of a consultation carried out with key stakeholders as part of the study;
  - Appendix C provides details of review carried out by Delft Hydraulics within the project to assess alternative approaches to mathematical formalisation; and
  - Appendix D provides a glossary of terms use din the Matlab code of the Prototype Simulator.

- Project Reports: In addition to this main technical Report, a series of project reports were produced from each of the project objectives (discussed above). The relevant project reports are referred to at the start of each section of this report and provide further information should this be required.

2. Overview of the Systems-Based Approach and Qualitative Modelling

2.1 Introduction

This initial overview of the systems-based approach provides the context for the remainder of the report through a discussion and review of the principles behind the methodology applied within EstSim. The section considers issues associated with the application of the systems-based approach, such as the use of systems diagrams and levels of systems abstraction. A discussion is then provided of the application of systems principles in estuarine environments. The section concludes with a discussion of the development of behavioural, or qualitative, models.

2.1.1 Project Context

Overall this section provides the background to the approaches developed within this project and their context within it. The element of work presented in this section was used to confirm the proposed approach and steer the remaining objective within the study.

This was achieved through (the completion of research within) Objectives 1 and 3 (‘System Conceptualisation and Behavioural Statements respectively). The outputs of these Objectives are reported within EstSim Project Reports 1 (ABPmer, 2004) and 2 (ABPmer, 2007a).

2.2 Review of Systems Approach

The systems-based approach involves separating out sub-systems and their interactions in order to understand the system organisation and define its behaviour. It thus combines both the physical elements and the dynamics of the interactions between those elements in order to explain how the different elements that make up the system interact and respond to change (Cowell & Thom, 1994; Capobianco *et al*. 1999).

The systems approach has been applied and reviewed by various workers (Chorley & Kennedy, 1971; White *et al*., 1984; Cowell & Thom, 1994; Capobianco *et al*., 1999; Townend, 2003) and some of the key issues identified from these studies are summarised here.

2.2.1 Systems Diagrams

Systems diagrams provide a means of capturing the key attributes of a system by identifying the system elements and their interactions. A systems diagram is a flowchart representation and its ability to capture the behaviour of the systems will depend upon the fundamental knowledge of coastal processes and the ways in which these are expressed. Different examples of system diagrams that demonstrate a number of key features are presented in Figures 1-4.

It is important to note that in the examples provided in Figures 1-4, the systems diagrams are attempting only to identify the presence of, and interactions between, the key elements within natural systems. The systems diagrams do not include any anthropogenic influences on these systems.

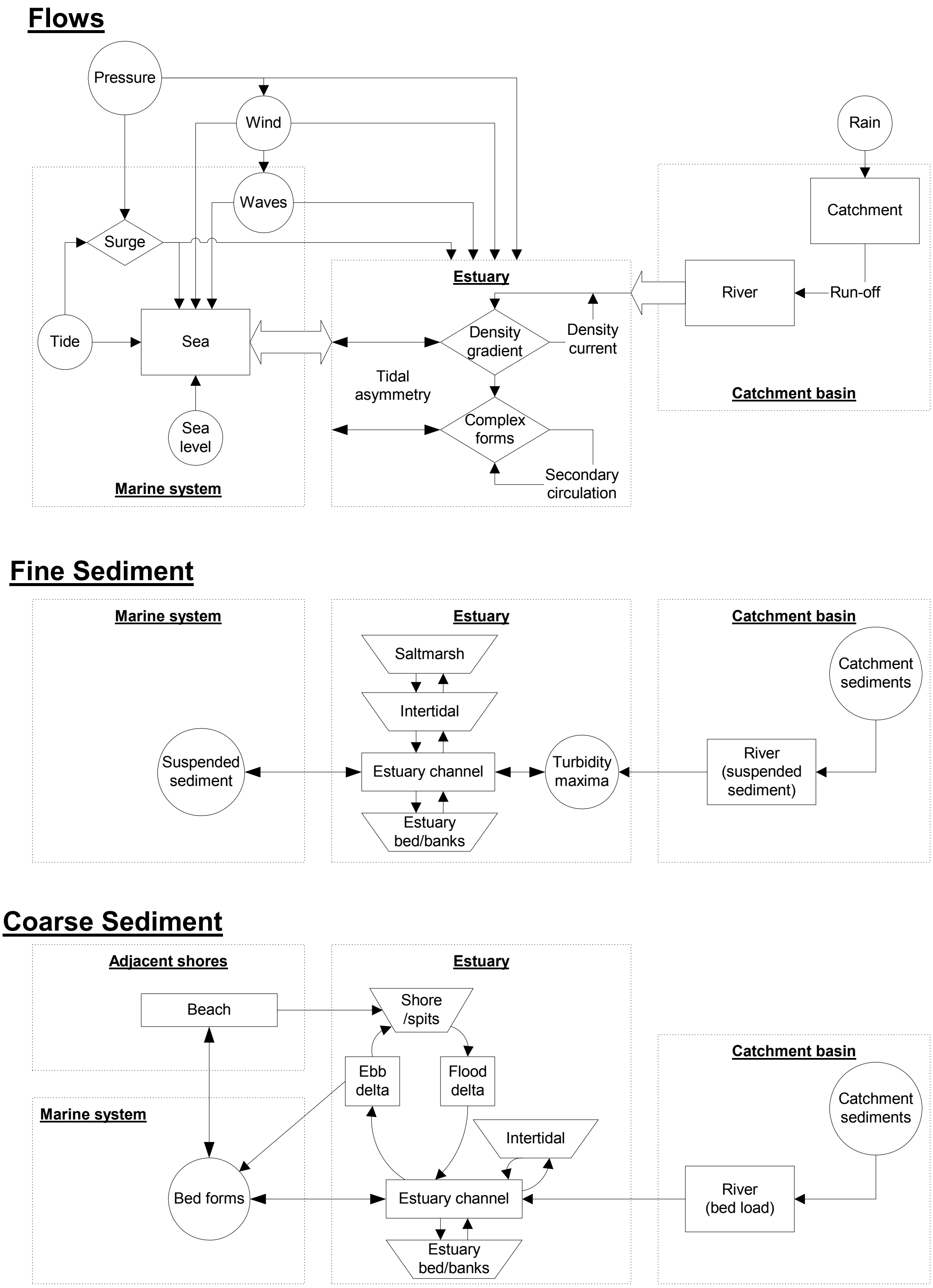


Figure 1. **Estuary represented as flows, fine and coarse sediment interactions (Townend, 2003)**

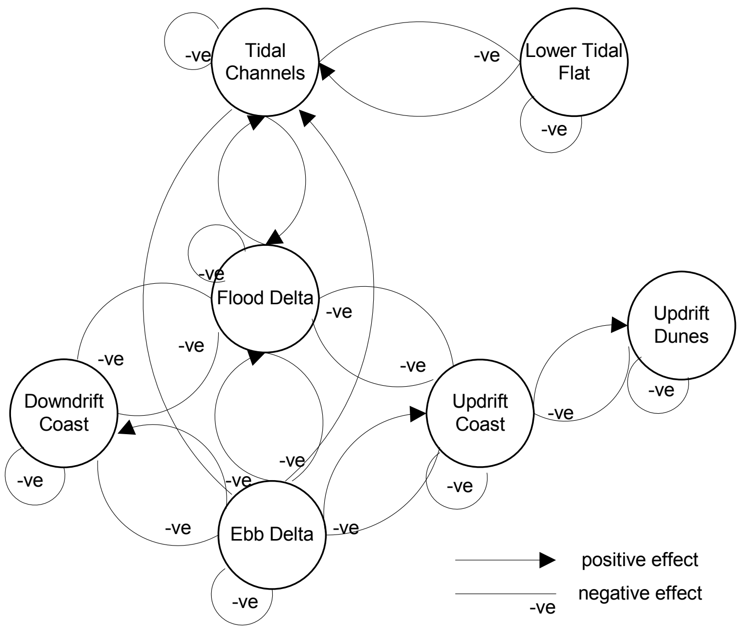


Figure 2. Signed graph representation for the impacts of sea-level rise on an inlet or lagoon entrance (Capobianco *et al.*, 1999)

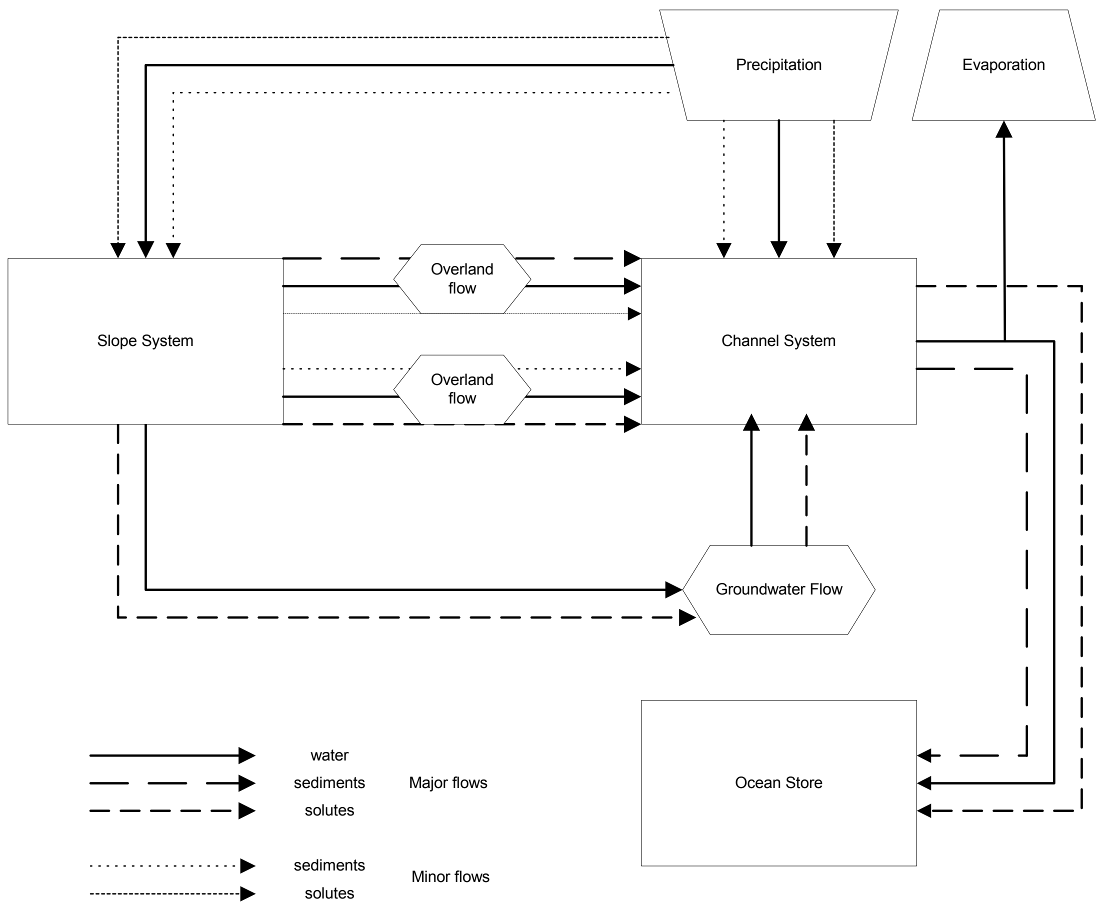
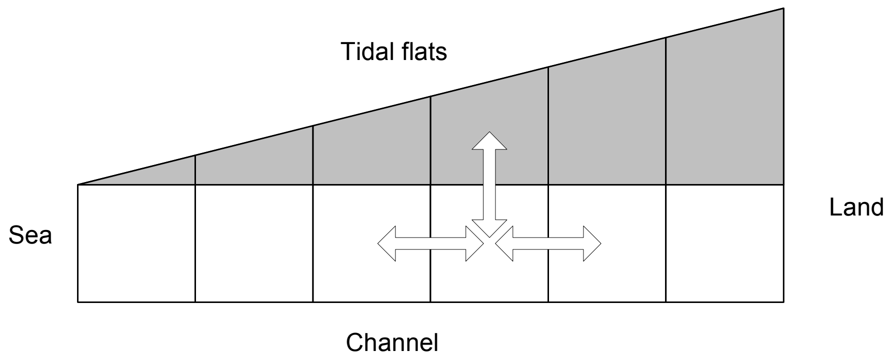
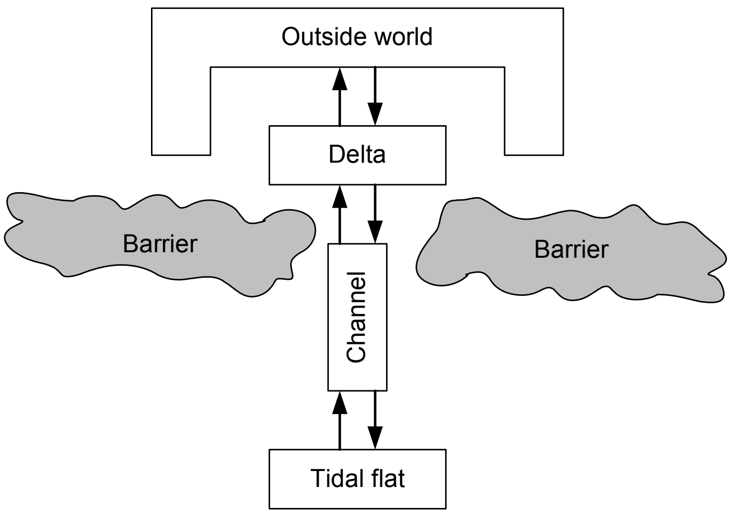


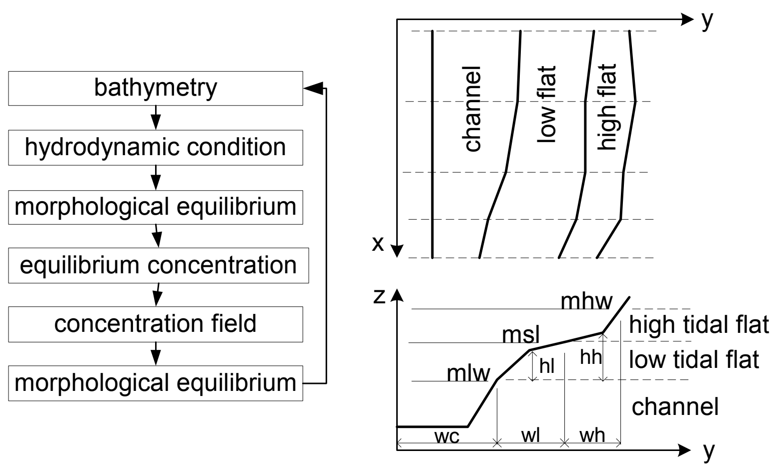
Figure 3. Diagram showing the pathways through the catchment basin system (White *et al.*, 1984)



a) Tidal basin schematisation used by van Dongeren and de Vriend (1994)



b) Schematisation of elements and exchanges within the ASMITA model



c) Procedure and schematisation used in ESTMORF (Wang et al, 1998)

Figure 4. Schematisations used in selected tidal inlet models

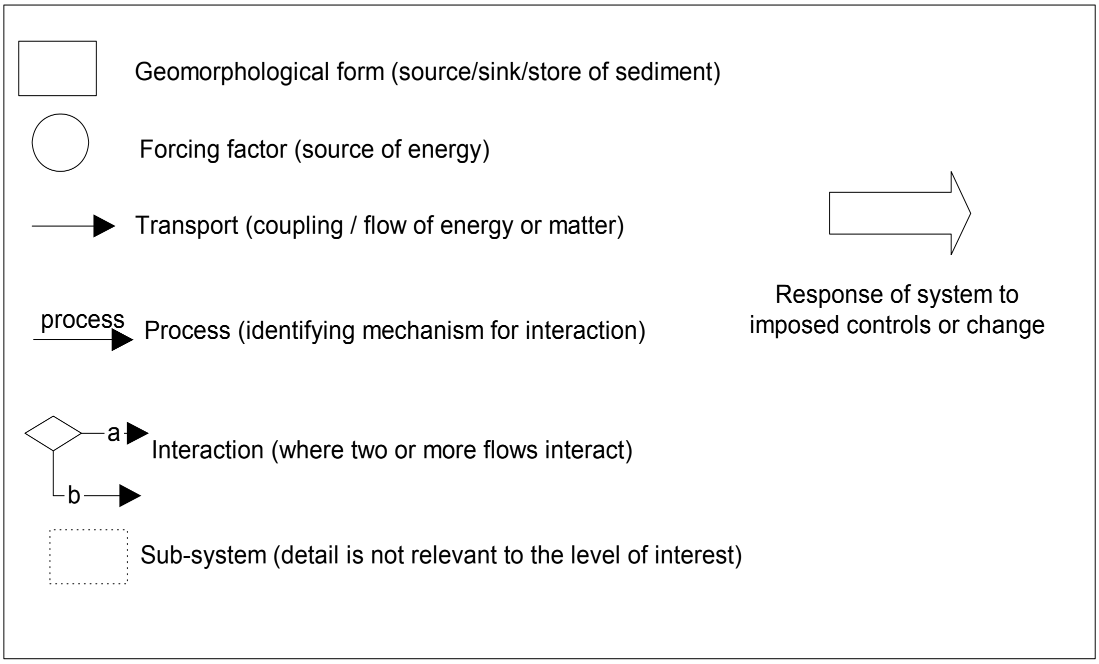
The objective of defining systems diagrams is to represent the interactions between system components. This should ideally capture the behavioural attributes of the system and inform abstraction and aggregation to different system levels.

The physical components of an estuary system can be simply identified within a systems diagram by different symbols/nomenclatures (Figure 5) after adapting the convention used by Wilson (1982).

In order to better express system interactions, this convention can be extended where the relationships between different system elements are known. For instance, the example given in Figure 2 shows how an interaction or coupling flow can be defined in terms of the nature of the element's response. In this case the response can be for a positive or negative tendency/effect.

A systems diagram can be used to show the relative dominance of interactions and flows (Figure 3), where minor and major flows are differentiated by the boldness of the connector. This system can also differentiate between the transport of different substances on the same system level by using a range of line types or colours.

Use of the above convention is not meant to constrain systems representation. Alternative techniques should be applied where these can convey the desired system behaviour or response.



Note: The nature of the geomorphological form in terms of its role as a source/store and/or sink will implicitly be given by the presence/absence of a connecting flow and the direction of transport.

Figure 5. System diagram symbol convention

2.2.2 Abstraction and Systems Levels

The complexity of the coastal system, range of physical processes present and relevant spatial and temporal scales will determine how the system is represented.

If every known system element and interaction were presented on one system diagram, the complexity would inhibit an understanding of the whole system. Hence, abstraction is an important procedure for separating the system into layers. Figure 1 demonstrates abstraction of different processes involving different mediums (water and coarse/fine sediments) into three separate layers operating over the same timescale. Abstraction must also be considered over the hierarchy of spatial and temporal scales (Figure 6).

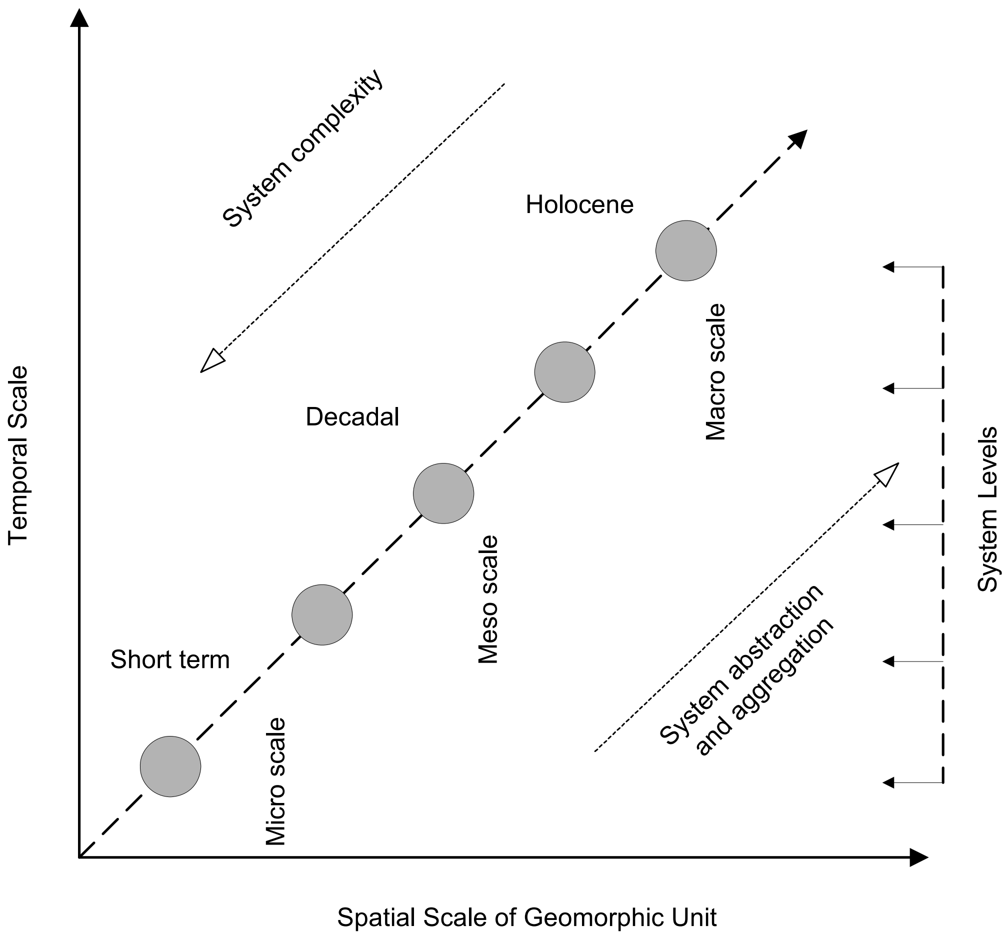


Figure 6. General relationship between temporal and spatial scales of geomorphic evolution showing different levels of system abstraction

For coastal geomorphology various levels of abstraction have been cited and categorised (Townend, 2003; Cowell *et al*., 2003).

One possible categorisation of spatial scales is as follows:

- Macro-scale - regional land mass behaviour;
- Meso-scale - geomorphological unit behaviour;
- Micro-scale - geomorphological features;
- Nano scale - particle behaviour;
- Atto scale - sub-atomic/quantum behaviour.

Each level of abstraction could be defined as a behaviour model, which can be chosen on the basis of the type of question we are seeking to answer.

At any one level of abstraction, elements and interactions that add detail and complexity, but make only a minor contribution to system response, can be omitted. This is an explicit process when abstracting from a high level of detail to subsequent lower levels but is also an important property of qualitative/behavioural modelling (aggregation) where the behavioural description of system interactions does not need to be based on the underlying physical processes. Essentially, it follows that the detailed system/processes that dominate the level of interest will be taking place at the next level down. Therefore each level is doing some form of averaging to relate the detailed structure at one level to the more general behaviour at the next level (Schumm & Lichty, 1965).

An example of a top-level abstraction of an estuary system, shown as a simple tidal inlet, is given by the ASMITA model (Figure 4b). Here, sub-systems could be added to provide the detail of subsequent lower levels. However, abstraction should be treated with care to ensure that relatively small exchanges at any one level are not ignored at a higher level purely on the basis of their scale, since the accumulation of these small exchanges may actually produce morphologically significant effects (Cowell *et al*., 2003).

In determining the rationale for system abstraction for each level, there does not seem to be an obvious choice. Each level may comprise elements that interact over the same temporal or spatial scales or may be more complex as noted above. Cowell *et al*. (2003) suggest the 'cascade' of levels is partitioned on the basis that each level forms an internally sediment-sharing system.

One of the driving aims behind this research is to inform decision-making concerning coastal management issues over the medium-term (decadal period) where uncertainties in current modelling approaches limit the accuracy of solutions.

2.2.3 Behavioural / Qualitative Modelling

The discussion in previous sections has focused on the role of the systems approach and systems diagrams to map out interactions within an estuarine system. This approach can map the system components (elements and interactions) at a specified level of interest. However, attempting to model this detailed system is limited by current understanding of the detailed processes and is one of the reasons why a behavioural systems approach is being investigated as an alternative to detailed process modelling.

The limitations of the systems diagram approach are, however, fully recognised (Townend, 2003). It is noted that that whilst systems diagrams make clear the nature of flows of energy and matter, and the interactions and feedbacks between elements, they say little about the relationship between components and the character of any response.

This is where behavioural or qualitative modelling (Capobianco *et al*., 1999) can be thought of as extending the basic systems approach. The concept of behavioural modelling is to develop an understanding of the behaviour of the system by capturing the nature of relationships between system components and mapping it onto a simple model, which exhibits the same behaviour, but which does not need to have any relationship to the underlying physical processes. Whereas systems diagrams highlight the presence of interactions, the behavioural approach places emphasis on developing the interaction as a relationship (response). The difference between the two approaches is evident in Figure 7, which both identifies interactions and provides a behavioural response. In the context of an estuarine system the identification of a behavioural system is an attempt to integrate geomorphological units that are spatially contiguous into a unified entity that reflects how it is likely to change.

A behavioural system representation of the coast is therefore essentially a top-down view as it seeks to capture an overall coastal response. However, it can be seen that arriving at such a system view could be developed in a number of ways such as from either a bottom-up ‘reductionist’ starting point with a gradual increase in abstraction and aggregation, or directly from the top after understanding a form of coastal response that can be captured by a behavioural relationship.

The potential of qualitative modelling as a means of providing indicative rather than strictly quantitative insights into the behaviour of systems specified in this manner, has been highlighted by Capobianco *et al.* (1999), who identified seven stages associated with the development of a qualitative model of system behaviour (Figure 7). These include the identification of qualitative variables and the causal linkages between them, which typically involve the construction of system diagrams of some form. Modelling of system behaviour then requires the definition of a mathematical quantity space to represent interaction between these qualitative state variables. Figure 2 shows a qualitative model for a generic tidal inlet system subject to a rise in sea level, wherein the quantity space is defined in terms of a signed graph, with positive or negative effects connecting the main system variables. Transfer rules and knowledge formalisation are then needed to convert either quantitative understanding (which might take the form of empirical scaling relationships or physically-based process laws) or linguistic understanding (e.g. a statement describing the behaviour of a sub-component) of system linkages into a set of cause-effect relationships.

1. *Identification of qualitative variables* and the likely relationships between them
2. *Conceptual representation* and definition of causal inference network
3. *Definition of a quantity space* - a finite set of symbols to define values of state variables
4. *Establish transfer rules* that can be used to develop qualitative relationships between variables
5. *Knowledge formalisation*, in which transfer rules are used to define cause-effect relationships
6. *Qualitative translation of measurements*, where variables are assigned values from the quantity space
7. *Application of qualitative calculus* to analyse characteristics of the model

(Adapted from Capobianco *et al.*, 1999)

Figure 7. Construction of a qualitative model

3. Definition of UK Estuary Systems

3.1 Introduction

This section provides a formal definition of UK estuary systems, which is presented as a classification of all UK estuaries. Seven estuarine behavioural types are identified based on the presence of constituent geomorphological elements. A protocol for systems diagrams and behavioural statements for UK estuaries is then presented. The results of the application of this protocol are then presented in the form of behavioural statements and systems diagrams for each identified estuary behavioural type and geomorphological element. This approach provides qualitative definition, at the generic level, of the estuary systems.

3.1.1 Project Context

Within the research, the classification of UK estuaries into behavioural types was completed in order to identify the range of geomorphological elements present within each behavioural type. This then provides the starting point for a formal definition of estuary systems found in the UK. Formal definition is provided through the mapping out of the geomorphological sub-systems and exploration of systems diagrams and their ability to encapsulate different types of behavioural response. The formal definition of UK estuary systems in turn provides the basis for the development of a behavioural model through mathematical formalisation of the defined systems.

This element of the research also acted to ensure the later work remained focussed on UK estuaries. In addition to this, the formal definition of UK estuaries in generic terms provides the framework for the production of estuary specific behavioural statements.

The work presented within this Section was completed within Objective 3, Behavioural Statements, the outputs of which are reported in Project Report 2 (ABPmer, 2007a).

3.2 Classification of UK Estuaries

3.2.1 Estuary Typology

The categorisation of estuaries can make use of many systems, including those based on origin, physical processes (tidal range and stratification) and characteristic geomorphological components. A number of recent classification schemes have been examined, including those of Hume & Herdendorf (1988) and Davidson (1991). Of particular relevance is the recent work undertaken by Dyer within the Futurecoast Consortium (Defra, 2002). The classification produced by Dyer is shown in Table 1.

Table 1. Estuary Classification Scheme (Futurecoast; Defra, 2002)

Type	Origin	Behavioural Type	Sub-Type
1a	Glacial valley	Fjord	With spits
1b			No spits
2a		Fjard	With spits
2b			No spits
3a	Drowned river valley	Ria	With spits
3b			No spits
4a		Spit-enclosed	Single spit
4b			Double spit
4c			Filled valley
5		Funnel-shaped	
6		Embayment	
7a	Drowned coastal plain	Tidal inlet	Symmetrical
7b			Asymmetrical

This classification (Table 1) was amended and simplified to provide a working typology with which to progress the study for UK estuaries (Table 2).

In particular, types (a) and (b) have been merged because these simply distinguish the presence of one geomorphological unit (spits). The filled valley has been omitted as a distinct type, since all estuaries have been subject to greater or lesser infilling over the Holocene and this simply reflects a particular state of a Type 4 estuary.

In terms of geomorphological elements, Table 2 combines the elements identified in Futurecoast with those defined by the EstSim project team. Specific amendments that have been made include the removal of 'shallow subtidal' as this is not considered to be an independent unit geomorphologically; the low water channel, as this is a variant of the ebb/flood channel (i.e. it dries); and also cheniers because they can be considered as a sub-component of mudflat and saltmarsh systems. Table 2 then identifies which geomorphological elements are potentially present in the different types of estuary.

Table 2. Estuary Typology (modified from Defra, 2002)

Type	Origin	Behavioural Type	Spits[1]	Barrier Beach	Dune	Delta	Linear Banks[2]	Channels[3]	Rock Platform	Sand Flats	Mud Flats	Salt marsh	Cliff	Flood Plain[4]	Drainage Basin
1	Glacial valley	Fjord	X					X	X	X			X		X
2		Fjard	0/1/2					X	X	X	X	X		X	X
3	Drowned river valley	Ria	0/1/2					X	X		X	X	X		X
4		Spit-enclosed	1/2		X	E/F		X/N		X	X	X	X	X	X
5		Funnel-shaped	X		X	E/F		X		X	X	X		X	X
6	Marine/fluvial	Embayment			X		X	X		X	X	X		X	
7	Drowned coastal plain	Tidal inlet	1/2	X	X	E/F		X		X	X	X		X	

Notes:
1 Spits: 0/1/2 refers to number of spits; E/F refers to ebb/flood deltas; N refers to no low water channel; X indicates a significant presence.
2 Linear Banks: considered as alternative form of delta.
3 Channels: refers to presence of ebb/flood channels associated with deltas or an estuary subtidal channel.
4 Flood Plain: refers to presence of accommodation space on estuary hinterland.

3.2.2 Estuary Classification

In order to test the typology presented in Table 2, a rule base was set-up (Table 3) and applied to the estuary data from EMPHASYS, Futurecoast and the JNCC inventory. This gives results that are reasonably consistent with previous classifications. The main differences arise due to the definition of a rock platform and the role this plays in determining whether an estuary of river origin is a ria or not. The revised classification also suggests some differences in the distinction between fjords and fjards. A number of the coastal bays or shorelines within the (Davidson) JNCC classification of estuaries are unclassified in this scheme (see Table 4).

The resultant classification for UK estuaries is presented in Table 4. This should be considered as provisional as there remain a number of uncertainties as to the validity of various attributions made in the source data and these are identified by the use of italics. The distinction between fjords and fjards also leads to some uncertainty, as already noted.

The classification for UK estuaries presented in Table 4 ensures that the behavioural statements and systems diagrams, presented in the following sections, are applicable to all the estuarine types found in the UK. In doing this, application of the classification ensures the behavioural relationships explored, developed and applied through the later stages of the project are also applicable and focused on UK.

Table 3. EstSim Rules to Identify Estuary Type Using the UK Estuaries Database

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

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

Table 4. Classification of UK Estuaries Based on Rule Base Defined in Table 3

Id	Estuary Name	Behavioural Type		Numeric Type	
		JNCC	EstSim	EstSim	Futurecoast
1	Hayle Estuary	Bar Built Estuary	Spit Enclosed	4	4b
2	Gannel Estuary	Ria	Ria	3	3b
3	Camel Estuary	Ria	Ria	3	3b
4	Taw-Torridge Estuary	Bar Built Estuary	Spit Enclosed	4	4b
5	Blue Anchor Bay	Embayment		0	0
6	Bridgwater Bay	Embayment	Spit Enclosed	4	4c
7	Severn Estuary	Coastal Plain	Funnel	5	3b
8	Thaw Estuary	Coastal Plain		0	0
9	Ogmore Estuary	Coastal Plain	Spit Enclosed	4	4a
10	Afan Estuary	Bar Built Estuary	Tidal inlet	7	7
11	Neath Estuary	Ria	Spit Enclosed	4	4c
12	Tawe Estuary & Swansea Bay	Embayment	Spit Enclosed	4	4c
13	Loughor Estuary	Coastal Plain	Spit Enclosed	4	4b
14	Carmarthen Bay	Embayment	Embayment	6	4b
15	Milford Haven	Ria	Ria	3	3b
16	Nyfer Estuary	Bar Built Estuary	Ria	3	4c
17	Teifi Estuary	Bar Built Estuary	Ria	3	4c
18	Aberystwyth	Bar Built Estuary	Spit Enclosed	4	3a
19	Dyfi Estuary	Bar Built Estuary	Spit Enclosed	4	3a
20	Dysynni Estuary	Bar Built Estuary	Spit Enclosed	4	4a
21	Mawddach Estuary	Bar Built Estuary	Spit Enclosed	4	3a
22	Artro Estuary	Bar Built Estuary	Spit Enclosed	4	7a
23	Traeth Bach	Bar Built Estuary	Ria	3	3a
24	Pwllheli Harbour	Bar Built Estuary	Spit Enclosed	4	2a
25	Foryd Bay	Bar Built Estuary	Tidal inlet	7	7b
26	Traeth Melynog	Bar Built Estuary	Tidal inlet	7	7b
27	Cefni Estuary	Bar Built Estuary	Ria	3	3b
28	Alaw Estuary	Fjard Macrotidal	Fjard	2	2b
29	Traeth Dulas	Bar Built Estuary	Ria	3	3a
30	Traeth Coch	Linear shore		0	0
31	Traeth Lavan	Embayment		0	0
32	Conwy Estuary	Coastal Plain	Spit Enclosed	4	3a
33	Clwyd Estuary	Coastal Plain	Spit Enclosed	4	4b
34	Dee Estuary & North Wirral	Coastal Plain	Spit Enclosed	4	4a
35	Mersey Estuary	Coastal Plain	Ria	3	3b
36	Alt Estuary	Coastal Plain	Spit Enclosed	4	0
37	Ribble Estuary	Coastal Plain	Funnel	5	5
38	Morecambe Bay	Embayment	Spit Enclosed	4	4b
39	Duddon Estuary	Coastal Plain	Spit Enclosed	4	4b
40	Esk Estuary (Cumbria)	Bar Built Estuary	Spit Enclosed	4	4b
41	Inner Solway Firth	Complex	Embayment	6	5

Id	Estuary Name	Behavioural Type		Numeric Type	
		JNCC	EstSim	EstSim	Futurecoast
42	Rough Firth Auchencairn Bay	Fjard	Fjard	2	0
43	Dee Estuary (Dumfries & Gallo	Fjard	Fjard	2	0
44	Water of Fleet	Fjard	Fjard	2	0
45	Cree Estuary	Fjard	Fjard	2	0
46	Luce Bay	Linear shore	Spit Enclosed	4	0
47	Garnock Estuary	Bar Built Estuary	Spit Enclosed	4	0
48	Hunterston Sands	Linear shore		0	0
49	Clyde Estuary	Fjord	Fjard	2	0
50	Ruel Estuary	Fjord	Fjord	1	0
51	Loch Gilp	Fjord	Fjord	1	0
52	Tràigh Cill-a-Rubha	Embayment	Fjard	2	0
53	Loch Gruinart	Fjard	Fjard	2	0
54	Loch Crinan	Fjard	Fjard	2	0
55	Kentra Bay	Fjard	Fjard	2	0
56	Loch Moidart	Fjard	Fjord	1	0
57	Tràigh Mhor	Embayment		0	0
58	Bagh Nam Faoilean	Fjard	Fjard	2	0
59	Oitir Mhor	Fjard	Fjard	2	0
60	Tràigh Valley	Fjard	Fjard	2	0
61	Oronsay	Fjard	Fjard	2	0
62	Scarista	Embayment	Fjard	2	0
63	Tràigh Luskentyre	Fjord		0	0
64	Camus Uig	Fjard	Fjard	2	0
65	Laxdale Estuary	Fjard	Fjard	2	0
66	Kyle of Durness	Fjard	Fjard	2	0
67	Kyle of Tongue	Fjard	Fjard	2	0
68	Torrisdale Bay	Fjard	Fjard	2	0
69	Melvich Bay	Fjard	Fjard	2	0
70	Otters Wick	Fjard	Fjard	2	0
71	Cata Sand	Bar Built Estuary	Tidal inlet	7	0
72	Kettletoft Bay	Fjard	Tidal inlet	7	0
73	Deer Sound and Peter's Pool	Fjard	Fjard	2	0
74	Loch Fleet	Bar Built Estuary	Spit Enclosed	4	0
75	Dornoch Firth	Complex	Ria	3	0
76	Cromarty Firth	Complex	Fjard	2	0
77	Inner Moray Firth	Complex	Ria	3	0
78	Lossie Estuary	Bar Built Estuary	Spit Enclosed	4	0
79	Spey Bay	Bar Built Estuary	Spit Enclosed	4	0
80	Banff Bay	Embayment	Ria	3	0
81	Ythan Estuary	Bar Built Estuary	Spit Enclosed	4	0
82	Don Estuary	Coastal Plain	Spit Enclosed	4	0
83	Dee Estuary (Grampian)	Coastal Plain	Ria	3	0

Id	Estuary Name	Behavioural Type		Numeric Type	
		JNCC	EstSim	EstSim	Futurecoast
84	St Cyrus	Bar Built Estuary	Spit Enclosed	4	0
85	Montrose Basin	Bar Built Estuary	Spit Enclosed	4	0
86	Firth of Tay	Complex	Spit Enclosed	4	0
87	Eden Estuary	Bar Built Estuary	Spit Enclosed	4	0
88	Firth of Forth	Complex	Ria	3	0
89	Tyninghame Bay	Bar Built Estuary	Spit Enclosed	4	0
90	Tweed Estuary	Complex	Ria	3	3b
91	Lindisfarne & Budle Bay	Barrier Beach	Tidal inlet	7	0
92	Alnmouth	Bar Built Estuary	Spit Enclosed	4	4b
93	Warkworth Harbour	Bar Built Estuary	Spit Enclosed	4	4a
94	Wansbeck Estuary	Coastal Plain	Spit Enclosed	4	4a
95	Blyth Estuary (Northumberland)	Bar Built Estuary	Ria	3	4a
96	Tyne Estuary	Complex	Ria	3	3b
97	Wear Estuary	Complex	Ria	3	3a
98	Tees Estuary	Coastal Plain	Spit Enclosed	4	4b
99	Esk Estuary (Yorkshire)	Complex	Ria	3	3b
100	Humber Estuary	Coastal Plain	Spit Enclosed	4	4a
101	The Wash	Embayment	Embayment	6	6
102	North Norfolk Coast	Barrier Beach	Tidal inlet	7	0
103	Breydon Water	Bar Built Estuary	Spit Enclosed	4	4a
104	Oulton Broad	Bar Built Estuary	Spit Enclosed	4	4a
105	Blyth Estuary (Suffolk)	Bar Built Estuary	Spit Enclosed	4	4a
106	Ore-Alde-Butley	Bar Built Estuary	Spit Enclosed	4	4a
107	Deben Estuary	Coastal Plain	Spit Enclosed	4	4b
108	Orwell Estuary	Coastal Plain	Spit Enclosed	4	4a
109	Stour Estuary	Coastal Plain	Spit Enclosed	4	0
110	Hamford Water	Embayment	Tidal inlet	7	4b
111	Colne Estuary	Coastal Plain	Spit Enclosed	4	4b
112	Blackwater Estuary	Coastal Plain	Spit Enclosed	4	4a
113	Dengie Flat	Linear shore		0	0
114	Crouch-Roach Estuary	Coastal Plain	Spit Enclosed	4	4a
115	Maplin Sands	Linear shore		0	0
116	Southend-on-Sea	Linear shore	Spit Enclosed	4	0
117	Thames Estuary	Coastal Plain	Funnel	5	5
118	South Thames Marshes	Linear shore		0	0
119	Medway Estuary	Coastal Plain	Spit Enclosed	4	4a
120	Swale Estuary	Coastal Plain	Spit Enclosed	4	4a
121	Pegwell Bay	Embayment	Spit Enclosed	4	4a
122	Rother Estuary	Bar Built Estuary	Spit Enclosed	4	4b/4c
123	Cuckmere Estuary	Coastal Plain	Spit Enclosed	4	4c
124	Ouse Estuary	Coastal Plain	Spit Enclosed	4	4a
125	Adur Estuary	Coastal Plain	Spit Enclosed	4	4a

Id	Estuary Name	Behavioural Type		Numeric Type	
		JNCC	EstSim	EstSim	Futurecoast
126	Arun Estuary	Coastal Plain	Spit Enclosed	4	4a
127	Pagham Harbour	Bar Built Estuary	Tidal inlet	7	7a
128	Chichester Harbour	Bar Built Estuary	Tidal inlet	7	7a
129	Langstone Harbour	Bar Built Estuary	Tidal inlet	7	7a
130	Portsmouth Harbour	Bar Built Estuary	Tidal inlet	7	7a
131	Southampton Water	Coastal Plain	Spit Enclosed	4	4a
132	Beaulieu River	Bar Built Estuary	Spit Enclosed	4	4a
133	Lymington Estuary	Coastal Plain	Spit Enclosed	4	4c
134	Bembridge Harbour	Coastal Plain	Spit Enclosed	4	4b
135	Wootton Creek & Ryde Sands	Coastal Plain	Spit Enclosed	4	4c
136	Medina Estuary	Coastal Plain	Funnel	5	3b
137	Newtown Estuary	Bar Built Estuary	Spit Enclosed	4	4c
138	Yar Estuary	Coastal Plain	Spit Enclosed	4	4c
139	Christchurch Harbour	Bar Built Estuary	Spit Enclosed	4	3a
140	Poole Harbour	Bar Built Estuary	Spit Enclosed	4	4b
141	The Fleet & Portland Harbour	Bar Built Estuary	Tidal inlet	7	4a
142	Axe Estuary	Bar Built Estuary	Spit Enclosed	4	4c
143	Otter Estuary	Bar Built Estuary	Spit Enclosed	4	4c
144	Exe Estuary	Bar Built Estuary	Spit Enclosed	4	4a
145	Teign Estuary	Ria	Spit Enclosed	4	4a
146	Dart Estuary	Ria	Ria	3	3b
147	Salcombe & Kingsbridge Estuary	Ria	Ria	3	3b
148	Avon Estuary	Ria	Ria	3	3b
149	Erme Estuary	Ria	Ria	3	3b
150	Yealm Estuary	Ria	Ria	3	3b
151	Plymouth Sound	Ria	Ria	3	3b
152	Looe Estuary	Ria	Ria	3	3b
153	Fowey Estuary	Ria	Ria	3	3b
154	Falmouth	Ria	Ria	3	3b
155	Helford Estuary	Ria	Ria	3	3b
156	Lough Foyle	Coastal Plain	Fjard	2	0
157	Bann Estuary	Bar Built Estuary	Spit Enclosed	4	0
158	Larne Lough	Coastal Plain	Fjard	2	0
159	Belfast Lough	Coastal Plain	Fjard	2	0
160	Strangford Lough	Complex	Fjard	2	0
161	Killough Harbour	Embayment	Ria	3	0
162	Dundrum Bay	Bar Built Estuary	Tidal inlet	7	0
163	Carlingford Lough	Complex	Fjard	2	0

Notes:

[1] The JNCC dataset includes Linear Shores. For completeness, the rule base presented in Table 3 has been applied to the whole dataset and as a result Linear Shores are also included in Table 4. However, these forms are not carried through into other tasks within the project.

For each estuary, the classification derived within the JNCC work and within Futurecoast is presented for comparative purposes. Alongside these data, the classification derived within this project through the application of the rule base presented in Table 4 is presented (labelled EstSim) in the form of the Behavioural Type and Numeric Type. It is this classification that is carried through to the remainder of the project.

3.3 Behavioural Mapping Protocols

The following section builds on the application of the estuary typology to classify the seven generic estuary types and the systems review presented in Section 2 to provide a simple protocol to present statements for each of the estuary types and eleven component geomorphic elements within estuaries. This mapping of system behaviour comprises two stages, including both a behavioural (textural) description and systems diagrams

3.3.1 Protocols for Behavioural Statements

The purpose of developing behavioural statements is to facilitate (i) our understanding of relationships between different elements and the key forcing factors, and (ii) the translation of these relationships into a model domain capable of simulation.

The textural description for each estuary type is at a high level identifying the main behavioural attributes, whilst for each geomorphic element the following sub headings provide a guide to the descriptive content required:

- **Definition of Geomorphic Element (GE):**
  Providing an overall definition of the GE in question through for example, a description of the key aspects of the form, formation, processes or location within an estuary system.

- **Function:**
  Defining the role of the GE within the physical system in terms of exchanges of energy and mass.

- **Formation and Evolution:**
  Providing details of the processes that lead to the formation of the particular GE and how the GE develops and evolves over time.

- **General Form:**
  Describing the characteristic shape (or component shapes) of the GE, where appropriate highlighting the prevailing conditions under which a particular form will be adopted.

- **General Behaviour:**
  The general behaviour of the GE is described in terms of how the GE may respond to the varying forcing to which it can be exposed.

- **Forcing Factors:**
  This section describes the key processes (for example, wave attack) responsible for shaping the GE, with details provided where appropriate of role of the forcing processes.

- **Evolutionary Constraints:**
  This section details the factors that may alter or constrain the development of the GE leading to a differing evolution due to that constraint.

- **Behavioural Timescales:**
  As discussed above, landforms will respond to forcing over a range of time and space scales, and will exhibit characteristic responses of differing scales. For each GE, the behaviour of the element is discussed over different timescales.

- **Interactions with Other Geomorphic Elements:**
  Each GE will be linked to other GEs present within a particular estuary system. This section identifies the interactions in terms of flows of energy and/or matter between GEs. Interactions are identified and discussed either in terms of general interactions (for both elements within the estuary system and external to the estuary system) or interaction with specific geomorphic elements.

In addition to the input from knowledge and methods presented within the Futurecoast project and the scientific literature referenced previously, completion of the geomorphological descriptions was aided by improved knowledge from the EstProc project (EstProc, 2004).

3.3.2 Protocols for Systems Diagrams

A mapping of the estuary system in terms of key geomorphological elements within the coastal and river basin setting is shown in Figure 8 and a more detailed representation of the generic estuary elements shown in Figure 9. Using this generic figure (Figure 9) as a basis, system diagrams have been prepared for each estuary type (Section 3.4).

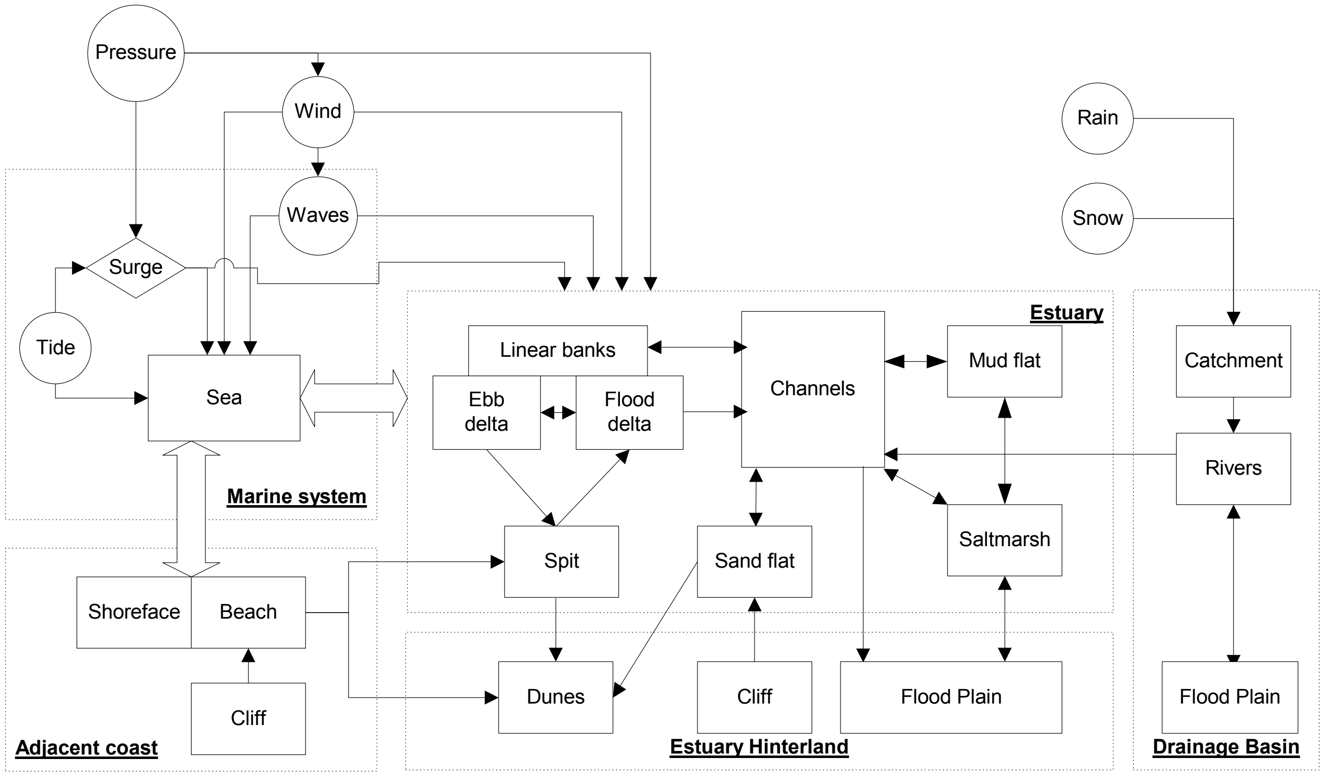


Figure 8. Systems map of the estuary within a coastal and catchment setting

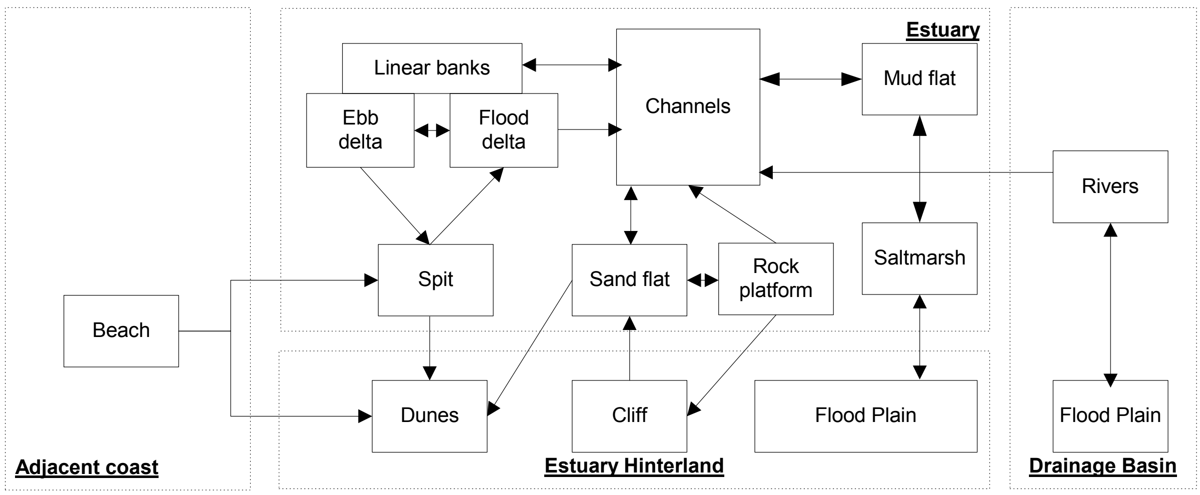


Figure 9. Generic estuary geomorphological units

Notes:
(i) Holocene bed is not shown, but will be present as a consequence of long-term accretion and consolidation.
(ii) Channels can include both ebb/flood channels and/or a subtidal channel.
(iii) Sand flats include mixed sediment beds.
(iv) Linear banks and the ebb/flood delta are alternatives (usually reflecting the tidal range).
(v) Flood plains are differentiated between those in the upstream drainage basin and those adjacent to the estuary, although they may represent a continuum.

Systems diagrams for both estuary type and geomorphic elements have applied the general convention shown in Section 3.3.1 to describe the nature of the interactions.

3.3.3 Temporal and Spatial Scales

Temporal and spatial scales within a systems approach and levels of systems abstraction are discussed in Section 2.2.2, and temporal scales are covered later in this section. Morphological behaviour will depend on, amongst other factors, the temporal and spatial scale of consideration, or the level of abstraction. Defining an appropriate level of abstraction for the behavioural statements is therefore central to capturing aspects of estuarine systems behaviour.

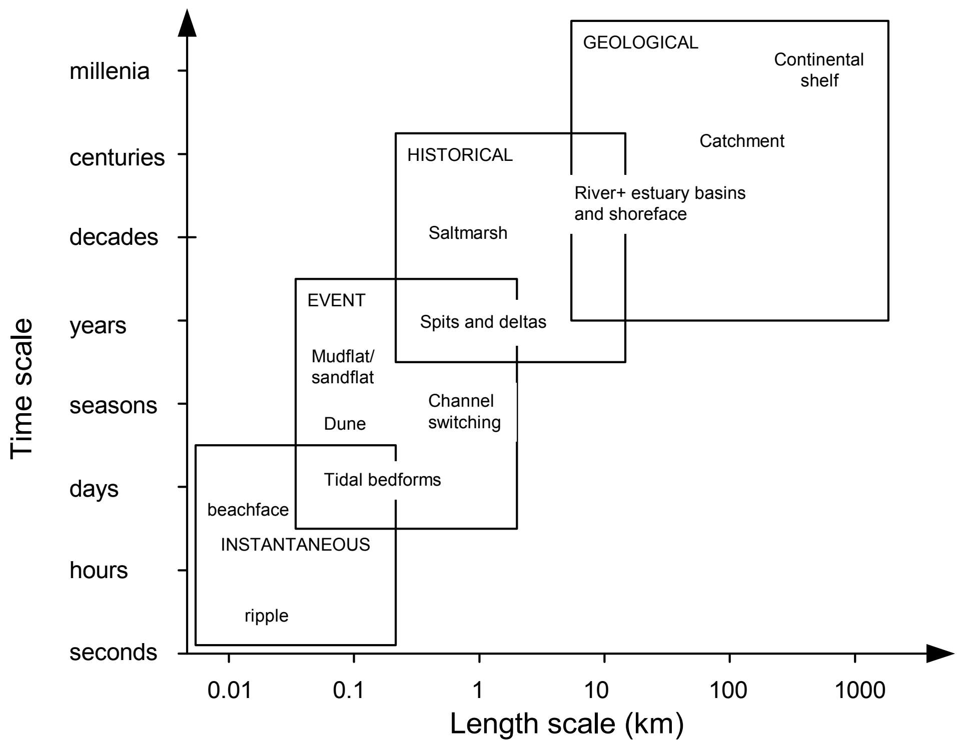


Figure 10. Temporal and spatial scales of behavioural responses (After Cowell & Thom, 1994)

Different processes will dominate different elements of the system over different timescales. This is clearly demonstrated by Figure 10, illustrating the different behavioural timescales for different system components.

The spatial scales for the production of behavioural statements within this report have been defined, i.e. at estuary wide level (estuary type statements) and geomorphic element level.

In terms of temporal scales, for the purpose of describing geomorphic systems within this report the emphasis is on the response of the systems to forcing factors and interactions with other elements, and three timescales have been chosen as an initial guide:

- Short -term (responses within a year);
- Medium-term (responses over decadal to century scale changes);
- Long-term (Responses over decadal to Holocene timescales, i.e. up to the last 10,000 years).

The short-term period can be thought of as how the system responds to maintain its form through interactions with other elements. Actions dominating this response duration will typically be continuous tidal and wave processes taking account of seasonal variability. Behavioural responses over the medium term will be dominated by intermittent or episodic forcing, such as storms, while in the longer term, morphological responses are likely to be dominated by forcing such as relative sea-level change or tectonics.

3.3.4 Application of Protocol

The above protocol for the development of the descriptive (textural) and diagrammatic components of the behavioural statement have been applied at two generic levels of system abstraction:

1. Estuary type statements: high level descriptions of each of the seven estuary behavioural types including identification of the component geomorphic elements, using a systems diagram based on the convention shown on Figure 9. These descriptions relate specifically to UK estuaries as this is the focus of the project. It should be noted that the properties of the different behavioural types are likely to vary in different areas of the world. These are presented in Section 3.4.

2. Geomorphic Element Statements: textural descriptions for each of the eleven geomorphic elements, based on the structure presented in Section 3.3.1. Each geomorphic element is represented by a systems diagram, which covers the short - medium-term and medium to long-term. These are provided in Appendix A.

At this stage of the project the intention is to capture, in a qualitative sense, the components and linkages at different levels within the estuary system in order that these definitions could be formalised for the next phase of development. At this stage therefore, the definition provided in the behavioural statements, at the two generic levels above, is for ‘natural systems’ and as such the statements do not account for anthropogenic effects or indeed the behaviour and responses that may result from anthropogenic influences within the systems that are being defined.

3.4 Estuary Behavioural Type Descriptions

This section provides a brief textural description and generic system diagram (Figure 9) of each of the estuarine behavioural types as identified in Section 3.2. The geomorphological units present within each different estuary type are highlighted on each system diagram (with infilled box) and the arrow indicate one or two way linkages.

3.4.1 Estuarine Behavioural Type 1: Fjord

Fjords are generally long, deep and narrow features that are bounded by relatively erosion-resistant, steeply rising slopes. They are formed by the submergence of glacially over deepened valleys (known as troughs) due to a rising relative sea level after the melting of the Pleistocene ice sheets. Fjords extend to great depths along most of their length, even close to their head, but tend to shallower depths close to their mouths to form a sill in rock. They generally have only small but highly seasonally variable river flow, often with tributary streams entering the system as waterfalls from hanging valleys. Only a small number of fjords exist in the UK, confined mainly to highland regions in Scotland. One of the best UK examples of a fjord is Loch Etive in Western Scotland.

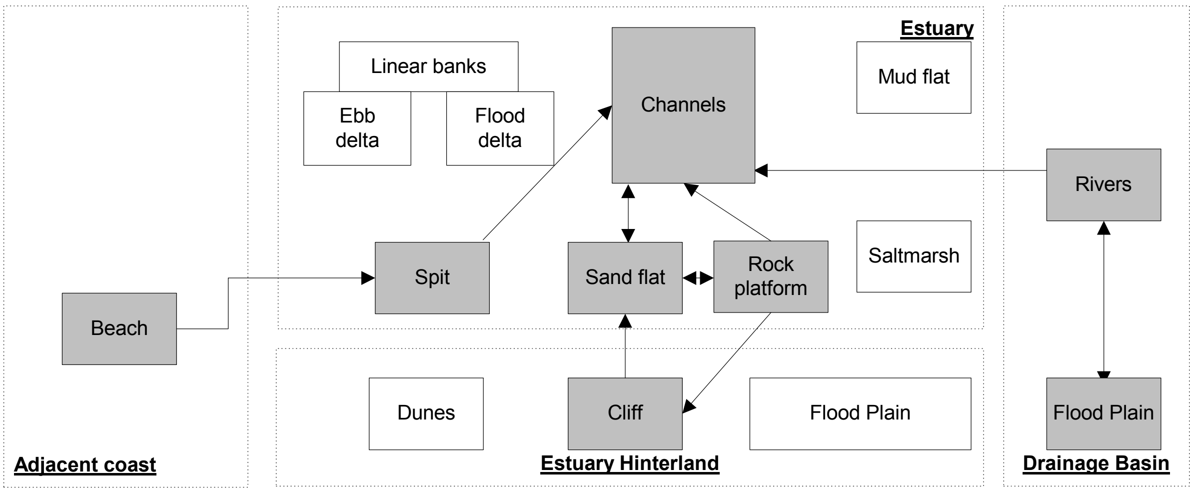


Figure 11. Generic fjord

3.4.2 Estuarine Behavioural Type 2: Fjard

Fjards are indented, drowned features fringing rocky, glaciated lowlands. Whilst they do not posses the deep glaciated troughs of a fjord, they generally reach greater depths than a ria. They generally have only small but highly seasonally variable river flow and have greater potential than fjords for the creation of spits at their mouths. Pwllheli Harbour in Wales is an example of a very small fjard with spits.

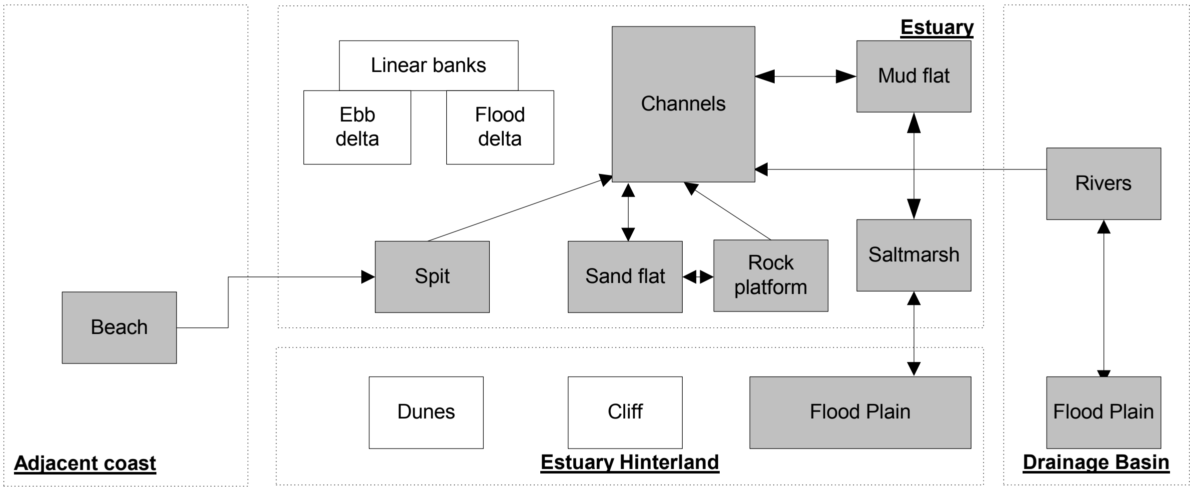
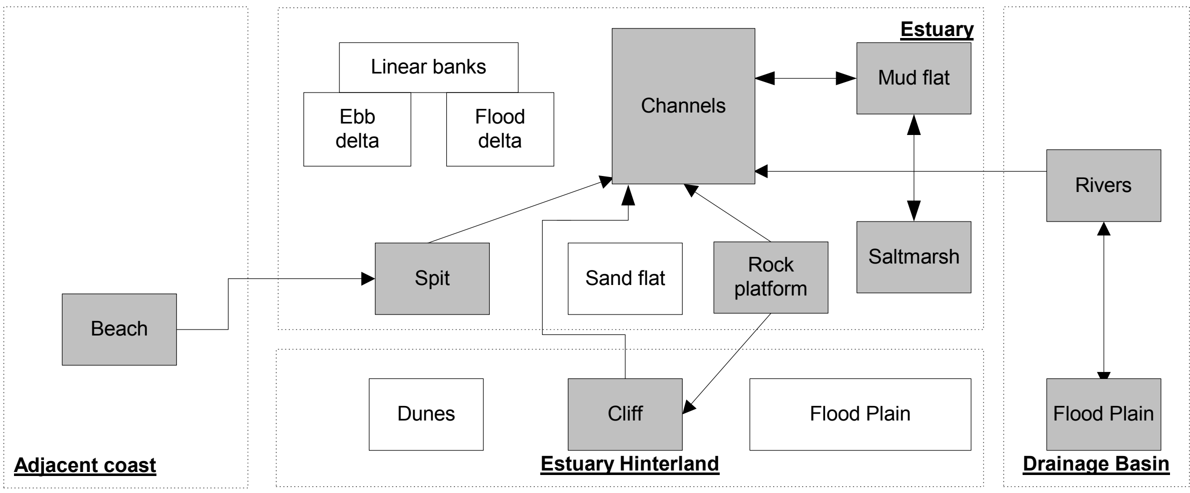


Figure 12. Generic fjard

3.4.3 Estuarine Behavioural Type 3: Ria

Rias are drowned valleys located in periglacial areas (that is areas which have been subject to cold climates, but not directly subject to glacial processes), with the original valley being created by fluvial process. Typically, rias are 'v-shaped' in cross-section, with the valley sides being relatively steep and composed of hard rock. In plan form, they exhibit the meandering form that is characteristic of other types of river valleys. Examples of rias with (e.g. Wear) and without (e.g. Tweed, Tyne) spits are common in northeast and southwest England and Wales.



N.B. Not all rias have spits.

Figure 13. Generic ria

3.4.4 Estuarine Behavioural Type 4: Spit-Enclosed Drowned River Valley

River valleys composed of soft rocks generally possess a more subdued relief than is experienced in harder rock areas, but have been subject to the same marine inundation processes caused by post-glacial (Holocene) sea-level rise. Many such areas possess drowned river valleys that have single or double spits at their mouths that tend to limit the mouth width and the physical processes occurring there. Many spit-enclosed estuaries, whilst experiencing high tidal velocities through their mouths, observe limited wave penetration due to the shelter provided by the spit(s) and at low water, salinity levels can be very low due to river flow. Often, spit-enclosed estuaries have flood and ebb tidal deltas and many examples of spit-enclosed drowned river valleys exist throughout eastern, southern and south-western England (e.g. the Teign), with the largest being the Humber, which has a single spit.

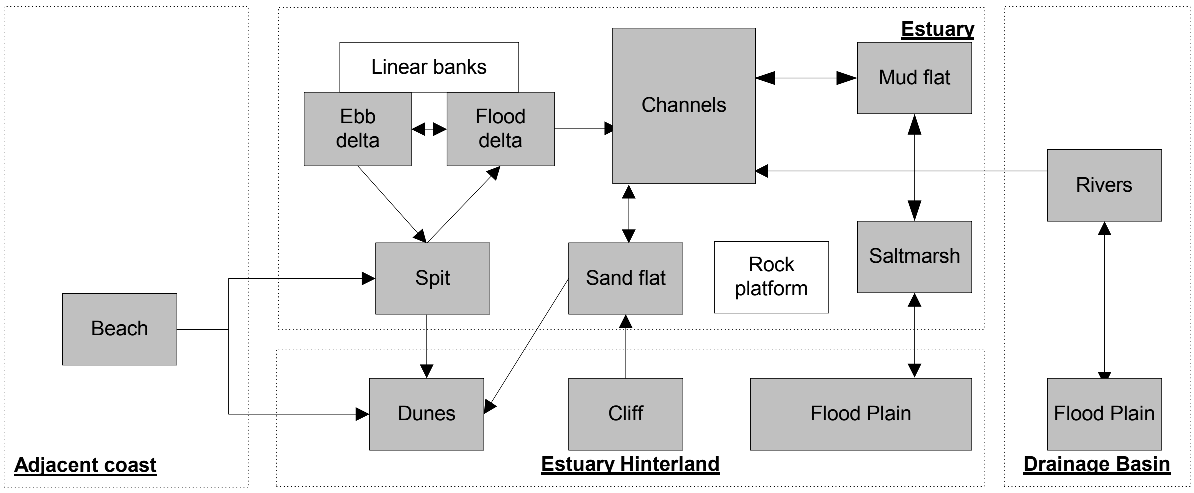


Figure 14. Generic spit-enclosed drowned river valley

3.4.5 Estuarine Behavioural Type 5: Funnel-Shaped Estuary

Funnel-shaped estuaries are considered likely to be close to the classical definition of equilibrium form. They do not possess spits, indicating a strong tidal motion and relatively weak littoral drift of sediment from the adjacent coasts. Often such estuaries will possess elongated linear sand banks within the area of the estuary mouth, aligned parallel to the current flow direction. The area of the estuary mouth can, in some cases, cover a large region. The rivers Thames and Ribble are examples of funnel-shaped estuaries.

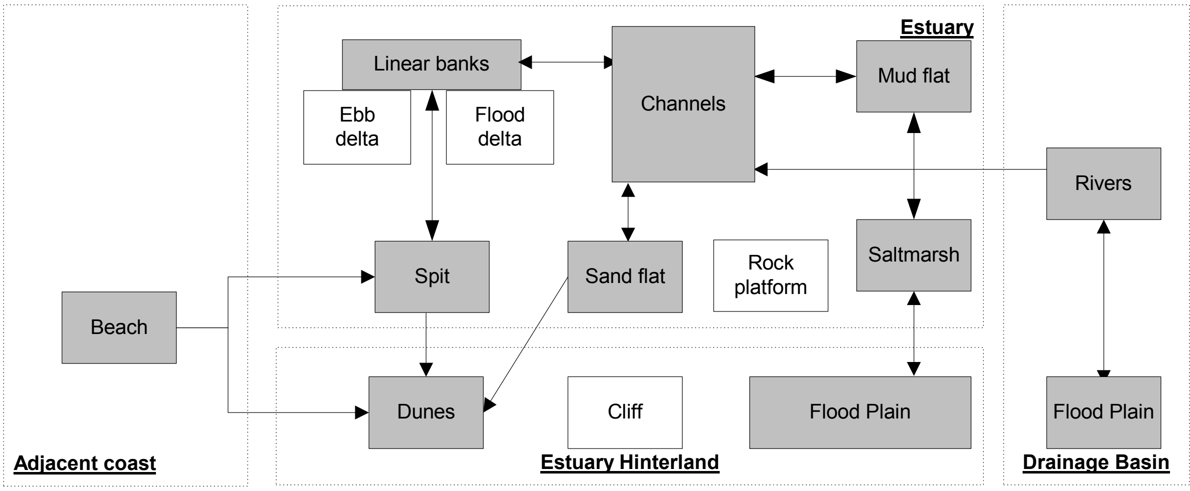


Figure 15. Generic funnel-shaped drowned river valley

3.4.6 Estuarine Behavioural Type 6: Embayment

Embayments are formed where several rivers converge and their joint valleys create a wide mouth area open to large wave and weather effects. They are characterised by large intertidal areas and high salinity throughout the embayment at high water. The Wash is a classic example of an embayment.

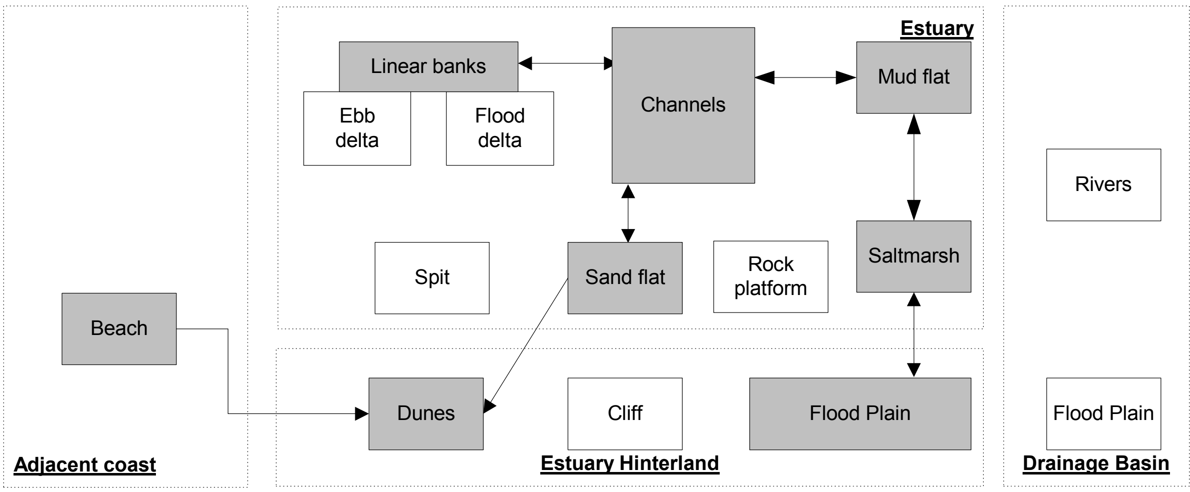


Figure 16. Generic embayment

3.4.7 Estuarine Behavioural Type 7: Tidal Inlet

Tidal inlets are produced where the relative sea-level rise has occurred over an extremely low relief coastal plain. These are characterised by narrow channels through fronting barrier beaches, and are backed by extensive tidal lagoons. In more tidally dominated areas, the inlet channel will typically be perpendicular to the coast, whilst in more wave-dominated areas the channel may be more obliquely aligned. Several examples of tidal inlets exist in close proximity along the south coast of England, namely Portsmouth, Langstone, Chichester and Pagham Harbours.

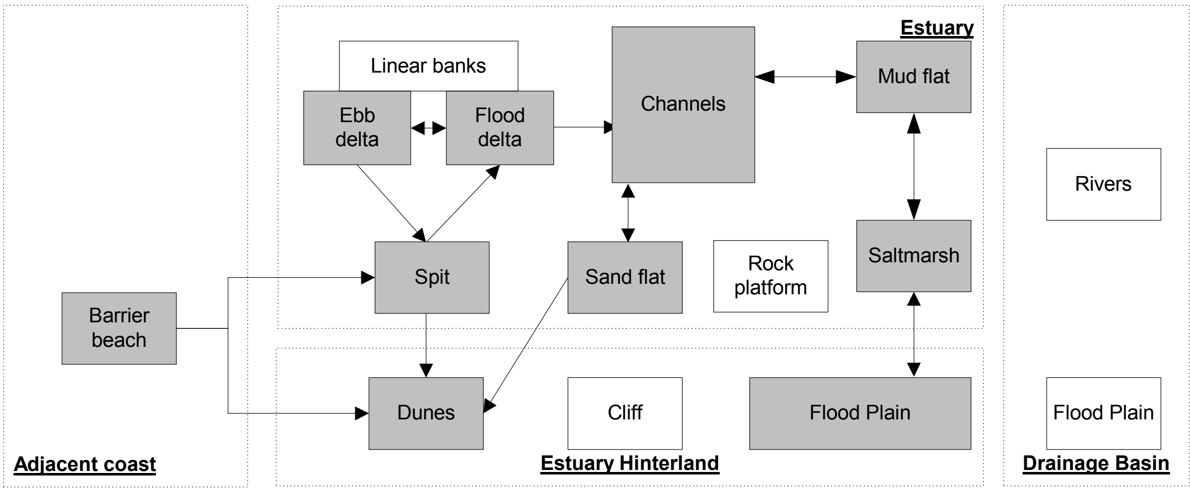


Figure 17. Generic tidal inlet

3.5 Geomorphological Element Descriptions

A textural description and generic system diagram in line with the protocol outlined in Section 3.3 for each of the geomorphological elements identified in the classification are presented in Appendix A.

4. Development of Prototype Simulator

4.1 Introduction

This section documents the development of the EstSim Prototype Simulator. This development has occurred in two phases, the first of which involved the formulation of a Boolean network model and the second involved the review of this Boolean approach and its further development into the Prototype Simulator.

An initial review of available approaches to mathematical formalisation is presented followed by some background to the approach developed within EstSim - the Boolean network approach. This approach is then applied to a number of generic estuary systems as a proof of concept. A discussion is then provided of the expansion of this approach to address a number of issues and initial application of the Prototype Simulator.

4.1.1 Project Context

The work documented in this section developed a mathematical framework to capture the formal definition of estuary systems as presented in the previous section. This initial work was then further expanded to develop a Prototype Simulator. The overall objective of this element of the research was to develop an approach capable of qualitatively modelling system behaviour.

Translation of a defined level of understanding of a given system into a simulation model, via some form of mathematical implementation, is a major challenge in qualitative modelling. In the project context, this was achieved during the completion of research within Objectives 4 and 5 ('Mathematical Formalisation' and 'System Simulation' respectively). The outputs of these Objectives are reported within EstSim Project Reports 3 Karunarathna & Reeve, 2007) and 4 (French & Burningham, 2007).

4.2 The Boolean Network Approach: Initial Development

4.2.1 Background

The Boolean network approach was described by Nicolis (1982) in a pioneering application of the technique to climate dynamics; and has since been developed with applications to different fields including seismology, climatology and meteorology (e.g. Ghil *et al.,* 1987, Wohlleben & Weaver 1995; Saunders & Ghil 2001; Zaliapin *et al.,* 2003). It reviews a modelling framework that is particularly suited to the mathematical formulation of conceptual models of systems that exhibit threshold behaviour, feedbacks and time delays. The approach is perhaps best considered to be an heuristic first step towards understanding problems currently too complex to model using systems of partial differential equations. Eventually it may well be possible to define and solve the exact equations that govern estuary morphology, however, in coastal morphodynamics and elsewhere in the natural sciences, much of the preliminary discourse is often conceptual. At the very least, Boolean expressions offer a formal mathematical language that may allow qualitative and quantitative approaches to be reconciled.

In this project, a Boolean approach has been used to develop mathematical formalisation of long-term morphodynamic evolution of complex estuary systems. This has involved development of Boolean networks combining geomorphological elements within the estuary system with external forcing driving the morphological evolution, and derivation of Boolean expressions that define the interactions between the (network) elements. The method provides a formal mathematical language that allows qualitative geomorphological ‘rules’ to be encapsulated and manipulated in a rigorous manner. The level of sophistication provided by the current formalisation is relatively simplistic and succeeds on the basis of some generalising assumptions. The success of the modelling approach largely depends on the correct linkages between system elements. It should also be noted that this approach treats the system elements as homogeneous sedimentary deposits and assumes that all/any transfer of sediment contributes to any of the geomorphological elements.

Nevertheless, this approach should be seen as an initial step in the development of more sophisticated Boolean networks that can address some of the acknowledged limitations. It should also be noted that in a hierarchical modelling framework, simple conceptual models are often employed to present hypotheses and identify mechanisms that are described in a qualitative or heuristic manner. In contrast, sophisticated process models are used to simulate the phenomena in more detail in order to compare results against observations in a quantitative manner. The Boolean approach provides the means to describe the dynamics of a complex system with a simple representation of the relevant geomorphological concepts.

Within Section 3, estuaries were classified into three categories (glacial valley, drowned river valley and drowned coastal plain) depending on their origin and subdivided into seven types (fjord, fjard, ria, spit-enclosed drowned river valley, funnel-shaped drowned river valley, embayment and tidal inlet) depending on their behaviour. A system diagram for each generic behavioural type was also presented, which incorporates system elements and their interactions. In addition, behavioural statements have been developed for each generic estuary at the whole estuary scale and for each individual geomorphological element at a generic level.

The mathematical formalisation of the estuary system behaviour has been developed using the Boolean approach to combine the estuary system diagrams and medium to long-term behavioural response of geomorphological elements presented in Section 3 of this report.

4.2.2 The Boolean Approach

The formulation of the problem is described as follows:

Let x be a state variable. If the rate of change of x is considered a continuous process, then the rate equation could be written as:

$$\frac{dx}{dt} = f(x,a) \quad (1)$$

where f is a nonlinear function of x and a set of external parameters a. In most cases, f can be split into two parts: a highly non-linear term $X(x,a)$ describing the specific feedbacks inherent in the dynamics of the system and a quasi-linear decay term kx. k is an appropriate decay coefficient. Thus, the equation (1) could be written as:

$$\frac{dx}{dt} = X(x,a) - kx \quad (2)$$

In the present context of estuary morphological evolution, the variable x represents the volume of a given geomorphological element within the estuary. The term a represents the set of external parameters which affect the rate of change of element volume and includes waves, tides, sediment exchange rate between elements, and so on.

Now assume that X is quite small for $0 < x < x_0$, but becomes quite appreciable for $x > x_0$ and saturates to a threshold value of X_{max} shortly afterwards. If we idealise this situation by considering that both x and X are zero when $0 < x < x_0$ and x and X equal to one when $x > x_0$ then, x and X can be considered as a discontinuous Boolean variable and a discontinuous Boolean function, respectively. We can then say that x is 'low' when $x < x_0$ and 'high' when $x > x_0$. This is illustrated in Figure 18. Similar considerations apply for X. The term kx in Equation (2) characterises a delay in temporal evolution of the Boolean function with respect to the Boolean variable.

4.2.3 Methodology

Boolean networks are constructed for each type of generic estuary. Each element in a Boolean network has two states, 'high' or 'low' (also called 'on' or 'off', 'true' or 'false'). To indicate its state, each element has an associated value 1 for 'high' and 0 for 'low'. The future state of one element in the network depends on the states of the other elements in the network, which are designated as that element's inputs. The element may feedback its own state as a self-input. The state of an element in a Boolean network at a future time is governed by a logical rule or Boolean function, which operates on the element's inputs. Each geomorphological element and the external forcing parameters that drive morphological changes in the estuary are represented by an individual element in the network. The network is formed by combining the estuary system diagram with medium to long-term behavioural response of geomorphological elements as specified in Section 3.

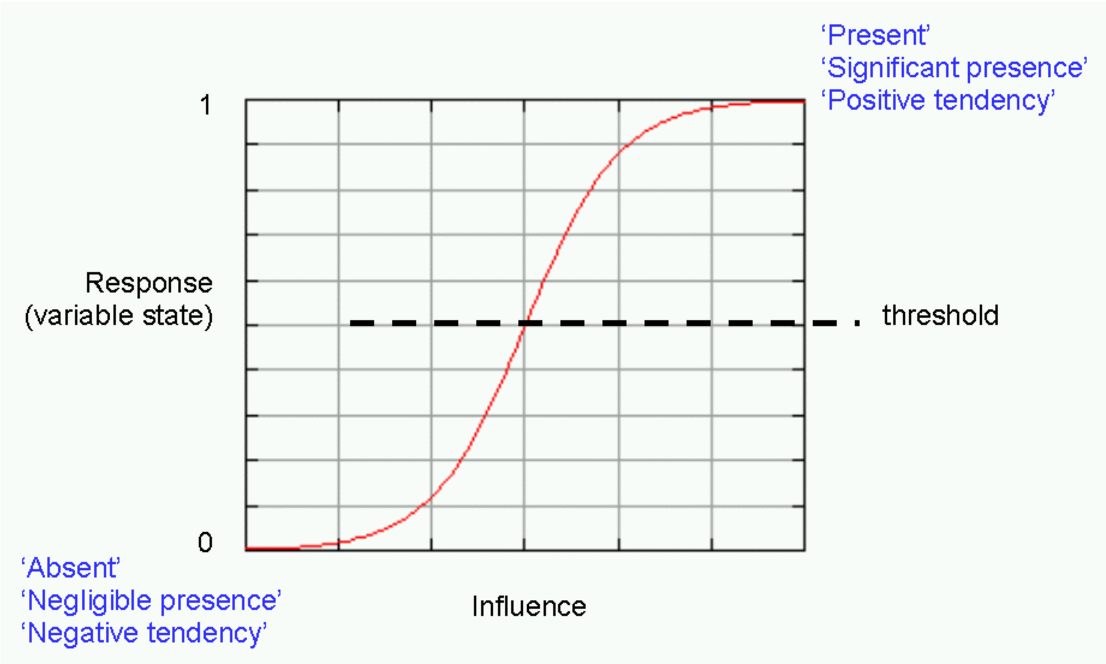
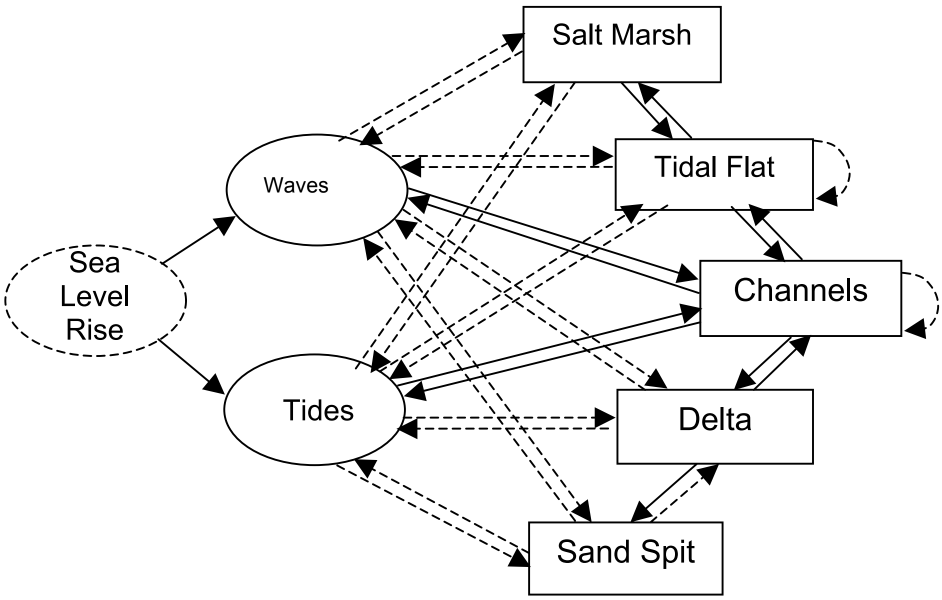


Figure 18. Boolean variables and threshold

Once the elements of the Boolean network are finalised based on the estuary system diagram, all possible feedback between geomorphological elements and external forcing that drives the morphological evolution of the estuary in the medium to long-term are derived from the behavioural description and the system diagram of the geomorphological elements given in the report. The effects of change in environmental forcing parameters on the morphological evolution of the estuary are incorporated through waves and tides. Human interference is modelled through feedback from control structures (e.g. training wall, jetties) and dredging. The feedbacks from the sub-systems are represented by the sediment flow.

4.2.4 Boolean Variables

Once the network is completed, a Boolean variable is assigned to each element in the network. Then, a Boolean function for each variable is derived by combining Boolean variables within a logical framework. The logical framework operates on the feedback from designated 'input' elements in the network. A truth table is then developed by solving the logical expressions for Boolean functions. The truth table gives Boolean states corresponding to various combinations of Boolean variables and resulting Boolean functions. The logical framework for the estuary system shown in Figure 19 is shown below.



Dark arrows and broken arrows in the network represent positive and negative feedback respectively

Figure 19. Boolean network for a generic tidal inlet (little or no sediment flow from outside)

$$
\left.
\begin{array}{llr}
W = sm' \vee tf' \vee cc \vee dd' \vee ss' & & \text{(a)} \\
T = sm' \vee tf' \vee cc \vee dd' \vee ss' & & \text{(b)} \\
SM = (w' \wedge t \wedge tf) & & \text{(c)} \\
TF = ((sm \vee cc) \wedge t) \vee (tf' \wedge w') & & \text{(d)} \\
CC = (w \vee t) \wedge (tf \vee dd) \vee cc' & & \text{(e)} \\
DD = (w' \vee t') \wedge ss' \vee (t \wedge cc) & & \text{(f)} \\
SS = (w' \vee t') \wedge dd & & \text{(g)}
\end{array}
\right\} \quad (3)
$$

Following notations stand for the variables used in Equation 3:

Network element	Boolean variable	Boolean function
Waves	*w*	*W*
Tides	*t*	*T*
Saltmarsh	*sm*	*SM*
Tidal flats	*tf*	*TF*
Channels	*cc*	*CC*
Delta	*dd*	*DD*
Sand spit	*ss*	*SS*

The following convention is used to form the logical expressions:

Convention	Description
a'	not *a*
a v *b*	*a* or *b*
a ^ *b*	*a* and *b*

The mathematical framework is a set of linear equations, which can be easily coded using any programming language (MATLAB was used for the examples presented here). Validity of the mathematical framework can be verified by the outcome of the truth table where an inconsistent logical framework leads to unrealistic Boolean output states.

Equations 3(a) and 3(b) express that little or no existence of saltmarsh, tidal flat, delta and sand spit individually enforce negative feedback on wave and tidal forcing as the presence of each of these geomorphological elements causes dissipation of wave and tidal energy. According to Equation 3(c), tidal forcing enforces a positive feedback on the saltmarsh by supplying sediment from tidal flats but wave forcing is low at the same time and will have the effect of reducing marsh erosion.

For each variable, the corresponding Boolean function is deduced from the logical expressions given in Equation (3) above. Having considered all possible combinations of Boolean variables, this then forms a Boolean matrix. The system has 2^7 = 128 states. Table 5 shows some selected states from the Boolean matrix. These states represent initial states of the tidal inlet that could realistically exist in nature.

Table 5. Some Selected States From rhe Boolean Matrix for Tidal Inlet With Constrained Sediment Inflow

	w	t	sm	tf	cc	dd	ss	W	T	SM	TF	CC	DD	SS
1	1	1	0	1	1	1	0	1	1	0	1	1	1	0
2	1	0	1	1	1	1	1	1	1	0	0	1	0	1
3	1	0	0	1	1	1	1	1	1	0	0	1	0	1
4	1	1	0	0	1	0	1	1	1	0	1	0	1	0
5	1	1	0	1	0	1	0	1	1	0	0	1	0	0
6	1	1	0	0	1	0	0	1	1	0	1	0	1	0
7	0	1	1	1	1	1	1	1	1	1	1	1	1	1
8	1	1	1	1	1	1	1	1	1	0	1	1	1	0
9	0	1	0	1	1	1	1	1	1	1	1	1	1	1

4.2.5 Boolean States

A Boolean state, in which all the Boolean variables and corresponding functions take the same value indicates a stable state where the system is bound to no further changes (Nicolis, 1987). When a stable state is reached, neither the Boolean variables nor the Boolean functions are bound to change further. In certain situations, the truth table indicates oscillatory system behaviour where the system evolves between two or more states and completes a cyclic evolutionary path. If the evolution of the system initiates from a state other than the stable state or the system does not follow an oscillatory evolutionary pattern, then, for certain initial states, the system follows one or more evolutionary stages to reach the stable state.

In the present case, the truth table corresponding to the logical framework given in Equation (3) indicates one stable state, shown by the encircled row in Table 5 (1101110). This state corresponds to a generic tidal flat with high wave and tidal forcing. At this state, the estuary possesses little or no saltmarshes and no sand spit due to lack of sediment flow from outside to maintain these geomorphological elements against sea level rise.

Now, consider the initial state where the generic tidal inlet is wave dominated and contains saltmarshes, tidal flats, a delta and a sand spit (row 2 of Table 5). Sea level rise increases wave and tidal forcing within the estuary system, and according to the logical matrix, saltmarshes, tidal flats and the delta structure begin to recede as the initial response to this sea level rise and increase in forcing. But, as the estuary evolves further by exchanging sediment between estuary elements, tidal flats accrete but channels become shallower. The delta is likely to change again and the sand spit recedes. The logical matrix shows that the estuary is likely to change once again to a state with deep channels, little or no tidal flats. Once the estuary reaches this state, the logical matrix indicates a reversal into the previous state thereby following a cyclic evolutionary pattern as shown below.

1011111 → 1100101 → 1101010 ↔ 1100100

Under constrained sediment supply, tidal flats in general recede before saltmarshes in the event of sea level rise. In this situation, the logical matrix shows that the estuary reaches a state where tidal flats are replenished by the sediment from receding saltmarshes before it reaches the cyclic evolutionary pattern as shown below.

1011111 → 1110101 → 1101010 ↔ 1100100

Within a tide dominated generic tidal inlet, which contains salt marshes, tidal flats, a sand spit and a delta (row 7 of Table 3), both tidal and wave forcing in the estuary increase as a result of sea level rise. For this initial state, the logical matrix indicates the following morphological evolutionary path against sea level rise:

011111 → 111111 → 110111

The salt marshes and the sand spit recede as the estuary evolves due to lack of sediment inflow to maintain them against sea level rise. The estuary reaches a stable state with little or no salt marshes and a sand spit. However, the decay rates of salt marshes and the sand spit are likely to be different, and therefore the estuary will have the following alternative evolutionary paths:

011111 → 111111 → 110111 → 110111 (Path 1)

011111 → 111111 → 111111 → 110111 (Path 2)

Irrespective of the difference in the decay rates of salt marshes and the sand spit, the estuary finally reaches the same stable state.

The selection of different evolutionary pathways depends on various factors. For example, estuary geometry, channel geometry, extent of saltmarshes and tidal flats, sediment composition and concentrations, flood and ebb tidal current intensity and patterns, biological aspects related to sediment flocculation and deposition, are some of the factors that affect the recession or accretion rate of geomorphological elements of estuaries.

In the event of anthropogenic influences such as dredging, the system is forced to a situation similar to a sudden removal of sediment. For example, if dredging of tidal flats is started at a state where tidal flats hold a state 'high' (associates value '1'), then before evolving to the next state, this value is artificially changed to '0' ('low').

4.2.6 Illustration of the Methodology

Let us consider a wave dominated tidal inlet with unconstrained sediment flow and well-developed tidal flats and shallow channels (initial state before dredging is 1011011). If dredging is undertaken to remove sediment from the tidal flats and channels, the system is forced to the state 1010111 (low tidal flats and deep channels). After this stage, the system evolves according to the logical matrix and the full evolutionary path before reaching a stable state is shown below:

1011011 → 1010111 → 1101111 → 1111111

After dredging is carried out to remove material from channels and tidal flats, sediment exchange takes place between tidal flats and saltmarshes resulting in tidal flat accretion and saltmarsh recession. With further increase in sea level and unconstrained sediment inflow, the estuary reaches a stable state with fully developed tidal flats and saltmarshes.

Similar analyses were done for generic glacial valley estuary and drowned river valley estuary (Karunarathna & Reeve, 2007).

It should be noted that considering fluvial discharge and its potential change associated with global climate change is significantly less than the tidal flows in most of the UK estuaries, river flow was not taken as an environmental forcing in the formation of Boolean networks at the initial stage. However, at a later stage, the generic estuaries were re-analysed taking fluvial discharge as an additional environmental forcing in Boolean networks. It was found that it did not affect the stable state, other evolutionary states of the estuary leading to the stable state, or the cyclic evolutionary nature.

4.3 Development of a Prototype Simulator

This initial development of the Boolean network approach presented in section 4.1 is extremely useful as a proof of concept exercise. The challenge is to expand the Boolean network model to incorporate a broader set of morphological and process components and a more realistic representation of estuary behaviour at a whole system level. Further development aimed at achieving this is presented in the following sub-sections.

4.3.1 Issues to be Addressed

In order to provide a more realistic formalisation of geomorphological knowledge within a Boolean framework requires a number of issues to be addressed, as follows:

1) Conceptual basis and terminology of abstraction

Qualitative models of system dynamics are typically not specified in a way that ensures global conservation of real world quantities such as water, sediment or energy. Neither are exchanges of mass and energy the only basis for understanding the operation of a system: in biology, the widespread adoption of network-based models has been stimulated by recognition of the role played by information transmission. In geomorphology, the appropriate basis for system conceptualisation is to some extent dependent on the scale of investigation. Thus, at a micro-scale, landform morphodynamics can ultimately be reduced to a set of physical interactions. Macro-scale evolution of morphology, however, is historically and spatially contingent (e.g. Cowell & Thom, 1994; Ahnert, 1994) to a degree that currently permits only a qualitative formalisation of the interactions between the component landforms and processes. Viewed at this scale, geomorphological systems are similar to biological systems in that their structural configuration results from progression along evolutionary pathways (Hopfield, 1994), and thinking in terms of flows of information may be an equally valid approach to the conceptualisation of the outcomes of landform - process interactions. Care must still be taken to ensure that the terminology used to represent these exchanges is capable of resolving the interaction between morphology and process in a meaningful way.

In the case of tides, for example, thinking merely in terms of presence or absence of tidal action is not very helpful. It might be more appropriate to think of tidal forcing in terms of high or low tidal ranges. In Boolean form, this could be handled through discrete but mutually exclusive categories (e.g. micro-, meso- and macro-tidal ranges) that can be qualitatively associated with various estuary morphologies. These associations clearly arise through fluxes of water and sediment mediated by a variety of geomorphological processes. From a modelling perspective, however, it is the information contained within the qualitative associations that is represented rather than the physical dynamics of the underlying processes.

2) Threshold assumption of the Boolean approach

A major assumption of the Boolean model is that changes in system variables can be represented by a threshold-type function (i.e. 'on / off' or 'presence / absence'). This is not always easy to justify and a minimal binary representation is sometimes insufficient to capture the required range of geomorphological behaviour. In the case of an estuary, *increases* in external forcing (e.g. the effect of *acceleration* in the rate of sea-level rise acting through an *increase* in wave or tidal action) cannot be defined using single-bit binary logic. Equally, defining saltmarsh as a single variable precludes the expansion of saltmarsh (for example, by removing flood protection from reclaimed tidal floodplain) in an estuary that already contains extensive saltmarsh. In both these cases, a variable is either present or absent (or high or low, depending on the interpretation) and if already present cannot be significantly increased. This has consequences if left unaddressed, since geomorphologists are accustomed to associating specific landform characteristics with gradients in environmental forcing. Obvious examples are the classification of barrier island morphology according to tidal range by Hayes (1979) and, at a larger scale, the estuarine facies model of Dalrymple *et al.* (1992) in which estuaries respond to broad continua of tidal, wave and fluvial energy, sediment supply and sea-level tendency. To some extent, inadequacies in the Boolean representation expose a failure to define the estuary system at a resolution commensurate with the processes to be modelled. Thus, progradational or transgressive responses of saltmarsh can be resolved through disaggregation of saltmarsh into multiple features (e.g. lower, upper and restored saltmarsh). The incorporation of gradational changes in process-related state variables such as sediment supply, sea level rise, or tidal prism poses slightly different problems. In some cases, the creation of additional sub-system variables may be appropriate. Sediment supply, for example, might be defined in terms of a set of virtual sediment sources of incrementally increasing volume. Alternatively, certain variables might be implemented using multiple-bit logic. For example, sea level change could be specified using two bits, the first indicating whether or not sea level is rising and the second indicating whether any rise is at a moderate or rapid rate (giving three useful states and one that is unused). Enhancement of initial Boolean network approach along these lines appears to be needed, but must be implemented with care in order to preserve the simplicity and computational tractability of the Boolean approach.

3) Aspatial representation of spatially distributed phenomena

The systems approach outlined in sections 2 and 3 generalises key aspects of estuary behaviour in an aspatial manner. Whilst features such as spits and tidal deltas are implicitly associated with the outer estuary, the distribution of other important features (tidal flat, saltmarsh) is unspecified. Most estuaries possess outer and inner zones that differ markedly in their landform assemblages and dominant processes. Indeed, a number of estuarine classifications are founded upon transitions in the relative importance of marine and fluvial processes between outer and inner estuary zones (e.g. Pritchard, 1967; Dalrymple *et al.*, 1992). Such distinctions are important for understanding the historic behaviour of estuaries in the UK. For example, the Ribble estuary in northwest England comprises an outer estuary dominated by sand flats and an inner estuary in which mudflat and saltmarsh are more extensive. Each zone has experienced distinct but rather different historic changes (van der Wal *et al.*, 2002) that would be hard to capture in an aspatial model. This is not a limitation of a Boolean network approach per se, but it does suggest the need to handle spatially distributed behaviour via the specification of separate but linked outer and inner estuary sub-systems.

4.3.2 Further Development of the Boolean Network Model

With the above issues in mind, further development of the Boolean network approach has been undertaken using a Prototype Simulator. MATLAB was selected as the preferred development platform on account of its programming, numerical computation and visualisation capabilities, as well as the support that it provides for the subsequent development of compiled standalone tools.

The estuary system conceptualisation presented in section 3 has been extended to incorporate a basic spatial division into an *outer estuary* sub-system (which interacts with elements of the adjacent *coastal system*, and potentially contains beach, spit, dune, and tidal delta or linear bank features, as well as sand or mud flat and saltmarsh) and an *inner estuary* sub-system (which contains an assemblage of sub-tidal channel and intertidal flat and saltmarsh features). Such a scheme resembles the estuary facies model of Dalrymple *et al.* (1992) in that outer and inner estuary zones are likely to be dominated by marine and marine-influenced fluvial processes respectively.

The generic scheme is visualised in Figure 20, which sets out the spatial arrangement of the major morphological components and various external and internal influences on their evolutionary behaviour. We distinguish between three broad types of system component:

1) External (imposed) forcing and interventions:

- Ocean waves;
- Longshore wave power;
- Tidal range;
- River discharge;
- Sediment supply (marine and fluvial sand and mud);
- Wind regime (onshore winds favourable for dune formation);
- Inherited geological constraints (resistant bedrock);
- Accelerated sea-level rise;
- Interventions (seawalls, erosion protection, dredging etc).

All of the above are imposed as part of the initial conditions of the system and are not changed by the evolutionary behaviour of the estuary. They can be altered to accommodate a change in boundary conditions, such as updrift coastal protection blocking the supply of marine sand, and specific external factors can be defined as required in order to handle anthropogenic influences such as the construction of a tidal barrage. As shown in Figure 20, strategies can optionally be defined to cover a set of interventions (e.g. 'hold the line' involves continued maintenance of all seawalls, groynes and protective structures).

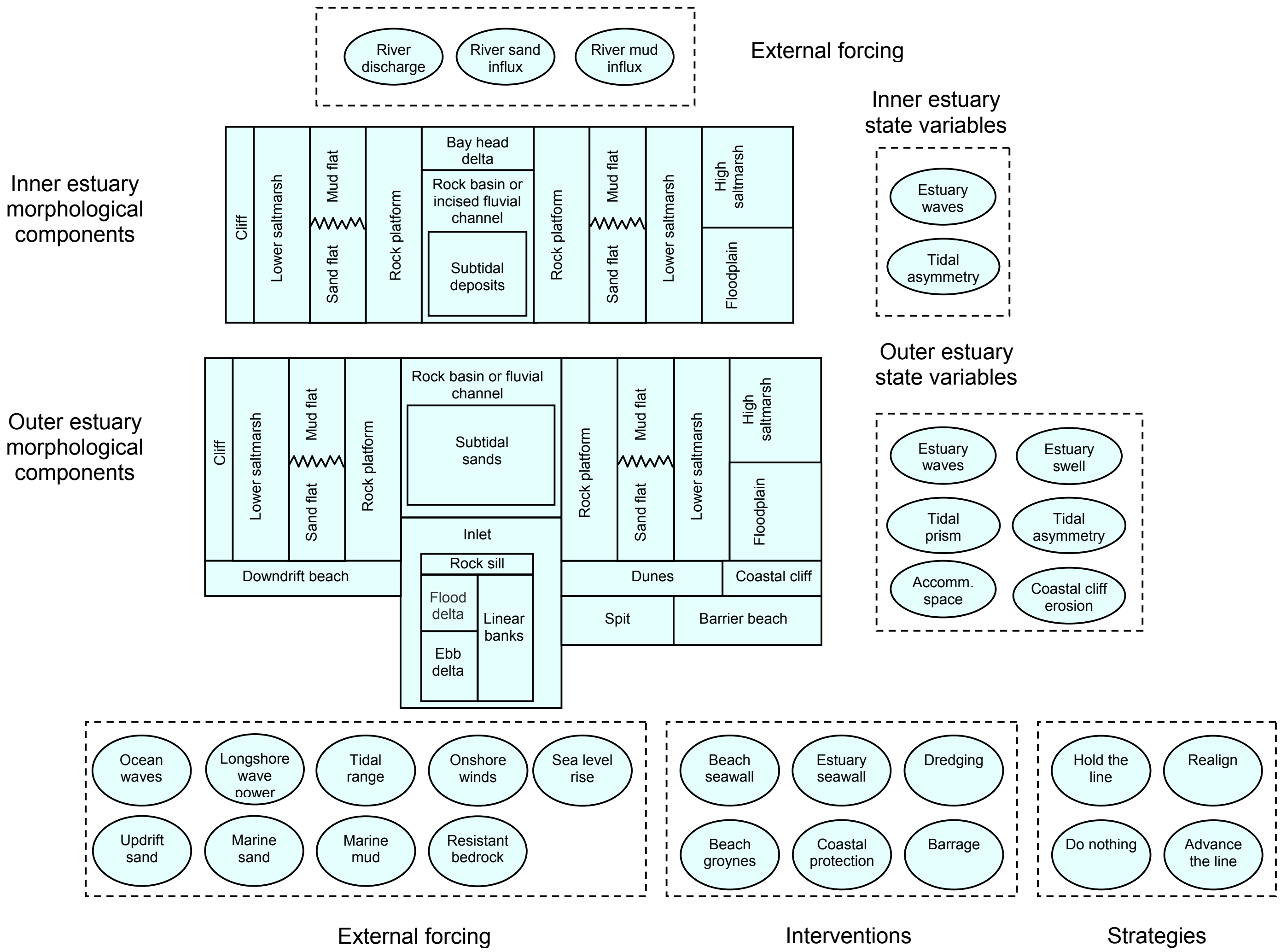


Figure 20. Morphological components of estuary simulator and various external and internal influences on their evolutionary behaviour

2) *Process state variables*

State variables represent processes (in the wider sense) that are not defined a priority but which change as estuary morphology evolves. The outer estuary is influenced by a broader range of processes, which include:

- Estuary waves, influenced mainly by tidal prism and its control on local fetch;
- Estuary swell, influenced by ocean waves and any protection afforded by a spit;
- Tidal prism, determined by infilling of the intertidal by sedimentary landforms, especially saltmarsh within both the outer and inner estuary;
- Accommodation space, determined by infilling of both subtidal and intertidal volume;
- Tidal asymmetry, determined by intertidal area and estuary depth (a simplified representation of a Dronkers (1986) γ-type velocity asymmetry); and
- Active erosion of coastal cliff, influenced by waves and coastal protection (if present).

The inner estuary is more simply represented using the following state variables:

- Estuary waves;
- Tidal asymmetry.

3) *Morphological components*

The basic set of morphological components is derived in section 3, with a few additions to discriminate more effectively between rock-controlled and alluvial morphologies and to improve the representation of the estuary-coast interaction. The basic set of components includes:

- Cliff, beach, spit and dune units (outer estuary);
- Various forms of tidal delta and inlet (outer estuary);
- Tidal sand flat and mud flat (which can co-exist in both outer and inner estuary);
- Lower and upper saltmarsh units (both outer and inner estuary);
- A rock platform that can be revealed by stripping of intertidal sedimentary cover if wave energy is high and the sediment supply negligible (both outer and inner estuary);
- Tidal floodplain that can evolve to high saltmarsh or be removed from the prism through reclamation (both outer and inner estuary);
- Estuary cliffs (in bedrock controlled situations);
- Rock basins (fjords and fjards) and fluvial channels (rias);
- Subtidal sands and muds (infilling of the estuary channel).

Intertidal depositional features are represented as vertically stacked sedimentary units that are not mutually exclusive but which can co-exist (for example, mudflat and sandflat and low or high saltmarsh). Except in the case of rock-controlled estuaries, channels are not represented as a discrete component but are incorporated implicitly as part of a subtidal morphology that can undergo deposition and erosion depending on the availability of sediment, changes in prism and/or tidal asymmetry, and dredging. Elements of this idealised stratigraphic framework for both alluvial and rock-controlled cases are summarised schematically in Figure 21.

The main morphological components are taken to be volumetric features, some of which are mutually exclusive in a manner that is consistent with the range of estuary types (e.g. different forms of inlet sand body), and some of which can co-exist (e.g. sandflat and mudflat). Morphological changes can interact directly with tidal prism as a key internal state variable; some also feedback to influence wave energy. Sediment supply variables are envisaged to take the form of stocks, or background concentrations in an essentially infinite ocean or coastal reservoir. Other forcing factors are taken to imply the existence or otherwise of sufficient tidal, wave or wind energy to accomplish the geomorphological work associated with each set of processes. Viewed in this way, the interactions or influences are more akin to information exchanges than the fluxes of energy or mass that form the basis of physically based models.

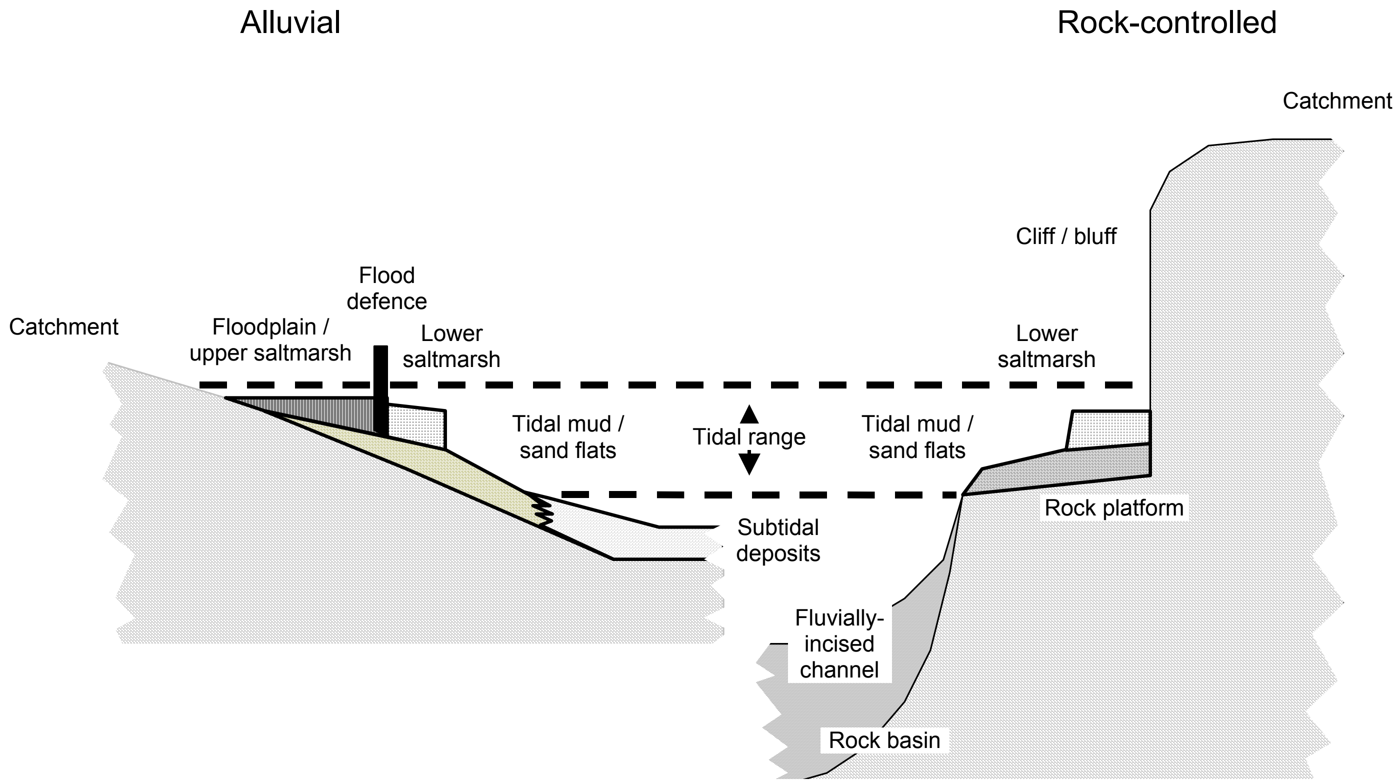
As a prelude to their implementation in model form, interactions between the major sets of system variables need to be summarised in a set of influence diagrams. Such diagrams can be highly detailed and can contain most or all of the functional logic governing system behaviour (e.g. the ‘causal loop diagrams’ employed by Puccia & Levins, 1985). In their simplest form, these diagrams merely identify the interactions and the direction of influence between all components of the system (e.g. the ‘directed graph’ of Capobianco *et al.*, 1999). Figure 22 adopts this level of detail in respect of the interaction between coastal and outer and inner estuary sub-systems. Similar influence diagrams describe the organisation of the outer and inner estuary sub-systems (Figures 23 and 24).

The influence diagrams in Figures 22-24 reflect the fact that the behaviour of the estuary system is known only in a very general sense and that each of the process and morphological variables is itself an abstraction of highly complex real world behaviour. Few of the interrelationships depicted here are well enough understood to permit the derivation of continuous mathematical functions or empirical scaling relationships. More often, what is being represented is merely accumulated experience derived variously from case studies supported by some appreciation of underlying processes studied at a small scale and in isolation.

Translating such a general level of understanding into a simulation model that is amenable both to some form of mathematical implementation and to rigorous interpretation of the modelled system behaviour is probably the biggest challenge in qualitative modelling. In particular, there is currently no means of automatically converting an influence diagram into a simulation model (see Wolstenholme, 1999; Smith, 2000). Formulation of mathematical functions to characterise the linkages between them is likely to incur a much high ‘operator variance’ than merely sketching out the components of the system (as in Figure 20).

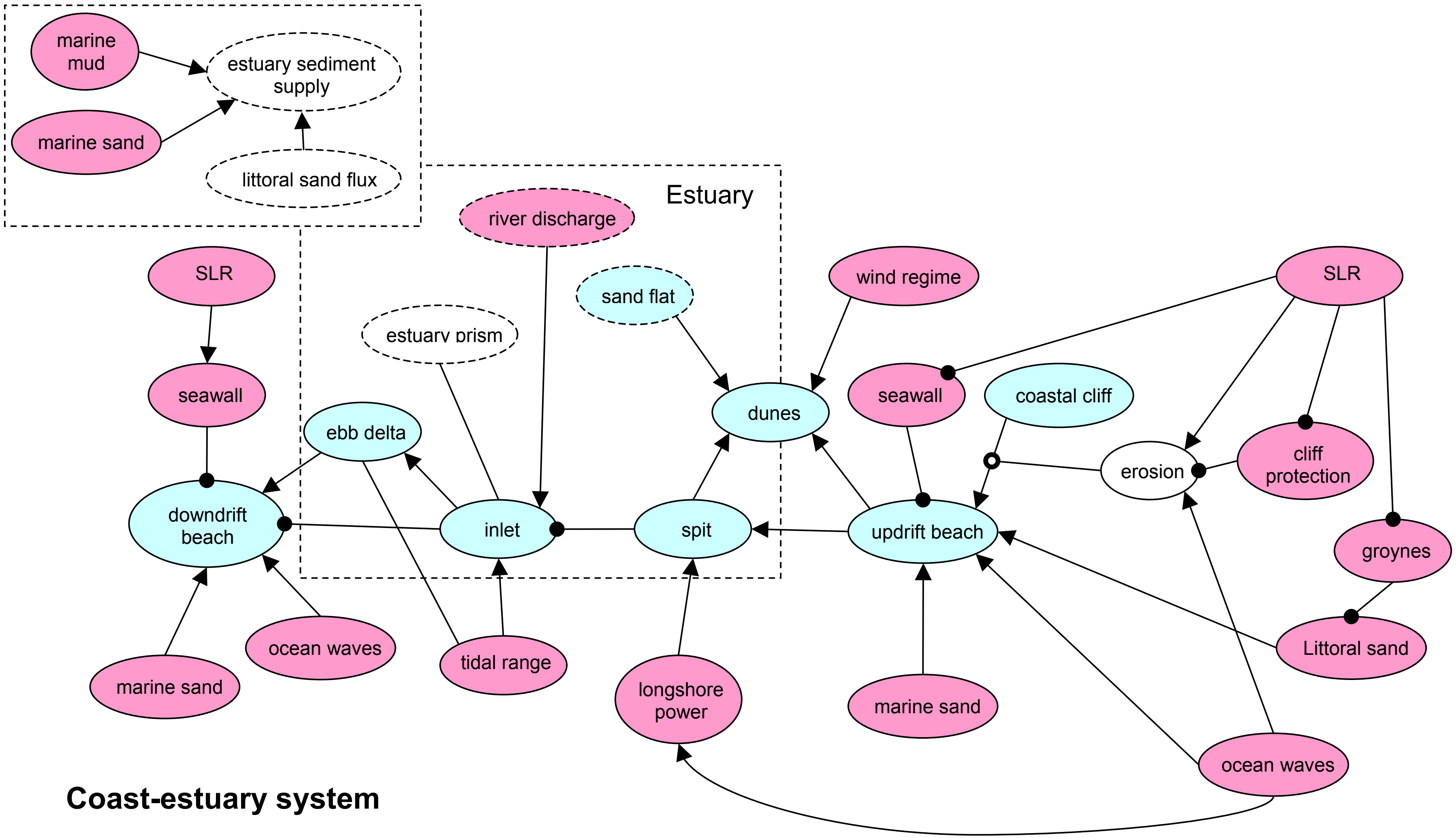
Table 6 summarises the main set of natural system variables drawn from the influence diagrams in Figures 22-24. A separate set of variables for engineering interventions is set out in Table 7. Tables 8, 9 and 10 express the linkages between these variables in the form of Boolean functions for the coast-estuary interface, outer estuary and inner estuary respectively.

System variables are indicated in lower case and are combined into associated Boolean functions, represented in upper case, defined using logical AND (& in MATLAB), OR (|) and NOT (~) operators. Note that self-input is also allowed, such that source variables can represent imposed external forcing and connected variables representing resistant features can exist in imposed or inherited states. Single-bit Boolean logic has been retained but model capability has been enhanced through the inclusion of additional state variables to handle gradational responses (e.g. for tidal range, where qualitative associations between micro-, meso- and macro-tidal conditions, and estuary inlet morphology are commonly referred to in the geomorphological literature). Boolean variable states might be interpreted in terms of either 'existence' or 'tendency'. The former convention is preferred here, such that Boolean states 0 and 1 refer to negligible or significant presence (in the limit, absence or presence). This allows a more consistent handling of both process and morphological components than is possible when thinking in terms of tendency (which can, in any case, be inferred from the evolutionary behaviour of the system). In practice, such distinctions do not seem to be of critical importance provided the implementation and terminology are consistent and the user is appropriately informed.



Not all morphological elements of Figure 8 are shown here.

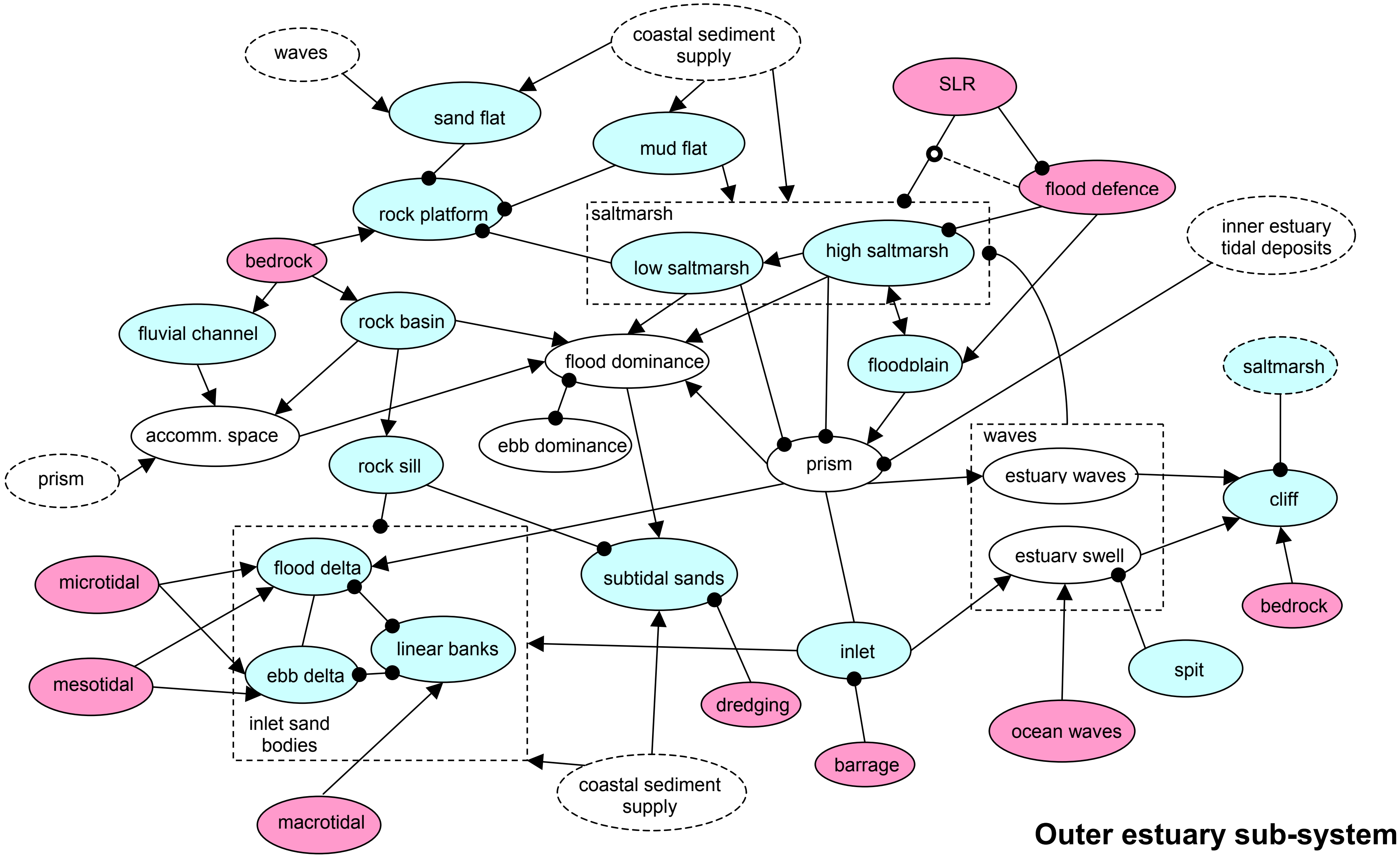
Figure 21. Schematic illustration of idealised stratigraphic framework alluvial and rock-controlled estuary sections



Coast-estuary system

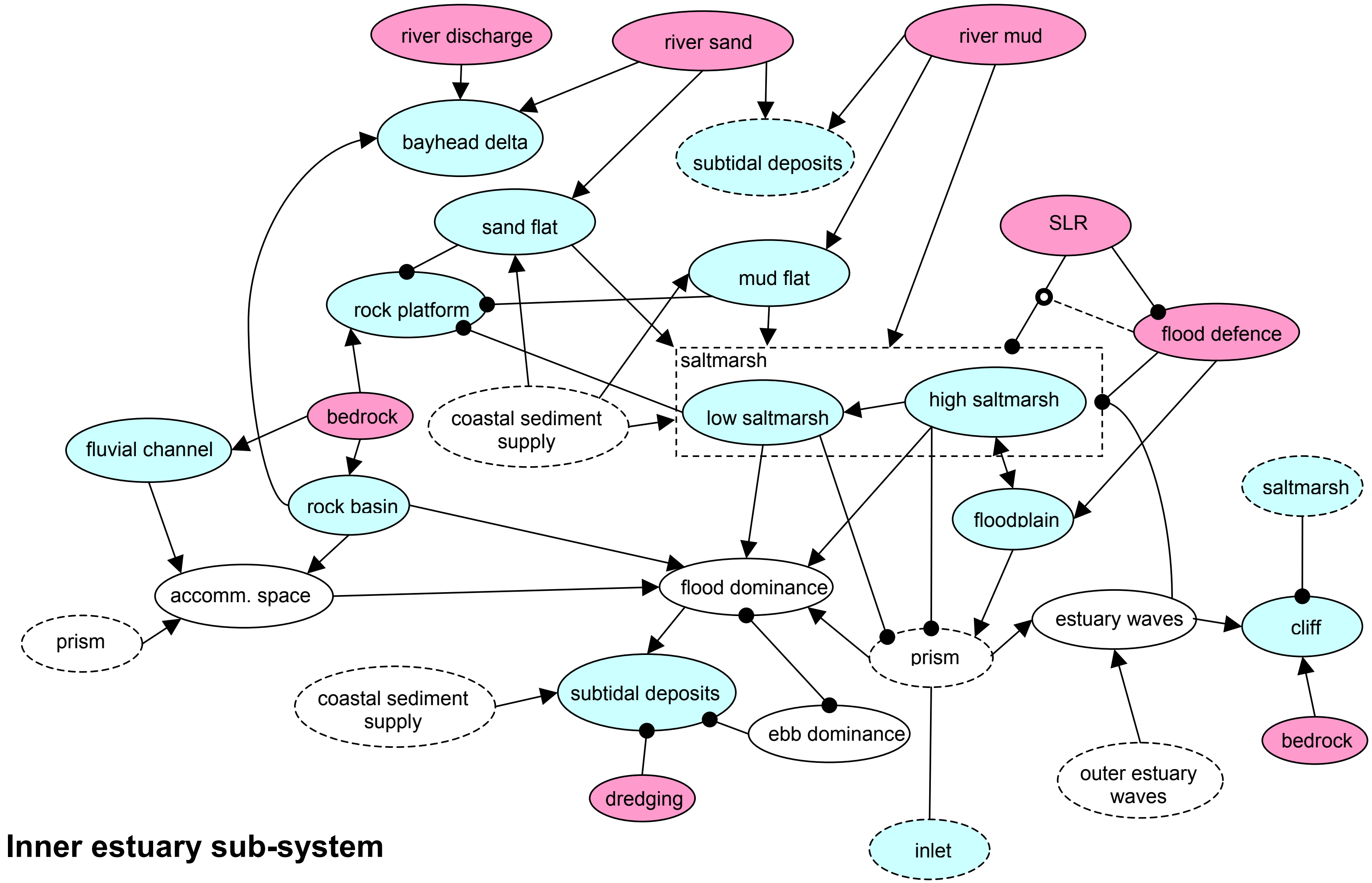
Arrows define linkages that are generally positive, whilst negative influences are indicated by —●.
Dashed lines bound parts of adjacent sub-system that are not fully represented here.
Shading highlights distinction between forcing, morphological and state variables.
Erosion mediates transfer of material from coastal cliff to beach.

Figure 22. Influence diagram for interface between coastal and outer estuary sub-systems



Arrows indicate positive linkages, whilst negative influences are indicated by —●.
Components bounded by dashed lines represent parts of adjacent sub-system that are not fully represented here.
The interaction between sea-level rise (SLR) and saltmarsh is shown controlled by the presence or absence of flood defence (which effectively functions as a kind of switch).

Figure 23. Influence diagram for outer estuary sub-system



Arrows indicate positive linkages, whilst negative influences are indicated by —●.
Components bounded by dashed lines represent parts of adjacent sub-system that are not fully represented here.

Figure 24. Influence diagram for inner estuary sub-system

Table 6. Basic Set of 55 Boolean Variables for Natural Estuary Systems. Coastal Cliffs are Here Considered to be Part of an Imposed Geology

Variable	Variable Class		
Coastal-Estuary Sub-System			
Ocean waves			{external forcing}
Longshore wave power			{external forcing}
Littoral sand			{external forcing}
Marine (offshore) sand			{external forcing}
Marine (offshore) mud			{external forcing}
Macro-tidal			{external forcing}
Meso-tidal			{external forcing}
Micro-tidal			{external forcing}
Sea level rise			{external forcing}
Coastal cliffs			{imposed geology}
Coastal cliff sand fraction			{imposed geology}
Coastal cliff mud fraction			{imposed geology}
Coastal cliff erosion		{state variable}	
Barrier beach - updrift	{morphology}		
Spit	{morphology}		
Inlet	{morphology}		
Barrier beach - downdrift	{morphology}		
Coastal dunes	{morphology}		
Wind regime favourable for dunes			{external forcing}
Outer Estuary Sub-System			
Tidal prism		{state variable}	
Accommodation space		{state variable}	
Ebb delta	{morphology}		
Flood delta	{morphology}		
Linear banks	{morphology}		
Bedrock (resistant)			{imposed geology}
Rock sill			{imposed geology}
Rock basin			{imposed geology}
Fluvially-incised channel			{imposed geology}
Outer estuary rock platform (exposed)	{morphology}		
Outer estuary flood dominance		{state variable}	
Outer estuary ebb dominance		{state variable}	
Outer estuary subtidal deposits (incl. channel sands)	{morphology}		
Outer estuary swell		{state variable}	
Outer estuary waves		{state variable}	
Outer estuary sand flat	{morphology}		
Outer estuary mud flat	{morphology}		
Outer estuary marsh - low	{morphology}		
Outer estuary marsh - high	{morphology}		
Outer estuary floodplain (0 if reclaimed)	{morphology}		
Outer estuary cliff	{morphology}		
Inner Estuary Sub-System			
Inner estuary rock platform (exposed)	{morphology}		
Inner estuary flood dominance		{state variable}	
Inner estuary ebb dominance		{state variable}	
Inner estuary subtidal deposits (channel sands/muds)	{morphology}		
Inner estuary waves		{state variable}	
Inner estuary sandflat	{morphology}		
Inner estuary mudflat	{morphology}		
Inner estuary marsh - low	{morphology}		
Inner estuary marsh - high	{morphology}		
Inner estuary floodplain (0 if reclaimed)	{morphology}		
Inner estuary cliff	{morphology}		
Bay head delta	{morphology}		
River discharge (moderate to high)			{external forcing}
River sand load (moderate to high)			{external forcing}
River mud load (moderate to high)			{external forcing}

Table 7. Additional Boolean Variables to Handle Engineering Intervention and Management Strategy

Variable	Variable Class
Coastal Estuary Sub-System	
Groyne field	Intervention
Cliff toe protection	Intervention
Seawall (coastal)	Intervention
Barrage	Intervention
Hold the line	Intervention - strategy
Realign	Intervention - strategy
Do nothing	Intervention - strategy
Advance the line	Intervention - strategy
Outer Estuary Sub-System	
Outer estuary flood defence	Intervention
Outer estuary dredging	Intervention
Inner Estuary Sub-System	
Inner estuary flood defence	Intervention
Inner estuary dredging	Intervention

Table 8. Boolean Functions (with Supporting Rationale) for Coast-Estuary Sub-System Variables

```
OCEAN_WAVES = ocean_waves
```
Straightforward implementation of ocean waves as a source variable (an external forcing factor).

```
LONGSHORE_POWER = longshore_power & ocean_waves
```

```
LITTORAL_SAND = littoral_sand
MARINE_SAND = marine_sand
MARINE_MUD = marine_mud
```

```
MACROTIDAL = macrotidal & ~barrage
MESOTIDAL = (mesotidal | (macrotidal & barrage) |
      (~macrotidal & ~mesotidal & ~microtidal))
MICROTIDAL = microtidal & ~(mesotidal | macrotidal)
```
Mutually exclusive tidal range classes with range of macrotidal tidal estuary reduced by construction of a barrage.

```
SLR = slr
```

```
COASTAL_CLIFF = coastal_cliff
```

```
CLIFF_SAND = cliff_sand & coastal_cliff
CLIFF_MUD = cliff_mud & coastal_cliff
```

```
COASTAL_CLIFF_EROSION = coastal_cliff & ocean_waves & ~coastal_protection
```

```
UPDRIFT_BEACH (((littoral_sand | (coastal_cliff_erosion & cliff_sand)) & longshore_power
& ~groynes) | ((marine_sand | (coastal_cliff_erosion & cliff_sand)) & ocean_waves)) &
~(slr & seawall)
```
Beach will form/persist if there is no SLR and seawall ('coastal squeeze') and given adequate/uninterrupted sediment supply.

```
SPIT = (~spit & updrift_beach & longshore_power & (littoral_sand |
(coastal_cliff_erosion & cliff_sand)) & ~groynes) | (spit & updrift_beach &
longshore_power & (littoral_sand | (coastal_cliff_erosion & cliff_sand)) & ~(slr &
groynes))
```
A spit will form if there is a strong littoral sediment flux but will not persist if SLR impacts groyne-protected coast.

```
INLET = (~(microtidal & ~(prism | river_discharge) & spit) | mesotidal | macrotidal) &
~barrage
```
Inlet exists at high tidal range and microtidal conditions unless blocked (spit and low prism / river flow, or barrage).

```
DOWNDRIFT_BEACH = (downdrift_beach & ~(slr & seawall)) | (((ebb_delta & spit) | ~inlet)
& updrift_beach & longshore_power)
```
Forms downdrift of updrift stores (spit, beach), given longshore power and bypassing (delta). Eroded under coastal squeeze.

```
DUNES = (wind & (updrift_beach | downdrift_beach | spit) & (marine_sand | littoral_sand
| (coastal_cliff_erosion & cliff_sand) | outer_sandflat)) | (dunes & ~slr)
```
Dunes forms under favourable wind regime in association with beaches or spit and a sand source, but erode under SLR.

```
WIND = wind
```

```
GROYNES = (groynes & (~slr | hold_the_line)) | advance_the_line
```
Imposed intervention. Fail under SLR without 'hold the line' strategy. Can also be imposed via 'advance the line' strategy.

```
COASTAL_PROTECTION = (coastal_protection & (~slr | hold_the_line)) | advance_the_line
```

```
SEAWALL = (seawall & (~slr | hold_the_line)) | advance_the_line
```

```
BARRAGE = barrage | advance_the_line
```

```
HOLD_THE_LINE = hold_the_line & ~(realign | do_nothing) | advance_the_line
REALIGN = realign & ~(hold_the_line | do_nothing | advance_the_line)
DO_NOTHING = do_nothing & ~(hold_the_line | realign | advance_the_line)
ADVANCE_THE_LINE = advance_the_line & ~(do_nothing | realign)
```

Table 9. Boolean Functions (with Rationale) for Outer Estuary Sub-System Variables

---

```
PRISM = (bedrock & inlet & ~(outer_marsh_low) & ~(inner_marsh_low & bayhead_delta)) |
(~bedrock & inlet & ~(outer_marsh_high | outer_flood_defence) & ~(inner_marsh_high &
(inner_marsh_low & bayhead_delta)))
```
In rock-controlled estuaries, tidal prism is reduced through formation of fringing marshes and bayhead delta. In alluvial estuaries, prism is reduced through infilling by more extensive marshes and/or removal of floodplain through reclamation. Infilling of outer estuary contributes greater reduction in prism than in inner estuary.

```
ACCOMM_SPACE = rock_basin | (fluvial_channel & ~macrotidal) | (fluvial_channel &
macrotidal & prism) | (~(rock_basin | fluvial_channel) & ((prism &
~outer_subtidal_sands) | (outer_dredging & inner_dredging)))
```
Overall estuary accommodation space is determined by presence of deep basins or fluvial channels and, according to context, the tidal prism.

```
EBB_DELTA = ~(linear_banks | rock_sill | rock_basin| fluvial_channel) & ((microtidal |
mesotidal) & inlet) & (marine_sand | (littoral_sand & longshore_power)) &
~outer_dredging
FLOOD_DELTA = ~(linear_banks | rock_sill | rock_basin | fluvial_channel) & (mesotidal |
(microtidal & spit & prism)) & (marine_sand | (littoral_sand & longshore_power)) &
~outer_dredging
LINEAR_BANKS = ~(ebb_delta | flood_delta | rock_sill | rock_basin | fluvial_channel) &
macrotidal  & (marine_sand | (littoral_sand & longshore_power))
```
Tidal deltas are mutually exclusive with respect to linear banks (which occur at higher tidal ranges). All these inlet sand bodies are restricted to alluvial estuary types (i.e. they do not occur in geologically-controlled settings).

```
BEDROCK = bedrock
```
Imposed geological constraint that discriminates between alluvial and non-alluvial estuaries.

```
ROCK_BASIN = bedrock & rock_basin
```
An inherited geological/geomorphological feature (characteristic of fjords and fjards).

```
ROCK_SILL = rock_sill & ~(ebb_delta | flood_delta | linear_banks) & rock_basin
```
An inherited geological/geomorphological feature (characteristic of fjords with overdeepened basins).

```
FLUVIAL_CHANNEL = bedrock & fluvial_channel
```
An inherited geological/geomorphological feature (characteristic of rias where a fluvially-eroded valley has been inundated).

```
OUTER_ROCK_PLATFORM = bedrock & ~(ebb_delta | flood_delta | linear_banks) &
~(outer_marsh_low | outer_sandflat | outer_mudflat)
```
Requires bedrock and a lack of sedimentary cover.

```
OUTER_FLOOD_DOMINANCE = (accomm_space | prism) & ~(outer_marsh_low & outer_marsh_high) &
~(microtidal & river_discharge) & inlet
OUTER_EBB_DOMINANCE = ~outer_flood_dominance & inlet
```
Flood-dominance occurs when depth is large (i.e. unfilled accommodation space or dredging) and when high intertidal area is not extensive. Otherwise, estuary becomes ebb-dominated.

```
OUTER_SUBTIDAL_SANDS = (~outer_subtidal_sands & ((((marine_sand | (((cliff_sand &
coastal_cliff_erosion) | littoral_sand) & longshore_power) ) & ~ rock_sill) &
outer_flood_dominance & (flood_delta | linear_banks))) & ~outer_dredging) |
(outer_subtidal_sands & ~outer_dredging)
```
Infilling of estuary subtidal occurs given coastal sediment supply, inlet sand bodies and flood dominance (but not if rock sill is present, or if material is removed through dredging).

```
OUTER_ESTUARY_SWELL = ocean_waves & inlet & ~spit

OUTER_ESTUARYWAVES = prism
```
Propagation of any ocean waves is facilitated by inlet but impeded by spit. Waves are generated within the outer estuary itself if the fetch is large enough - approximated here by the tidal prism.

```
OUTER_SANDFLAT = ((marine_sand | (((cliff_sand & coastal_cliff_erosion) | littoral_sand)
& longshore_power)) & ~ rock_sill) & (outer_estuary_swell | outer_estuarywaves |
macrotidal)
```
Forms under conditions of sand supply (from one or more of marine, coastal cliff or beach sources, unimpeded by rock sill) and significant wave and/or macrotidal action.

Table 9. (Continued)

OUTER_MUDFLAT = (~outer_mudflat & (marine_mud | (cliff_mud & coastal_cliff_erosion)) & ~(outer_estuary_swell & outer_estuarywaves)) | ((marine_mud | (cliff_mud & coastal_cliff_erosion)) & ~(outer_estuary_swell & outer_estuarywaves))
Forms under conditions of mud supply (from marine or coastal cliff sources) and negligible wave action.

OUTER_MARSH_LOW = (~outer_marsh_low & (outer_mudflat | outer_sandflat) & (outer_flood_defence | outer_marsh_high | outer_cliff) & (marine_mud | (cliff_mud & coastal_cliff_erosion)) & ~(outer_estuary_swell & outer_estuarywaves)) | (outer_marsh_low & (outer_mudflat | outer_sandflat) & ~(outer_estuary_swell) & ~(((outer_flood_defence | outer_marsh_high | bedrock) & slr) & (slr | ~(marine_mud | (cliff_mud & coastal_cliff_erosion)))))
Forms under conditions of mud supply (from marine or coastal cliff sources) and negligible wave action. Can be lost through coastal squeeze if backed by higher marsh, cliff, or flood defence and subjected to SLR.

OUTER_MARSH_HIGH = (~outer_marsh_high & (marine_mud | (cliff_mud & coastal_cliff_erosion)) & ~bedrock & ~outer_flood_defence & ~(outer_estuary_swell & outer_estuarywaves)) | (outer_marsh_high & ~outer_flood_defence & ~(slr & ~(marine_mud | (cliff_mud & coastal_cliff_erosion))) & ~outer_estuarywaves)
Forms under conditions of mud supply (from marine or coastal cliff sources) and negligible wave action. Can be lost if subjected to SLR with inadequate sediment supply.

OUTER_FLOOD_DEFENCE = ((outer_flood_defence & (~slr | hold_the_line)) | ~outer_flood_defence & advance_the_line) & ~realign
Intervention that protects flood plain from tidal inundation. Will fail under SLR unless maintained ('hold the line'). Can be removed or constructed through broader 'realignment' and 'advance the line' strategies respectively.

OUTER_FLOODPLAIN = ~(outer_cliff & bedrock) & outer_flood_defence
Floodplain in this sense refers to reclaimed upper estuarine intertidal that can potentially be converted to saltmarsh (through removal of the flood defence). Assumed not to be a significant component in rock-controlled estuaries.

OUTER_CLIFF = bedrock & ~(outer_marsh_high | outer_marsh_low | inner_flood_defence | inner_floodplain) & (outer_estuarywaves | outer_estuary_swell)
Estuary cliff characteristic of rock-controlled settings, with wave action and no fronting saltmarsh.

OUTER_DREDGING = outer_dredging

Table 10. Boolean Functions (with Rationale) for Inner Estuary Sub-System Variables

INNER_ROCKPLATFORM = bedrock & ~(inner_marsh_low | inner_sandflat | inner_mudflat)

INNER_FLOOD_DOMINANCE = (accomm_space & prism) & ~(inner_marsh_low & inner_marsh_high) & ~(inner_marsh_low & inner_dredging) & ~((microtidal | mesotidal) & river_discharge) & inlet

INNER_EBB_DOMINANCE = ~inner_flood_dominance & inlet

INNER_SUBTIDAL_DEPOSITS = (((outer_subtidal_sands & inner_flood_dominance) | river_sand | river_mud) & ~inner_dredging & ~(rock_basin & rock_sill)) | (inner_subtidal_deposits & ~inner_dredging)

INNER_ESTUARYWAVES = outer_estuarywaves & ~(inner_marsh_high | inner_marsh_low | inner_sandflat | inner_mudflat)
Waves can propagate from high energy outer estuary, or else be generated within the inner estuary itself if the fetch is large enough.

INNER_SANDFLAT = inner_subtidal_deposits & ((((marine_sand | (((cliff_sand & coastal_cliff_erosion) | littoral_sand) & longshore_power)) & ~ rock_sill) & outer_flood_dominance) | river_sand) | (inner_sandflat & ~(slr & ~((((marine_sand | (((cliff_sand & coastal_cliff_erosion) | littoral_sand) & longshore_power)) & ~ rock_sill) & outer_flood_dominance) | river_sand))

INNER_MUDFLAT = (~inner_mudflat & ((marine_mud | (cliff_mud & coastal_cliff_erosion)) | river_mud) & ~inner_estuarywaves) | (((marine_mud | (cliff_mud & coastal_cliff_erosion)) | river_mud) & ~(inner_estuarywaves & inner_ebb_dominance & outer_ebb_dominance & slr))

INNER_MARSH_LOW = (~inner_marsh_low & (inner_mudflat | inner_sandflat) & (inner_flood_defence | inner_marsh_high | inner_cliff) & (((marine_mud | (cliff_mud & coastal_cliff_erosion)) | river_mud) & ~(inner_estuarywaves | (slr & (inner_flood_defence | inner_cliff))))) | (inner_marsh_low & (inner_mudflat | inner_sandflat) & (~(((inner_flood_defence | inner_marsh_high | inner_cliff | bedrock) & slr) | (slr | ~((marine_mud | (cliff_mud & coastal_cliff_erosion)) | river_mud)))))

INNER_MARSH_HIGH = (~inner_marsh_high & ((marine_mud | (cliff_mud & coastal_cliff_erosion)) | river_mud) & ~inner_flood_defence & ~bedrock & (inner_mudflat | inner_sandflat) & ~inner_estuarywaves) | (inner_marsh_high & ~inner_flood_defence & ~(slr & ~((marine_mud | (cliff_mud & coastal_cliff_erosion)) | river_mud) & inner_estuarywaves))

INNER_FLOOD_DEFENCE = (inner_flood_defence & (~slr | hold_the_line)) | ~inner_flood_defence & advance_the_line & ~realign

INNER_FLOODPLAIN = ~(inner_cliff & bedrock) & inner_flood_defence

INNER_CLIFF = bedrock & ~(inner_marsh_high | inner_flood_defence | inner_floodplain | inner_marsh_low)
Estuary cliff characteristic of rock-controlled settings where there is no fronting saltmarsh.

INNER_DREDGING = inner_dredging

BAYHEAD_DELTA = rock_basin & river_discharge & river_sand & ~((bayhead_delta & inner_flood_defence & slr & ~(river_discharge | river_sand)))
Sand and/or gravel deposits at estuary head under conditions of significant river discharge and coarse sediment load. Less accommodation space is available in rock controlled estuaries, and can be replaced by saltmarsh in either rock-controlled or alluvial settings. Delta can be lost under SLR if sediment supply is removed.

RIVER_DISCHARGE = river_discharge
RIVER_SAND = river_sand & river_discharge
RIVER_MUD = river_mud & river_discharge
External fluvial system inputs

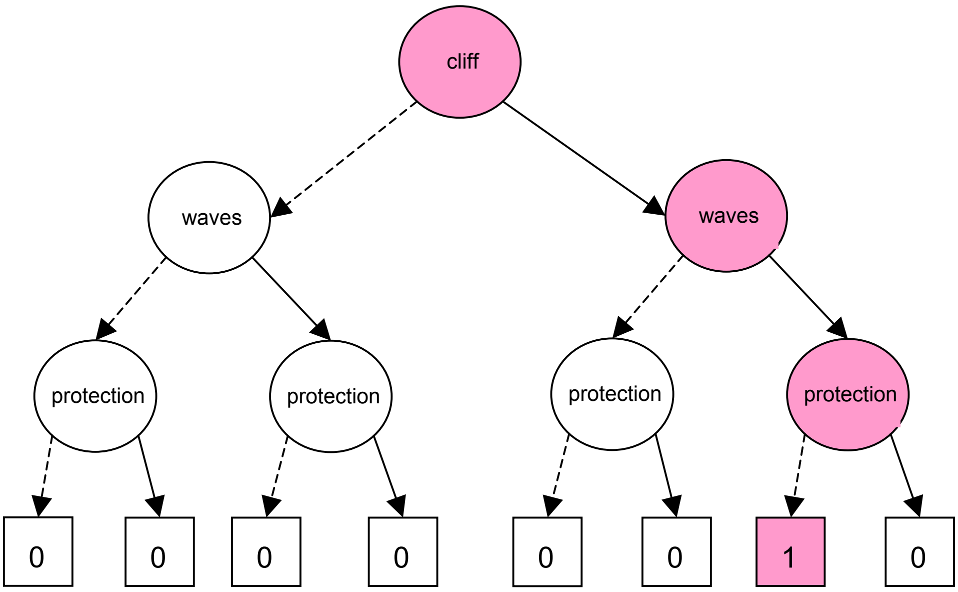
The operation of the Boolean logic can be illustrated more clearly with reference to the truth table for one of the simpler functions. As an example, Figure 25 shows the logic for coastal cliff erosion. Inspection of the truth table and its associated binary decision tree confirms that only one combination of input values (presence of the cliff morphological element, existence of significant wave action, and absence of coastal protection) results in the Boolean expression evaluating to TRUE (i.e. a logical 1). All other combinations yield FALSE (logical 0). Within **Qualitative reasoning,** our representation of coastal cliff erosion dictates that this requires the presence of both a cliff and significant wave action but that erosion will cease with installation of cliff toe protection. The **Boolean function** that incorporates this reasoning is taken from Table 9:

```
COASTAL_CLIFF_EROSION = coastal_cliff & ocean_waves & ~coastal_protection
```

Truth table for this function:

COASTAL_CLIFF_EROSION	coastal_cliff	ocean_waves	coastal_protection
FALSE	0	0	0
FALSE	0	0	1
FALSE	0	1	0
FALSE	0	1	1
FALSE	1	0	0
FALSE	1	0	0
FALSE	1	0	1
TRUE	1	1	0
FALSE	1	1	1

Binary decision tree:



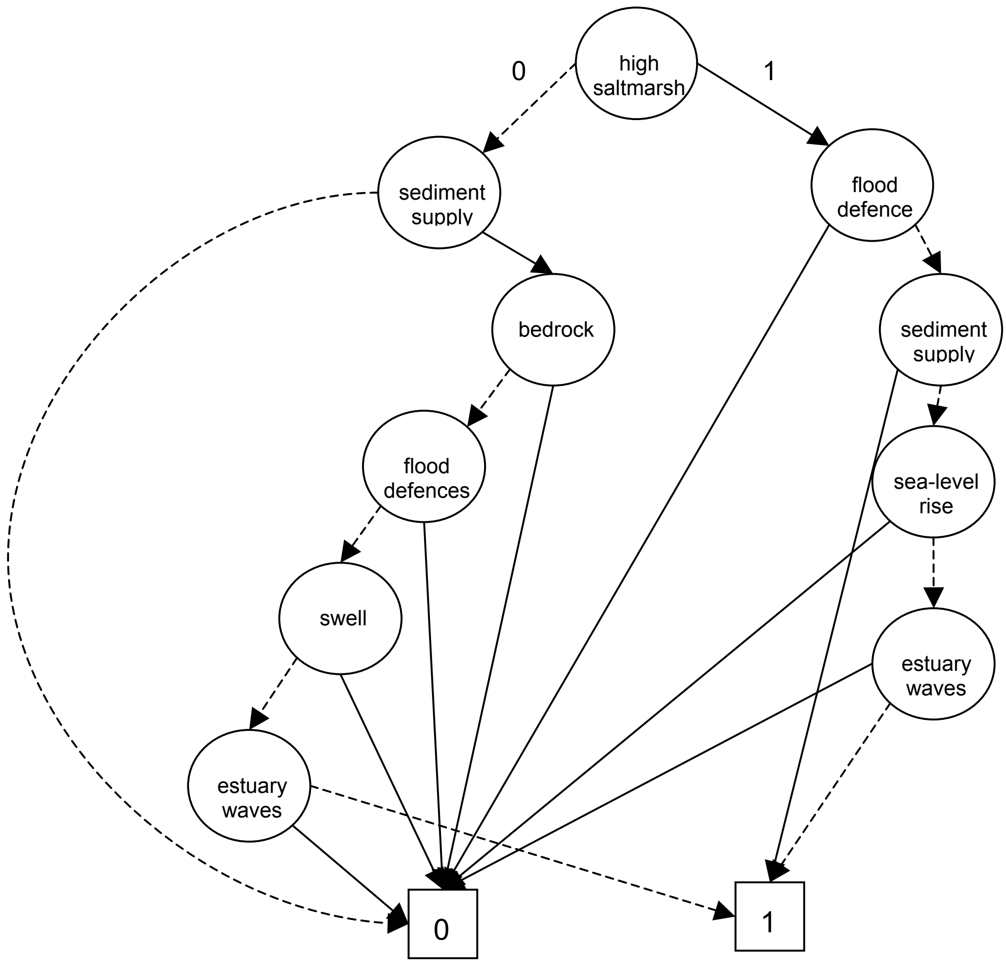
In binary decision tree, solid 'edges' lead to high (true) states and dashed 'edges' lead to low (false) states.

Figure 25. Illustration of Boolean logic for coastal cliff erosion

Although the formalisation of knowledge represented by Figure 25 is straightforward, the truth tables for more complex functions can become very large. The function for the high saltmarsh element within the outer estuary (Table 9), for example, includes 9 terms (including self-input). The truth table thus contains 512 (i.e. 2^9) states. To some extent, this additional complexity can be managed by the aggregation of related terms into temporary variables. Thus, a ‘sediment supply’ variable can be created from the combination of marine mud, cliff mud and coastal cliff erosion, thereby reducing the function to 7 terms with 128 potential states. Such aggregate variables can be eliminated once the functions are fully coded and tested but could equally be retained in the final system representation if less importance is attached to minimising the eventual variable set.

Another way of managing function complexity exploits the fact that Boolean functions are often extremely sparse and contain many zero states and outcomes that depend on a small fraction of the possible 2^N states. In this case, the Boolean decision trees can be implemented more efficiently by judicious ordering of the variables, deletion of redundant nodes and sharing of equivalent sub-graphs to give a Binary Decision Diagram (BDD; Bryant, 1986; Minato & Arimura, 2004). Figure 26 shows a BDD for the high saltmarsh element of the outer estuary. A new saltmarsh forms in the presence of a sediment supply (here, a function of marine mud and coastal cliff-derived mud) in settings not characterised by bedrock, enclosure of the upper intertidal by flood defences, and significant swell or estuary-generated waves. Existing saltmarsh will persist if it remains unenclosed by flood defences and if sustained by sediment (in which case it can track sea level rise) or in the absence of sea level rise and estuary waves.

Although computational tools are available to support rigorous graph-based analysis of Boolean functions (e.g. Bryant, 1986), the construction of influence diagrams for geomorphological systems and the formalisation of geomorphological knowledge into sets of Boolean functions remains much more subjective. It follows that neither the influence diagrams nor the derived Boolean functions presented here are unique. Given a set of morphological components and process variables (Figure 26) different individuals (or ‘experts’) will inevitably conceptualise and code system behaviour in terms of different indicative linkages and Boolean functions. Ideally, the variance associated with this procedure should be investigated, and optimal representations arrived at through consensus (e.g. expert workshops). The functions set out in Tables 8-10 should thus be considered purely as a starting point from which to explore the potential and limitations of a Boolean approach. They do *not* constitute a definitive formalisation of coastal and estuary geomorphological knowledge, and both the functions and the variable set is likely to require further customisation for application to specific estuaries.



See text for explanation

Figure 26. Binary Decision Diagram (BDD) for outer estuary high saltmarsh

4.3.3 Initial Simulation of Generic Estuary Types

The first test of the Prototype Simulator model is whether or not it is capable of discriminating between the seven generic estuary types defined in section 3. These are defined at a fairly high level of abstraction and some further effort is needed to implement each type using the expanded variable set developed in the preceding section.

From the 67 possible variables in Tables 6 and 7 a minimal set of 50 can be used to define all of the generic estuary types in their natural state (neglecting accelerated sea level rise). A matrix of variables and their initial states for each estuary type is given in Table 11. Only forcing variables (including imposed geological features) are defined at the outset for each type: morphological components and state variables are otherwise free to evolve. Not all possibilities are considered for each type. Fjords, fjards and rias, for example, are modelled without the potential for spit formation. By default, a meso-tidal range is assumed, except for funnel-shaped estuaries and embayments, which are here assumed to be macro-tidal.

Table 11. Initial Conditions Used for Simulation of Generic Estuary Types, Using Minimal Variable Set for Natural System (i.e. No Interventions or Accelerated Sea Level Rise Modelled at This Stage)

Estuary Type	Fjord	Fjard	Ria	Spit-Enclosed	Funnel	Embayment	Inlet
ocean_waves	1	1	1	1	1	1	1
longshore_power	0	0	0	1	0	0	1
littoral_sand	0	0	0	1	1	1	1
marine_sand	0	0	1	1	1	1	1
marine_mud	0	0	1	0	1	1	1
macrotidal	0	0	0	0	1	1	0
mesotidal	1	1	1	1	0	0	1
microtidal	0	0	0	0	0	0	0
updrift_beach	0	0	0	0	0	0	0
spit	0	0	0	0	0	0	0
inlet	1	1	1	1	1	1	1
rock_basin	1	1	0	0	0	0	0
fluvial_channel	0	0	1	0	0	0	0
downdrift_beach	0	0	0	0	0	0	0
dunes	0	0	0	0	0	0	0
wind	1	1	1	1	1	1	1
prism	1	1	1	1	1	1	1
accomm_space	1	1	1	1	1	1	1
ebb_delta	0	0	0	0	0	0	0
flood_delta	0	0	0	0	0	0	0
linear_banks	0	0	0	0	0	0	0
bedrock	1	1	1	0	0	0	0
rock_sill	1	0	0	0	0	0	0
outer_rock_platform	0	0	0	0	0	0	0
outer_flood_dominance	0	0	0	0	0	0	0
outer_ebb_dominance	0	0	0	0	0	0	0
outer_subtidal_sands	0	0	0	0	0	0	0
outer_estuary_swell	0	0	0	0	0	0	0
outer_estuarywaves	0	0	0	0	0	0	0
outer_sandflat	0	0	0	0	0	0	0
outer_mudflat	0	0	0	0	0	0	0
outer_marsh_low	0	0	0	0	0	0	0
outer_marsh_high	0	0	0	0	0	0	0
outer_floodplain	0	0	0	0	0	0	0
outer_cliff	0	0	0	0	0	0	0
inner_rockplatform	0	0	0	0	0	0	0
inner_flood_dominance	0	0	0	0	0	0	0
inner_ebb_dominance	0	0	0	0	0	0	0
inner_subtidal_deposits	0	0	0	0	0	0	0
inner_estuarywaves	0	0	0	0	0	0	0
inner_sandflat	0	0	0	0	0	0	0
inner_mudflat	0	0	0	0	0	0	0
inner_marsh_low	0	0	0	0	0	0	0
inner_marsh_high	0	0	0	0	0	0	0
inner_floodplain	0	0	0	0	0	0	0
inner_cliff	0	0	0	0	0	0	0
bayhead_delta	0	0	0	0	0	0	0
river_discharge	1	1	1	1	1	0	0
river_sand	1	1	1	1	1	0	0
river_mud	0	1	1	1	1	0	0

Simulated evolutionary end points for each set of generic initial conditions are presented in Table 12. The evolutionary behaviour for each of the 7 types is briefly described overleaf.

Type 1: Fjord. This is modelled as a sediment deficient system, with the exception of a supply of river sand (which allows formation of a bay head delta). There are no tidal deltas or linear banks; no intertidal sedimentary units; and tidal prism and accommodation remain large (i.e. unfilled by sediment). A steady state, characterised by active cliffs and rock platforms emerges after just

3 steps. Some fjords do have spits; the Boolean functions in Table 8 allow spits to form where an updrift beach is fed by littoral sand flux, but allow the presence of a rock sill to impede coarse sediment transport into the fjord. Some assumption of this kind is required in order to prevent infilling of the accommodation space and conversion to another estuary type (such as a funnel-shaped estuary). Alternatively, a spit can originate from reworking of relict sediment sources (e.g. offshore fluvial-glacial sands and gravels). In this case, a spit might persist where an updrift barrier beach is imposed, longshore transport is significant and sea-level rise is low. Such a feature would degenerate under accelerated sea-level rise (i.e. with no new sediment input).

Type 2: Fjard. As noted, the distinction between fjords and fjards is rather subtle. The former are over-deepened through glacial erosion and exhibit a shallower sill near the mouth; the latter typically contain rather more extensive intertidal deposits, including inner estuary saltmarsh. Here, the presence or absence of an imposed rock sill allows slightly different behaviours and a supply of mud (fluvial or marine) allows the formation of some saltmarsh in the limited accommodation space. With only a river sand influx, a steady state emerges after 4 steps (not shown in Table 12 but similar to a fjord, with the addition of inner estuary sandflats). The addition of a marine mud input (as specified in the initial conditions of Table 11) leads to an evolution towards a steady state after 5 steps in which saltmarsh forms within the inner estuary.

Type 3: Ria. Rias can potentially contain a range of intertidal depositional features, which implies a supply of sand and/or mud. However, the accommodation space remains substantially unfilled by Holocene sedimentation and their inherited fluvial planform contrasts with that of sediment-rich funnel-shaped (type 5) systems. This can be accommodated via the inclusion of a fluvially-incised outer estuary channel. This effectively imposes an accommodation space that does not favour wave-driven movement of coarse sediment into the estuary (wave action is less effective in larger water depth) and impedes bypassing of sediment across the inlet given relatively deep water and an absence of tidal deltas. Deposition in the inner estuary is facilitated by marine fluvial mud input. Dunes can form if a spit is present. With the initial configuration given in Table 11, a cyclical endpoint (involving inner estuary marsh) is reached at steps 4 - 6.

Type 4: Spit-enclosed drowned river valley. This system is forced with the imposition of a longshore wave power component and sediment supply that will lead to the formation of a protective spit. A river inflow is also imposed and distinguishes this type from a tidal inlet (type 7). The end point is cyclic between steps 8 and 11, cyclic behaviour is confined to the outer estuary and involves interaction between high saltmarsh, prism and estuary waves. More generally, the evolution of this estuary morphology involves long-term infilling of both outer and inner estuary units, aided by the protection afforded by a spit. Ebb and flood deltas form within the estuary inlet and dunes are formed in association within the beaches and spit.

Table 12. End States Simulated for Generic Estuary Types Using Initial Conditions Specified in Table 11

Estuary Type:	Fjord	Fjard	Ria	Spit-Enclosed	Funnel	Embayment	Inlet
ocean_waves	1	1	1 ↔ 1	1 ↔ 1	1 ↔ 1	1 ↔ 1	1 ↔ 1
longshore_power	0	0	1 ↔ 1	1 ↔ 1	1 ↔ 1	1 ↔ 1	1 ↔ 1
littoral_sand	0	0	1 ↔ 1	1 ↔ 1	1 ↔ 1	1 ↔ 1	1 ↔ 1
marine_sand	0	0	0 ↔ 0	1 ↔ 1	1 ↔ 1	1 ↔ 1	0 ↔ 0
marine_mud	0	0	0 ↔ 0	1 ↔ 1	1 ↔ 1	1 ↔ 1	0 ↔ 0
macrotidal	0	0	0 ↔ 0	0 ↔ 0	1 ↔ 1	1 ↔ 1	0 ↔ 0
mesotidal	1	1	1 ↔ 1	1 ↔ 1	0 ↔ 0	0 ↔ 0	1 ↔ 1
microtidal	0	0	0 ↔ 0	0 ↔ 0	0 ↔ 0	0 ↔ 0	0 ↔ 0
updrift_beach	0	0	1 ↔ 1	1 ↔ 1	1 ↔ 1	1 ↔ 1	1 ↔ 1
spit	0	0	1 ↔ 1	1 ↔ 1	0 ↔ 0	0 ↔ 0	1 ↔ 1
inlet	1	1	1 ↔ 1	1 ↔ 1	1 ↔ 1	1 ↔ 1	1 ↔ 1
rock_basin	1	1	0 ↔ 0	0 ↔ 0	0 ↔ 0	0 ↔ 0	0 ↔ 0
fluvial_channel	0	0	1 ↔ 1	0 ↔ 0	0 ↔ 0	0 ↔ 0	0 ↔ 0
downdrift_beach	0	0	0 ↔ 0	1 ↔ 1	0 ↔ 0	0 ↔ 0	1 ↔ 1
dunes	0	0	1 ↔1	1 ↔ 1	1 ↔ 1	1 ↔ 1	1 ↔ 1
wind	0	0	1 ↔ 1	1 ↔ 1	1 ↔ 1	1 ↔ 1	1 ↔ 1
prism	1	0	1 ↔ 1	0 ↔ 0	0 ↔ 0	0 ↔ 0	0 ↔ 0
accomm_space	1	1	1 ↔ 1	0 ↔ 0	0 ↔ 0	0 ↔ 0	0 ↔ 0
ebb_delta	0	0	0 ↔ 0	1 ↔ 1	0 ↔ 0	0 ↔ 0	1 ↔ 1
flood_delta	0	0	0 ↔ 0	1 ↔ 1	0 ↔ 0	0 ↔ 0	1 ↔ 1
linear_banks	0	0	0 ↔ 0	0 ↔ 0	1 ↔ 1	1 ↔ 1	0 ↔ 0
bedrock	1	1	1 ↔ 1	0 ↔ 0	0 ↔ 0	0 ↔ 0	0 ↔ 0
rock_sill	1	1	0 ↔ 0	0 ↔ 0	0 ↔ 0	0 ↔ 0	0 ↔ 0
outer_rock_platform	1	1	0 ↔ 0	0 ↔ 0	0 ↔ 0	0 ↔ 0	0 ↔ 0
outer_flood_dominance	1	1	1 ↔ 1	0 ↔ 0	1 ↔ 1	1 ↔ 1	0 ↔ 0
outer_ebb_dominance	0	0	0 ↔ 0	1 ↔ 1	0 ↔ 0	0 ↔ 0	1 ↔ 1
outer_subtidal_sands	0	0	0 ↔ 0	1 ↔ 1	1 ↔ 1	1 ↔ 1	1 ↔ 1
outer_estuary_swell	1	1	0 ↔ 0	0 ↔ 0	1 ↔ 1	1 ↔ 1	0 ↔ 0
outer_estuarywaves	1	1	1 ↔ 1	1 ↔ 1	1 ↔ 1	1 ↔ 1	1 ↔ 1
outer_sandflat	0	0	1 ↔ 1	0 ↔ 0	1 ↔ 1	1 ↔ 1	1 ↔ 1
outer_mudflat	0	0	0 ↔ 0	1 ↔ 1	0 ↔ 0	0 ↔ 0	1 ↔ 1
outer_marsh_low	0	0	0 ↔ 0	1 ↔ 1	0 ↔ 0	0 ↔ 0	1 ↔ 1
outer_marsh_high	0	0	0 ↔ 0	1 ↔ 1	0 ↔ 0	0 ↔ 0	1 ↔ 1
outer_floodplain	0	0	0 ↔ 0	0 ↔ 0	0 ↔ 0	0 ↔ 0	0 ↔ 0
outer_cliff	1	1	1 ↔ 1	0 ↔ 0	0 ↔ 0	0 ↔ 0	0 ↔ 0
inner_rockplatform	1	1	0 ↔ 0	0 ↔ 0	0 ↔ 0	0 ↔ 0	0 ↔ 0
inner_flood_dominance	0	0	0 ↔ 0	0 ↔ 0	0 ↔ 0	0 ↔ 0	0 ↔ 0
inner_ebb_dominance	1	1	1 ↔ 1	1 ↔ 1	1 ↔ 1	1 ↔ 1	1 ↔ 1
inner_subtidal_deposits	0	1	1 ↔ 1	1 ↔ 1	1 ↔ 1	1 ↔ 1	1 ↔ 1
inner_estuarywaves	1	0	0 ↔ 0	0 ↔ 0	0 ↔ 0	0 ↔ 0	0 ↔ 0
inner_sandflat	0	1	0 ↔ 0	1 ↔ 1	1 ↔ 1	1 ↔ 1	1 ↔ 1
inner_mudflat	0	1	1 ↔ 1	1 ↔ 1	1 ↔ 1	1 ↔ 1	1 ↔ 1
inner_marsh_low	0	1	0 ↔ 0	1 ↔ 1	1 ↔ 1	1 ↔ 1	1 ↔ 1
inner_marsh_high	0	0	0 ↔ 0	1 ↔ 1	1 ↔ 1	1 ↔ 1	1 ↔ 1
inner_floodplain	0	0	0 ↔ 0	0 ↔ 0	0 ↔ 0	0 ↔ 0	0 ↔ 0
inner_cliff	1	0	0 ↔ 0	0 ↔ 0	0 ↔ 0	0 ↔ 0	0 ↔ 0
bayhead_delta	1	1	0 ↔ 0	0 ↔ 0	0 ↔ 0	0 ↔ 0	0 ↔ 0
river_discharge	1	1	1 ↔ 1	1 ↔ 1	1 ↔ 1	0 ↔ 0	0 ↔ 0
river_sand	1	1	0 ↔ 0	1 ↔ 1	1 ↔ 1	0 ↔ 0	0 ↔ 0
river_mud	0	1	1 ↔ 1	1 ↔ 1	1 ↔ 1	0 ↔ 0	0 ↔ 0

N.B. Oscillating cyclical end points are indicated, with variables participating in cycle shown in **bold.**

Type 5: Funnel-shaped drowned river valley. This is defined as a macro-tidal system and shows a tendency to infill, with the outer and inner estuary intertidal areas being sand and mud-dominated respectively. Although the total accommodation space is reduced over time, the tidal prism remains large since the outer estuary is wave-dominated and does not infill with saltmarsh. Linear banks replace the ebb and flood deltas of meso-tidal sediment-rich systems. The inner estuary saltmarsh leads to an ebb-dominated regime, although the outer estuary remains flood-dominant. This configuration evolves towards a cyclical state after steps 6 to 9. This cyclicity is due to interaction between waves, high saltmarsh and tidal asymmetry in the outer estuary.

Type 6: Embayment. As presently defined, embayments differ from the preceding funnel-shaped estuary type only in the lack of any single major river inflow. Given that the latter is not always significant in funnel-shaped systems, little difference in behaviour is to be expected. This is borne out by the model results, which show evolution towards a state characterised by outer linear banks and sandflats, and inner mudflats and saltmarsh. The evolution is cyclical after steps 6 to 9 due to interaction between waves, high saltmarsh and tidal asymmetry in the outer estuary. Embayments are modelled here as a macro-tidal system. Under meso-tidal or micro-tidal conditions, linear banks are replaced by tidal deltas, which is not necessarily realistic for an unconfined inlet geometry.

Type 7: Tidal inlet. In reality, distinctive elements of a tidal inlet include the absence of any river flow and the tendency for one or more spits and tidal deltas at the estuary mouth. From the minimal set of initial conditions imposed in Table 11 such a system does indeed evolve. The end point is essentially the same as that for a spit-enclosed estuary and is cyclic between steps 8 and 11. Under micro-tidal conditions, however, there is provision in the Boolean functions for the inlet to block in the presence of littoral drift and the absence of significant river flow.

Overall, this analysis shows that the set of functions in Tables 8-10 are fairly effective in discriminating between the 7 generic estuary types, and that a range of evolutionary outcomes and behaviours emerge from relatively small variations in model input. The complexity of the morphodynamic behaviour varies between steady state and cyclical systems, and according to the extent and variety of sedimentary infilling.

If persistently inactive components are neglected, the evolutionary paths are easier to understand. The sequence of states for a fjord (Table 13) involves only 21 components and achieves steady state equilibrium in just 3 steps. The evolution of a fjard is a little more complex, involving 24 components over 5 steps (Table 14).

Table 13. Evolution of Generic Fjord Towards Steady State Equilibrium

1	2	3	Step
1	1	1	ocean_waves
1	1	1	mesotidal
1	1	1	inlet
1	1	1	rock_basin
1	1	1	prism
1	1	1	accomm_space
1	1	1	bedrock
1	1	1	rock_sill
0	1	1	outer_rock_platform
0	1	1	outer_flood_dominance
0	1	0	outer_ebb_dominance
0	1	1	outer_estuary_swell
0	1	1	outer_estuarywaves
0	0	1	outer_cliff
0	1	1	inner_rockplatform
0	1	1	inner_ebb_dominance
0	0	1	inner_estuarywaves
0	1	1	inner_cliff
0	1	1	bayhead_delta
1	1	1	river_discharge
1	1	1	river_sand

N.B. Step 1 corresponds to the initial conditions given in Table 11

Table 14. Evolution of Generic Fjard Towards Steady State Equilibrium

1	2	3	4	5	Step
1	1	1	1	1	ocean_waves
1	1	1	1	1	mesotidal
1	1	1	1	1	inlet
1	1	1	1	1	rock_basin
1	1	1	0	0	prism
1	1	1	1	1	accomm_space
1	1	1	1	1	bedrock
0	1	1	1	1	outer_rock_platform
0	1	1	1	1	outer_flood_dominance
0	1	0	0	0	outer_ebb_dominance
0	1	1	1	1	outer_estuary_swell
0	1	1	1	0	outer_estuarywaves
0	0	1	1	1	outer_cliff
0	1	0	0	0	inner_rockplatform
0	1	1	1	1	inner_ebb_dominance
0	1	1	1	1	inner_subtidal_deposits
0	0	1	1	1	inner_sandflat
0	1	1	1	1	inner_mudflat
0	0	1	1	1	inner_marsh_low
0	1	1	0	0	inner_cliff
0	1	1	1	1	bayhead_delta
1	1	1	1	1	river_discharge
1	1	1	1	1	river_sand
1	1	1	1	1	river_mud

The evolution of a spit-enclosed estuary is more complex, involving 34 variables and the emergence of a cyclical end point after 11 steps (Table 15). The cycle length is 4 steps, i.e. the interval between steps 8 and 11. Here, some artefacts of the synchronous updating are evident. At step 2, for example, the inner estuary appears to be both flood- and ebb-dominated. This is resolved over subsequent steps (including an intermediate state of neither flood- nor ebb-dominance) and ebb-dominance is finally established by step 6. Within the cycle, there is an interaction between prism, waves and high saltmarsh that owes more to the coding of the Boolean functions than a real cycle within the corresponding natural system. It is not immediately clear whether the cyclical behaviour evident in this and other estuary types is an emergent property of the system structure or whether it is a consequence of the synchronous updating scheme. This issue is considered further below.

Table 15. Evolution of Generic Spit-Enclosed Estuary Towards Cyclical Equilibrium

1	2	3	4	5	6	7	8	9	10	11	Step
1	1	1	1	1	1	1	**1**	**1**	**1**	**1**	ocean_waves
1	1	1	1	1	1	1	**1**	**1**	**1**	**1**	longshore_power
1	1	1	1	1	1	1	**1**	**1**	**1**	**1**	littoral_sand
1	1	1	1	1	1	1	**1**	**1**	**1**	**1**	marine_sand
1	1	1	1	1	1	1	**1**	**1**	**1**	**1**	marine_mud
1	1	1	1	1	1	1	**1**	**1**	**1**	**1**	mesotidal
0	1	1	1	1	1	1	**1**	**1**	**1**	**1**	updrift_beach
0	0	1	1	1	1	1	**1**	**1**	**1**	**1**	spit
1	1	1	1	1	1	1	**1**	**1**	**1**	**1**	inlet
0	0	0	1	1	1	1	**1**	**1**	**1**	**1**	downdrift_beach
0	0	1	1	1	1	1	**1**	**1**	**1**	**1**	dunes
1	1	1	1	1	1	1	**1**	**1**	**1**	**1**	wind
1	1	0	1	1	0	1	**0**	**0**	**1**	**0**	prism
1	1	1	0	0	0	0	**0**	**0**	**0**	**0**	accomm_space
0	1	1	1	1	1	1	**1**	**1**	**1**	**1**	ebb_delta
0	1	1	1	1	1	1	**1**	**1**	**1**	**1**	flood_delta
0	1	1	1	1	1	0	**0**	**0**	**0**	**0**	outer_flood_dominance
0	1	0	0	0	0	0	**1**	**1**	**1**	**1**	outer_ebb_dominance
0	0	1	1	1	1	1	**1**	**1**	**1**	**1**	outer_subtidal_sands
0	1	1	0	0	0	0	**0**	**0**	**0**	**0**	outer_estuary_swell
0	1	1	0	1	1	0	**1**	**0**	**0**	**1**	outer_estuarywaves
0	0	1	1	0	1	1	**0**	**1**	**0**	**0**	outer_sandflat
0	1	0	0	1	1	1	**1**	**1**	**1**	**1**	outer_mudflat
0	0	0	0	0	1	1	**1**	**1**	**1**	**1**	outer_marsh_low
0	1	0	0	1	0	1	**1**	**0**	**1**	**1**	outer_marsh_high
0	1	1	1	1	1	1	**1**	**1**	**1**	**1**	inner_ebb_dominance
0	1	1	1	1	1	1	**1**	**1**	**1**	**1**	inner_subtidal_deposits
0	0	1	1	1	1	1	**1**	**1**	**1**	**1**	inner_sandflat
0	1	1	1	1	1	1	**1**	**1**	**1**	**1**	inner_mudflat
0	0	0	1	1	1	1	**1**	**1**	**1**	**1**	inner_marsh_low
0	0	1	1	1	1	1	**1**	**1**	**1**	**1**	inner_marsh_high
1	1	1	1	1	1	1	**1**	**1**	**1**	**1**	river_discharge
1	1	1	1	1	1	1	**1**	**1**	**1**	**1**	river_sand
1	1	1	1	1	1	1	**1**	**1**	**1**	**1**	river_mud

N.B. Cyclical end sequence incorporating steps 8 to 11 indicated in **bold**.

4.3.4 Form-Process Feedback: Addition of Decay Term

A problem with the model, as presently formulated, is that transitions between states can result in unrealistic intermediate configurations. This can be attributed to the use of a discrete time step and to synchronous updating of all state variables at each step. However, in reality geomorphological system behaviour is conditioned by the temporal lag effects in respect of the morphological components. Some landforms, such as beaches, tend to respond rapidly to a change in forcing processes (perhaps over months or years), whilst others, such as saltmarshes, respond over longer timescales (perhaps decades or centuries). These lags tend to characterise the effect of a change in process on morphology. In contrast, changes in morphology (such as the breakdown of a spit) can often effect a near-instantaneous feedback on processes.

This aspect of system behaviour can be approximated with recourse to the decay term in the rate equation derived in Section 4.2 for the response of a state variable to a set of external parameters (Equation 2). Any state variable can thus be assigned a decay term (or lag value) that controls the rate at which it changes state in response to inputs from connected state variables. If we retain synchronous updating at discrete time steps, then an obvious way to implement this is to assign arbitrary lag values (measured in discrete time steps) to selected components and to allow these components to change state only when subjected to persistent external stimulation for the duration of the lag. A spit, for example, might be assigned a lag of 3 steps. If the spit is subjected to external forcing that would result in its destruction, this must persist for at least 3 consecutive steps before its state variable will change state (in this case from logical 1 to 0). Multiple short-lived stimuli, in contrast, do not effect any change.

To evaluate the effect of such an implementation, decay terms can be applied to all of the morphological components that are free to adjust as the system evolves, and imposed features such as rock basin, rock sill, fluvially-incised channel and cliffs can be excluded. Rapidly responding features were assigned an arbitrary decay of 3 steps, and slowly responding features a decay of 5 steps (Table 16).

Revised state variable matrices for the evolution of each of the generic estuary types in the absence of engineering intervention or accelerated sea level rise are presented in Tables 17-23.

Table 16. Assignment of Decay Terms to Morphological Variables

Variable	Decay
Coastal-Estuary Sub-System	
Coastal cliffs (imposed feature)	None
Barrier beach updrift	Rapid
Spit	Slow
Inlet	Rapid
Barrier beach downdrift	Rapid
Coastal dunes	Slow
Outer Estuary Sub-System	
Ebb delta	Rapid
Flood delta	Rapid
Linear banks	Rapid
Rock sill (imposed feature)	None
Rock basin (imposed feature)	None
Fluvially-incised meandering channel (imposed feature)	None
Outer estuary rock platform (exposed)	Rapid *
Outer estuary subtidal deposits (incl. channel sands)	Rapid
Outer estuary sandflat	Rapid
Outer estuary mudflat	Rapid
Outer estuary marsh - low	Slow
Outer estuary marsh - high	Slow
Outer estuary floodplain (0 if reclaimed)	Rapid
Outer estuary cliff (imposed feature)	None
Inner Estuary Sub-System	
Inner estuary rock platform (exposed)	Rapid*
Inner estuary subtidal deposits (channel sands/muds)	Rapid
Inner estuary sandflat	Rapid
Inner estuary mudflat	Rapid
Inner estuary marsh - low	Slow
Inner estuary marsh - high	Slow
Inner estuary floodplain (0 if reclaimed)	Rapid
Outer estuary feature (imposed feature)	None
Bay head delta	Slow

* Rock platforms can be rapidly exposed by erosion of sediment cover but slower erosional development is not modelled.

Table 17. Evolution of Generic Fjord Towards Steady State

1	2	3	4	5	6	Step
1	1	1	1	1	1	ocean_waves
1	1	1	1	1	1	mesotidal
1	1	1	1	1	1	inlet
1	1	1	1	1	1	rock_basin
1	1	1	1	1	1	prism
1	1	1	1	1	1	accomm_space
1	1	1	1	1	1	bedrock
1	1	1	1	1	1	rock_sill
0	1	1	1	1	1	outer_rock_platform
0	1	1	1	1	1	outer_flood_dominance
0	1	1	1	1	1	outer_estuary_swell
0	1	1	1	1	1	outer_estuarywaves
0	0	1	1	1	1	outer_cliff
0	1	1	1	1	1	inner_rockplatform
0	0	1	1	1	1	inner_ebb_dominance
0	0	1	1	1	1	inner_estuarywaves
0	1	1	1	1	1	inner_cliff
0	0	0	0	0	1	bayhead_delta
1	1	1	1	1	1	river_discharge
1	1	1	1	1	1	river_sand

Table 18. Evolution of Generic Fjard Towards Steady State

1	2	3	4	5	6	7	8	9	10	Step
1	1	1	1	1	1	1	1	1	1	ocean_waves
1	1	1	1	1	1	1	1	1	1	mesotidal
1	1	1	1	1	1	1	1	1	1	inlet
1	1	1	1	1	1	1	1	1	1	rock_basin
1	1	1	1	1	1	1	1	0	0	prism
1	1	1	1	1	1	1	1	1	1	accomm_space
1	1	1	1	1	1	1	1	1	1	bedrock
0	1	1	1	1	1	1	1	1	1	outer_rock_platform
0	1	1	1	1	1	1	1	1	1	outer_flood_dominance
0	1	1	1	1	1	1	1	1	1	outer_estuary_swell
0	1	1	1	1	1	1	1	1	0	outer_estuarywaves
0	0	1	1	1	1	1	1	1	1	outer_cliff
0	1	1	1	0	0	0	0	0	0	inner_rockplatform
0	0	1	1	1	1	1	1	1	1	inner_ebb_dominance
0	0	0	1	1	1	1	1	1	1	inner_subtidal_deposits
0	0	1	1	0	0	0	0	0	0	inner_estuarywaves
0	0	0	0	0	0	1	1	1	1	inner_sandflat
0	0	0	1	1	1	1	1	1	1	inner_mudflat
0	0	0	0	0	0	0	1	1	1	inner_marsh_low
0	1	1	1	1	1	1	1	0	0	inner_cliff
0	0	0	0	0	1	1	1	1	1	bayhead_delta
1	1	1	1	1	1	1	1	1	1	river_discharge
1	1	1	1	1	1	1	1	1	1	river_sand
1	1	1	1	1	1	1	1	1	1	river_mud

Table 19. Evolution of Generic Ria Towards Steady State

1	2	3	4	5	6	7	8	9	**Step**
1	1	1	1	1	1	1	1	1	ocean_waves
1	1	1	1	1	1	1	1	1	longshore_power
1	1	1	1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	1	1	1	mesotidal
0	0	0	1	1	1	1	1	1	updrift_beach
0	0	0	0	0	0	1	1	1	spit
1	1	1	1	1	1	1	1	1	inlet
1	1	1	1	1	1	1	1	1	fluvial_channel
0	0	0	0	0	0	0	0	1	dunes
1	1	1	1	1	1	1	1	1	wind
1	1	1	1	1	1	1	1	1	prism
1	1	1	1	1	1	1	1	1	accomm_space
1	1	1	1	1	1	1	1	1	bedrock
0	1	1	1	1	0	0	0	0	outer_rock_platform
0	1	1	1	1	1	1	1	1	outer_flood_dominance
0	1	1	1	1	1	1	1	1	outer_estuarywaves
0	0	0	0	1	1	1	1	1	outer_sandflat
0	0	1	1	1	1	1	1	1	outer_cliff
0	1	1	1	0	0	0	0	0	inner_rockplatform
0	0	1	1	1	1	1	1	1	inner_ebb_dominance
0	0	0	1	1	1	1	1	1	inner_subtidal_deposits
0	0	1	1	0	0	0	0	0	inner_estuarywaves
0	0	0	1	1	1	1	1	1	inner_mudflat
0	0	0	0	0	0	0	1	1	inner_marsh_low
0	1	1	1	1	1	1	1	0	inner_cliff
1	1	1	1	1	1	1	1	1	river_discharge
1	1	1	1	1	1	1	1	1	river_mud

Table 20. Evolution of Generic Spit-Enclosed Drowned River Valley Towards Steady State

1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**Step**
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	ocean_waves
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	longshore_power
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	marine_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	marine_mud
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	mesotidal
0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	updrift_beach
0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	spit
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inlet
0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	downdrift_beach
0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	dunes
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	wind
1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	prism
1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	accomm_space
0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	ebb_delta
0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	flood_delta
0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	outer_flood_dominance
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	outer_ebb_dominance
0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	outer_subtidal_sands
0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	outer_estuary_swell
0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	outer_estuarywaves
0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	outer_sandflat
0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	outer_mudflat
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	outer_marsh_low
0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	outer_marsh_high
0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	outer_floodplain
0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_ebb_dominance
0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_subtidal_deposits
0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	inner_estuarywaves
0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	inner_sandflat
0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_mudflat
0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	inner_marsh_low
0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	inner_marsh_high
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	river_discharge
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	river_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	river_mud

Table 21. Evolution of Generic Funnel-Shaped Estuary To Steady State

1	2	3	4	5	6	7	8	9	10	11	12	13	Step
1	1	1	1	1	1	1	1	1	1	1	1	1	ocean_waves
1	1	1	1	1	1	1	1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	marine_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	marine_mud
1	1	1	1	1	1	1	1	1	1	1	1	1	macrotidal
0	0	0	1	1	1	1	1	1	1	1	1	1	updrift_beach
1	1	1	1	1	1	1	1	1	1	1	1	1	inlet
0	0	0	0	0	0	0	0	1	1	1	1	1	dunes
1	1	1	1	1	1	1	1	1	1	1	1	1	wind
1	1	1	1	1	1	1	1	1	1	1	1	1	prism
1	1	1	1	1	1	1	0	0	0	0	0	0	accomm_space
0	0	0	1	1	1	1	1	1	1	1	1	1	linear_banks
0	1	1	1	1	1	1	1	1	1	1	1	1	outer_flood_dominance
0	0	0	0	0	0	1	1	1	1	1	1	1	outer_subtidal_sands
0	1	1	1	1	1	1	1	1	1	1	1	1	outer_estuary_swell
0	1	1	1	1	1	1	1	1	1	1	1	1	outer_estuarywaves
0	0	0	1	1	1	1	1	1	1	1	1	1	outer_sandflat
0	1	1	1	1	1	1	1	0	0	0	0	0	inner_flood_dominance
0	0	0	0	0	0	0	0	0	0	1	1	1	inner_ebb_dominance
0	0	0	1	1	1	1	1	1	1	1	1	1	inner_subtidal_deposits
0	0	1	1	0	0	0	0	0	0	0	0	0	inner_estuarywaves
0	0	0	0	0	0	1	1	1	1	1	1	1	inner_sandflat
0	0	0	1	1	1	1	1	1	1	1	1	1	inner_mudflat
0	0	0	0	0	0	0	0	0	0	0	0	1	inner_marsh_low
0	0	0	0	0	0	0	0	0	1	1	1	1	inner_marsh_high
1	1	1	1	1	1	1	1	1	1	1	1	1	river_discharge
1	1	1	1	1	1	1	1	1	1	1	1	1	river_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	river_mud

Table 22. Evolution of Generic Embayment Towards Steady State

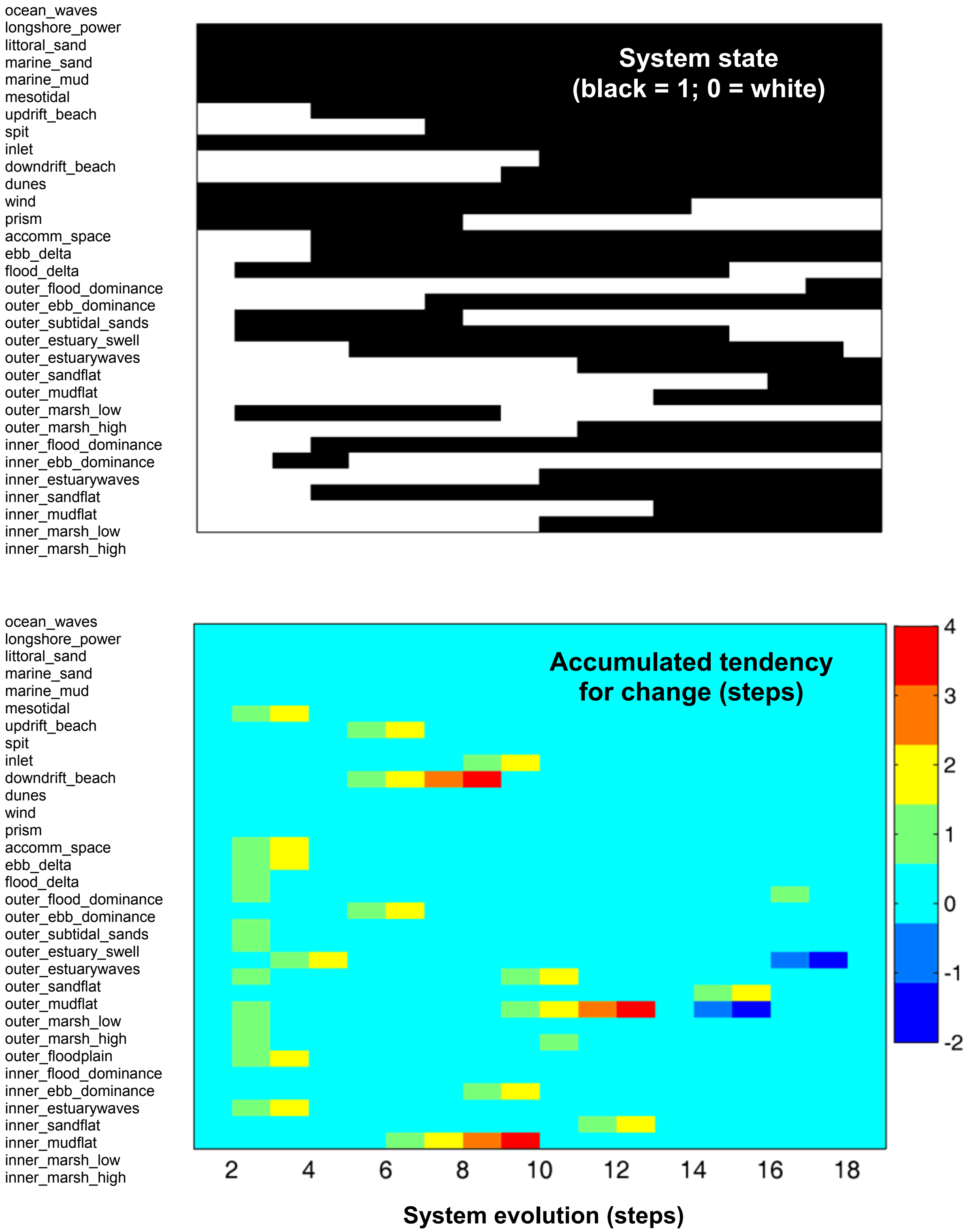
1	2	3	4	5	6	7	8	9	10	11	12	13	Step
1	1	1	1	1	1	1	1	1	1	1	1	1	ocean_waves
1	1	1	1	1	1	1	1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	marine_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	marine_mud
1	1	1	1	1	1	1	1	1	1	1	1	1	macrotidal
0	0	0	1	1	1	1	1	1	1	1	1	1	updrift_beach
1	1	1	1	1	1	1	1	1	1	1	1	1	inlet
0	0	0	0	0	0	0	0	1	1	1	1	1	dunes
1	1	1	1	1	1	1	1	1	1	1	1	1	wind
1	1	1	1	1	1	1	1	1	1	1	1	1	prism
1	1	1	1	1	1	1	0	0	0	0	0	0	accomm_space
0	0	0	1	1	1	1	1	1	1	1	1	1	linear_banks
0	1	1	1	1	1	1	1	1	1	1	1	1	outer_flood_dominance
0	0	0	0	0	0	1	1	1	1	1	1	1	outer_subtidal_sands
0	1	1	1	1	1	1	1	1	1	1	1	1	outer_estuary_swell
0	1	1	1	1	1	1	1	1	1	1	1	1	outer_estuarywaves
0	0	0	1	1	1	1	1	1	1	1	1	1	outer_sandflat
0	1	1	1	1	1	1	1	0	0	0	0	0	inner_flood_dominance
0	0	0	0	0	0	0	0	0	0	1	1	1	inner_ebb_dominance
0	0	0	1	1	1	1	1	1	1	1	1	1	inner_subtidal_deposits
0	0	1	1	0	0	0	0	0	0	0	0	0	inner_estuarywaves
0	0	0	0	0	0	0	0	0	1	1	1	1	inner_sandflat
0	0	0	1	1	1	1	1	1	1	1	1	1	inner_mudflat
0	0	0	0	0	0	0	0	0	0	0	0	1	inner_marsh_low
0	0	0	0	0	0	0	0	0	1	1	1	1	inner_marsh_high

Table 23. Evolution of Generic Tidal Inlet Towards Steady State

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Step
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	ocean_waves
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	longshore_power
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	marine_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	marine_mud
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	mesotidal
0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	updrift_beach
0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	spit
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inlet
0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	downdrift_beach
0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	dunes
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	wind
1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	prism
1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	accomm_space
0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	ebb_delta
0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	flood_delta
0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	outer_flood_dominance
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	outer_ebb_dominance
0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	outer_subtidal_sands
0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	outer_estuary_swell
0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	outer_estuarywaves
0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	outer_sandflat
0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	outer_mudflat
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	outer_marsh_low
0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	outer_marsh_high
0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	inner_flood_dominance
0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	inner_ebb_dominance
0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	inner_estuarywaves
0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_sandflat
0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_mudflat
0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	inner_marsh_low
0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	inner_marsh_high
0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	inner_floodplain

The most obvious result of the added decay terms is that all of these generic estuary types now evolve towards a steady state endpoint. In the case of the fjord and fjard, the evolutionary end points are identical with or without decay terms, although the inclusion of the latter means that system evolution now extends over more steps.

Some differences are apparent in the evolution of alluvial estuary types. In all cases, spurious oscillations are removed through the inclusion of decay terms and a more orderly sequence of landform development is generated. The effect of the decay terms can be seen more clearly by considering the evolution of the system ‘memory’ in parallel with the actual changes in state. Figure 27 shows this graphically for the case of a tidal inlet. The upper diagram shows the binary changes in system state. The lower diagram shows the accumulated tendencies for change, with positive and negative values corresponding to tendencies towards landform formation or destruction respectively. In one sense, this can be interpreted as the memory of the morphological components in response to changes resulting from the combined influences of other components and processes.



Upper diagram shows state matrix.
Lower diagram shows accumulated tendency for variables to change
(number of successive steps at which a variable is subject to positive or negative influence).

Figure 27. Graphical summary of system evolution for generic tidal inlet towards a steady state

4.3.5 External Forcing: Engineering Interventions and Accelerated Sea-Level Rise

The simulations presented so far relate to generic estuary types free to evolve towards a hypothetical natural equilibrium. However, provision is made in the Boolean functions for an estuary to be constrained in its morphological evolution by various human interventions. These include interferences with sediment supply (chiefly within the littoral drift system) and the imposition of fixed defences (with implications for the extent of saltmarsh and tidal prism). When present, interventions can result in a metastable equilibrium (e.g. Thorn & Welford, 1994) in which the system is stable for the duration of the constraint imposed by the intervention. If this constraint is removed the system evolves towards a different equilibrium condition.

Evolution of estuary morphology will also be influenced by changes in sea level. Indeed all modern estuaries have formed as a result of marine inundation, with varying degrees of sedimentary infilling since the last glaciation (Dalrymple *et al.*, 1992; Chappell & Woodroffe, 1995). In the formulation of the Simulator it is assumed that, prior to the significant human interventions of the last 200 years to so, the morphological evolution of UK estuaries incorporates a reduced influence of sea level rise relative to that during the height of the mid-Holocene transgression. Accelerated sea level rise associated with climate change will constitute a significant change in external forcing, however, and some of the indicative effects of this are incorporated in the model. These chiefly involve the tendency for intertidal landforms to diminish in extent where transgressive migration of estuary shorelines is checked by steep terrain or fixed defences ('coastal squeeze'). Sea level rise also threatens the viability of defensive structures, such that these will fail unless they are actively maintained. The impact of accelerated sea level rise on estuaries presently constrained in a metastable state is thus contingent upon management strategy.

Examples of possible intervention and sea level scenarios are considered here, with reference to the behaviour of a tidal inlet. Table 24 shows the effect of imposing flood defences and then coastal protection and groynes, to a tidal inlet that has previously evolved to a natural equilibrium configuration. The result is a straightforward cessation of coastal cliff erosion and loss of the inner and outer saltmarsh, which is replaced by a protected floodplain. The loss of saltmarsh is delayed owing to the decay term associated with this landform. In the case of sea defence construction, the decay is unrealistic since the loss should be effectively instantaneous after imposition of a structure. There is no simple way to correct this in the Simulator, since no mathematical distinction is made between process-forcing and management interventions.

Table 25 shows the effect of subsequently imposing accelerated sea level rise on the engineered inlet. In this scenario it is assumed that a 'hold the line' strategy is implemented, such that all structures are maintained and upgraded to cope with rising sea level. The effect is the loss of various morphological components due to a sediment deficit in the littoral drift system and 'coastal squeeze' where transgressive migration of the intertidal is impeded by defences. If a switch is then made to a 'do nothing' strategy, the defences eventually reach the end of the life (defined by their decay term) at which time the estuary is free to evolve towards an unconstrained state (Table 25). In this particular case, this corresponds to a cyclical equilibrium involving the lower marsh units in both outer and inner estuary.

This set of scenarios shows that generalised management scenarios can be accommodated within the Boolean framework, and that broadly realistic estuary behaviour can be simulated using quite a simple generic rule base.

Table 24. Effect of Imposing Coastal Protection, Groynes, Beach Seawall, and Estuary Flood Defences on a Natural Tidal Inlet

1	2	3	4	5	6	7	Step
1	1	1	1	1	1	1	ocean_waves
1	1	1	1	1	1	1	longshore_power
1	1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	1	marine_sand
1	1	1	1	1	1	1	marine_mud
1	1	1	1	1	1	1	mesotidal
1	1	1	1	1	1	1	coastal_cliff
1	1	1	1	1	1	1	cliff_sand
1	1	1	1	1	1	1	cliff_mud
1	0	0	0	0	0	0	coastal_cliff_erosion
1	1	1	1	1	1	1	updrift_beach
1	1	1	1	1	1	1	spit
1	1	1	1	1	1	1	inlet
1	1	1	1	1	1	1	downdrift_beach
1	1	1	1	1	1	1	dunes
1	1	1	1	1	1	1	wind
1	1	1	1	1	1	1	groynes
1	1	1	1	1	1	1	coastal_protection
1	1	1	1	1	1	1	seawall
1	1	1	1	1	1	1	ebb_delta
1	1	1	1	1	1	1	flood_delta
1	1	1	1	1	1	1	outer_ebb_dominance
1	1	1	1	1	1	1	outer_subtidal_sands
1	1	1	1	1	1	1	outer_mudflat
1	1	1	1	1	1	1	outer_marsh_low
1	1	1	1	1	0	0	outer_marsh_high
1	1	1	1	1	1	1	outer_flood_defence
0	0	0	0	0	0	1	outer_floodplain
1	1	1	1	1	1	1	inner_ebb_dominance
1	1	1	1	1	1	1	inner_subtidal_deposits
1	1	1	1	1	1	1	inner_sandflat
1	1	1	1	1	1	1	inner_mudflat
1	1	1	1	1	1	1	inner_marsh_low
1	1	1	1	1	0	0	inner_marsh_high
1	1	1	1	1	1	1	inner_flood_defence
0	0	0	0	0	0	1	inner_floodplain

Table 25. Effect of Accelerated SLR On Heavily Engineered Natural Tidal Inlet of Table 24, Assuming That a 'Hold the Line' Strategy is Pursued

1	2	3	4	5	6	7	8	9	10	11	12	Step
1	1	1	1	1	1	1	1	1	1	1	1	ocean_waves
1	1	1	1	1	1	1	1	1	1	1	1	longshore_power
1	1	1	1	1	1	1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	1	1	1	1	1	1	marine_sand
1	1	1	1	1	1	1	1	1	1	1	1	marine_mud
1	1	1	1	1	1	1	1	1	1	1	1	mesotidal
1	1	1	1	1	1	1	1	1	1	1	1	slr
1	1	1	1	1	1	1	1	1	1	1	1	coastal_cliff
1	1	1	1	1	1	1	1	1	1	1	1	cliff_sand
1	1	1	1	1	1	1	1	1	1	1	1	cliff_mud
1	1	1	0	0	0	0	0	0	0	0	0	updrift_beach
1	1	1	0	0	0	0	0	0	0	0	0	spit
1	1	1	1	1	1	1	1	1	1	1	1	inlet
1	1	1	1	1	1	0	0	0	0	0	0	downdrift_beach
1	1	1	1	1	1	1	1	1	1	1	0	dunes
1	1	1	1	1	1	1	1	1	1	1	1	wind
1	1	1	1	1	1	1	1	1	1	1	1	groynes
1	1	1	1	1	1	1	1	1	1	1	1	coastal_protection
1	1	1	1	1	1	1	1	1	1	1	1	seawall
1	1	1	1	1	1	1	1	1	1	1	1	hold_the_line
1	1	1	1	1	1	1	1	1	1	1	1	prism
1	1	1	1	1	1	1	1	1	1	1	1	ebb_delta
1	1	1	1	1	1	1	1	1	1	1	1	flood_delta
1	1	1	1	1	1	1	1	1	1	1	1	outer_flood_dominance
1	1	1	1	1	1	1	1	1	1	1	1	outer_subtidal_sands
0	0	0	0	1	1	1	1	1	1	1	1	outer_estuary_swell
1	1	1	1	1	1	1	1	1	1	1	1	outer_estuarywaves
1	1	1	1	1	1	1	1	1	1	1	1	outer_sandflat
1	1	1	1	1	1	1	0	0	0	0	0	outer_mudflat
1	1	1	0	0	0	0	0	0	0	0	0	outer_marsh_low
1	1	1	1	1	1	1	1	1	1	1	1	outer_flood_defence
1	1	1	1	1	1	1	1	1	1	1	1	inner_ebb_dominance
1	1	1	1	1	1	1	1	1	1	1	1	inner_subtidal_deposits
1	1	1	1	1	1	1	1	1	1	1	1	inner_sandflat
1	1	1	1	1	1	1	1	1	1	1	1	inner_mudflat
1	1	1	0	0	0	0	0	0	0	0	0	inner_marsh_low
1	1	1	1	1	1	1	1	1	1	1	1	inner_flood_defence

Table 26. Effect of Abandoning the 'Hold the Line' Strategy in Favour of a 'Do Nothing' Strategy

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	Step
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	ocean_waves
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	Longshore_power
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	marine_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	marine_mud
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	Mesotidal
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	Slr
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	coastal_cliff
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	cliff_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	cliff_mud
0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	coastal_cliff_erosion
0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	updrift_beach
0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	Spit
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	Inlet
0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	downdrift_beach
0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	Dunes
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	Wind
1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Groynes
1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	coastal_protection
1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Seawall
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	do_nothing
0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	Prism
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	ebb_delta
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	flood_delta
0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	outer_flood_dominance
1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	outer_ebb_dominance
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_subtidal_sands
1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	outer_estuary_swell
0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	outer_estuarywaves
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	outer_sandflat
1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_mudflat
0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	1	1	1	outer_marsh_low
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	outer_marsh_high
1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	outer_flood_defence
1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	outer_floodplain
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_ebb_dominance
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_subtidal_deposits
0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	inner_sandflat
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_mudflat
0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	1	1	1	0	0	0	1	1	1	0	inner_marsh_low
0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_marsh_high
1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	inner_flood_defence
1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	inner_floodplain

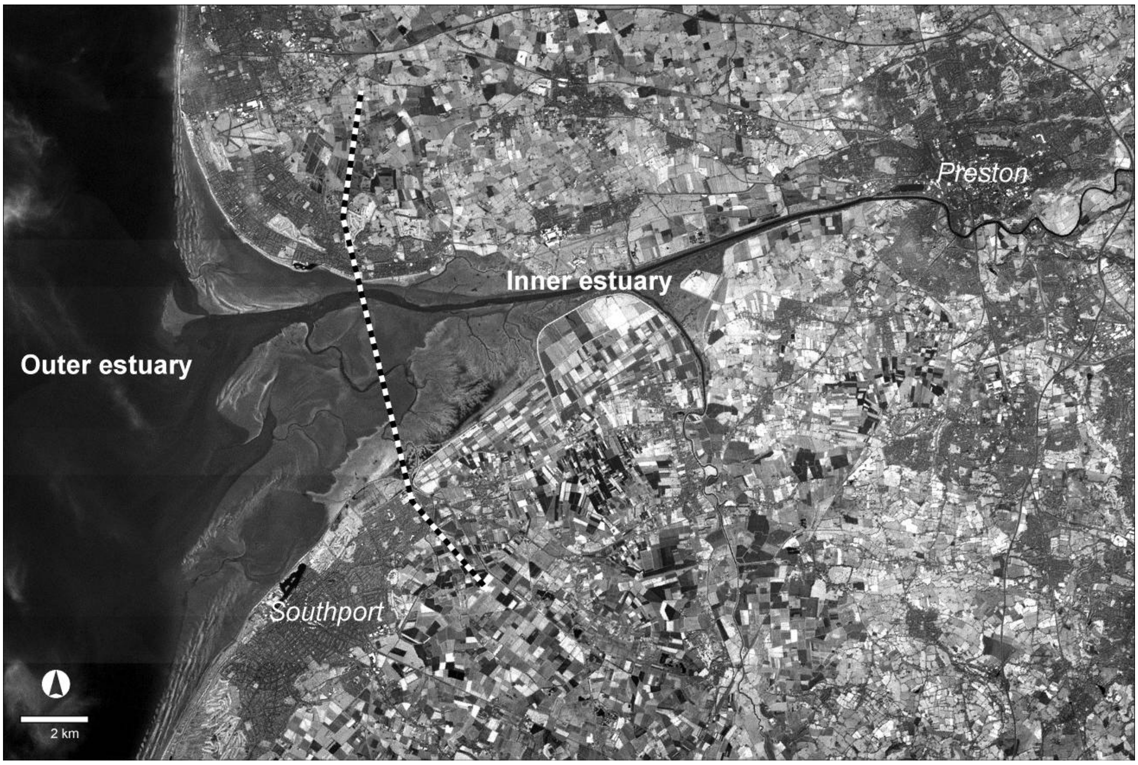
4.3.6 EstSim Boolean Model Applied to Historic Change: Ribble Estuary and Southampton Water

As part of the development phase, the prototype simulator has been tested, without modification, on two case study estuaries. The Ribble (a funnel-shaped estuary) and Southampton Water (as an example of a spit-enclosed system) were selected as good examples of their respective types, and also due to their inclusion with earlier ERP Phase 1 studies (EMPHASYS, 2000).

The Ribble

The Ribble estuary, northwest England, is a classic example of a funnel-shaped (drowned river valley) estuary (EstSim estuary type 5), although a significant portion of the system has been reclaimed over the last 200 years (Figure 28). With regard to the 'inner - outer' spatialisation, the contemporary Ribble estuary comprises:

- Outer estuary: extensive sandflat (upper and lower), beach, dune, trained channel;
- Inner estuary: extensive saltmarsh (upper and lower), narrow sand and mud flats, trained channel.



(Landsat ETM, 2002)

Figure 28. Delineation of outer and inner systems of the Ribble estuary

A series of detailed bathymetric charts span the last 150 years or so, and these have been used by van der Wal *et al.* (2002) to produce a synthesis of morphological change over this period. The estuary is subject to a macro-tidal regime (mean spring tidal range of up to 8 m) and tidal flows are large compared to freshwater inflow from the River Ribble (and its main tributary the River Douglas). Wave energy along the coast and in the outer estuary is moderate. Although fluvial and estuarine sediment sources are fairly minimal, the potential offshore supply is extremely large: the system is thought to be infilling in the main from this marine source, with additional alongshore contributions from the open coasts to the north and south.

Table 27 encapsulates the major changes in the morphology of the estuary since the 1840s into a series of time periods (corresponding to the main bathymetric surveys) and approximate system states, defined using the enhanced set of Boolean variables proposed in Section 4.2. The Ribble has experienced a number of human-induced perturbations to system dynamics over this historical period, including reclamation, construction of training walls and intermittent dredging, and is hence a useful case study for this modelling application. Subjective judgements are required in order to abstract the subtleties of the documented changes into a form that is commensurate with the resolution of the Prototype Simulator.

Table 27. Summary of Historic Changes in the Ribble Estuary, Northwest England

	pre-1840s Description	1904 Description	1951 Description	1994 Description	Remarks
External forcing					
Ocean waves	High	High	High	High	
Longshore wave power	Low	Low	Low	Low	
Marine sand supply	High	High	High	High	
Marine mud supply	High	High	High	High	
Tidal regime	Macrotidal	Macrotidal	Macrotidal	Macrotidal	
Wind regime for dunes	Favourable	Favourable	Favourable	Favourable	
Sea-level rise	Low	Low	Low	Accelerated	
River inflow	Yes + mud	Yes + mud	Yes + mud	Yes + mud	
Dredging	No	Yes	Yes	No	
System state variables					
Total tidal prism	High	Greatly reduced	Low	Low	19th century reclamation
Accommodation space	High	Reduced but dredged		Infilling, post-dredging	Dredged 1905-1980
Outer estuary waves	High	High	High	High	
Inner estuary waves	High	Low	Low	Low	
Outer estuary morphology					
Beach	Present	Present	Present	Present	
Dunes	Present	Present	Present	Present	
Spit	None	None	None	None	
Subtidal	Wide, deep	Narrow, shallow	Narrow, deep	Narrow, shallow	Dredged 1905-1980
Tidal delta	Linear banks	None	None	None	
Sand flat	small, low	extensive low	extensive high	extensive high	Extensive sandflat accretion
Mud flat	absent	absent	absent	absent	
Salt marsh	absent	absent	absent	small	Spartina planted 1930s, spreads 1960s-70s
Flood defences	None	Yes	Yes	Yes	19th century reclamation
Floodplain	None	Yes	Yes	Yes	
Inner estuary morphology					
Subtidal	Wide, shallow	Narrow, shallow	Narrow, deep	Narrow, shallow	Dredged 1905-1980
Sand flat	Extensive	Medium	Small	Absent	Sand flat replaced by mud flat, then marsh
Mud flat	Small	Small	Medium	Medium	Sud flat expands at expense of sand flat
Salt marsh	High marsh	None	Low marsh	Low marsh	Spartina planted 1930s, spreads 1960s-70s
Flood defences	None	Yes	Yes	Yes	19th century reclamation
Floodplain	None	Yes	Yes	Yes	

(Largely adapted from van der Wal *et al*. (2002)

In essence, Table 27 charts a transition from a rather wide system dominated by extensive low sandflats, to a narrower and deeper system, which exhibits a clear transition from an intertidal sand-dominated outer estuary to mixed sediment, saltmarsh dominated inner estuary. Reclamation throughout the 19th century significantly reduced the tidal prism and intertidal area within the inner estuary: subsequent sedimentation, particularly during periods of dredging in the mid-20th century, preferentially infilled the reduced intertidal zone leading to an expanse of saltmarsh at the expense of intertidal flat. The channel in this region has been trained throughout the period considered here, and is now flanked by narrow strips of sand and mudflat. In the outer estuary, training walls constructed in the late 19th and early 20th century have replaced the multiple and dynamic character with a single, relatively stable channel, resulting in accretion across the intertidal flats. The cessation of dredging in the latter half of the 20th century has caused some local erosion of sand banks as the channel has started to accommodate some of the estuarine sediment volume.

Evolutionary end points predicted by the Prototype Simulator represent long-term equilibrium configurations. An initial difficulty encountered during evaluation of the output against the documented change for the Ribble concerns the extent to which the real world system can be considered to have achieved equilibrium. Van der Wal *et al.* (2002) suggest that given the abundance of sediment and low rate of relative sea level rise, the gross morphology of the Ribble was probably close to a state of dynamic equilibrium at the beginning of the 19th century. After that date, a succession of human interventions (reclamation, dredging, planting of saltmarsh, cessation of dredging) occurred at intervals that were probably much shorter than the relaxation time towards new equilibrium states. It is likely, therefore, that we need to scrutinise not just the simulated end states but also their evolutionary trajectories. This needs to be done with care, bearing in mind the observation made in the previous section that some intermediate states are likely to be artefacts of the synchronous updating of the Boolean network.

As a first step, pre-1840 process forcing was approximated by high onshore wave energy, abundant sediment and no human intervention and the model allowed to run to equilibrium (see Table 28). A steady state emerges after 13 steps and this corresponds closely to the natural state described by van der Wal *et al*. (2002) and summarised in Table 27. Overall, the picture during this epoch is one of sedimentary infilling, with sandy intertidal deposits dominating the outer estuary (where wave action remains significant) and mudflat and saltmarsh being more widespread in the inner estuary. The fluvial mud input is trapped within the inner estuary and was known to be a cause of siltation within Preston Docks (van der Wal *et al*., 2002). The general behaviour of this system in its pre-1840 state is thus captured very well.

Table 28. Simulated Evolution of Ribble Estuary for Pre-1840 Epoch

1	2	3	4	5	6	7	8	9	10	11	12	13	Step
1	1	1	1	1	1	1	1	1	1	1	1	1	ocean_waves
1	1	1	1	1	1	1	1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	marine_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	marine_mud
1	1	1	1	1	1	1	1	1	1	1	1	1	macrotidal
1	1	1	1	1	1	1	1	1	1	1	1	1	updrift_beach
1	1	1	1	1	1	1	1	1	1	1	1	1	inlet
0	0	0	0	0	1	1	1	1	1	1	1	1	dunes
1	1	1	1	1	1	1	1	1	1	1	1	1	wind
1	1	1	1	1	1	1	1	1	1	1	1	1	prism
1	1	1	1	1	1	1	0	0	0	0	0	0	accomm_space
0	0	0	1	1	1	1	1	1	1	1	1	1	linear_banks
0	1	1	1	1	1	1	1	1	1	1	1	1	outer_flood_dominance
0	0	0	0	0	0	1	1	1	1	1	1	1	outer_subtidal_sands
0	1	1	1	1	1	1	1	1	1	1	1	1	outer_estuary_swell
0	1	1	1	1	1	1	1	1	1	1	1	1	outer_estuarywaves
0	0	0	1	1	1	1	1	1	1	1	1	1	outer_sandflat
0	1	1	1	1	1	1	1	0	0	0	0	0	inner_flood_dominance
0	0	0	0	0	0	0	0	0	0	1	1	1	inner_ebb_dominance
0	0	0	1	1	1	1	1	1	1	1	1	1	inner_subtidal_deposits
0	0	1	1	0	0	0	0	0	0	0	0	0	inner_estuarywaves
0	0	0	0	0	0	0	0	0	1	1	1	1	inner_sandflat
0	0	0	1	1	1	1	1	1	1	1	1	1	inner_mudflat
0	0	0	0	0	0	0	0	0	0	0	0	1	inner_marsh_low
0	0	0	0	0	0	0	0	0	1	1	1	1	inner_marsh_high
1	1	1	1	1	1	1	1	1	1	1	1	1	river_discharge
1	1	1	1	1	1	1	1	1	1	1	1	1	river_mud

The major human interventions during the 19th century were reclamation of a large part of the inner estuary intertidal and a smaller part of the outer estuary along the southern shore (with a reduction in the area of the tidal floodplain and saltmarsh). The result of this change imposed on the endpoint of the pre-1840 run is shown in Table 29. The main effect is a large reduction in prism, with loss of high saltmarsh. In the outer estuary, there is now a tendency for low marsh to form, although this is unstable and results in a cyclical equilibrium after 6 to 12 steps. A shift towards ebb dominance in the outer estuary is not very realistic (the Ribble seems to have remained flood dominated), and results from what is probably a significant over-estimation of the reduction in tidal prism through reclamation.

Table 29. Simulated Evolution of Ribble Estuary for 1840-1904 Epoch

1	2	3	4	5	6	7	8	9	10	11	12	Step
1	1	1	1	1	1	1	1	1	1	1	1	ocean_waves
1	1	1	1	1	1	1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	1	1	1	1	1	1	marine_sand
1	1	1	1	1	1	1	1	1	1	1	1	marine_mud
1	1	1	1	1	1	1	1	1	1	1	1	macrotidal
1	1	1	1	1	1	1	1	1	1	1	1	updrift_beach
1	1	1	1	1	1	1	1	1	1	1	1	inlet
1	1	1	1	1	1	1	1	1	1	1	1	dunes
1	1	1	1	1	1	1	1	1	1	1	1	wind
1	0	0	0	0	0	0	0	0	0	0	0	prism
1	1	1	1	1	1	1	1	1	1	1	1	linear_banks
1	1	0	0	0	0	0	0	0	0	0	0	outer_flood_dominance
0	0	0	0	1	1	1	1	1	1	1	1	outer_ebb_dominance
1	1	1	1	1	1	1	1	1	1	1	1	outer_subtidal_sands
1	1	1	1	1	1	1	1	1	1	1	1	outer_estuary_swell
1	1	0	0	0	0	0	0	0	0	0	0	outer_estuarywaves
1	1	1	1	1	1	1	1	1	1	1	1	outer_sandflat
0	0	0	0	0	1	1	1	1	1	1	1	outer_mudflat
0	0	0	0	0	1	1	1	0	0	0	1	outer_marsh_low
1	1	1	1	1	1	1	1	1	1	1	1	outer_flood_defence
0	1	1	1	1	1	1	1	1	1	1	1	outer_floodplain
1	1	1	1	1	1	1	1	1	1	1	1	inner_ebb_dominance
1	1	1	1	1	1	1	1	1	1	1	1	inner_subtidal_deposits
1	1	1	1	1	1	1	1	1	1	1	1	inner_sandflat
1	1	1	1	1	1	1	1	1	1	1	1	inner_mudflat
1	1	1	1	1	1	1	1	1	1	1	1	inner_marsh_low
1	1	1	1	1	0	0	0	0	0	0	0	inner_marsh_high
1	1	1	1	1	1	1	1	1	1	1	1	inner_flood_defence
0	1	1	1	1	1	1	1	1	1	1	1	inner_floodplain
1	1	1	1	1	1	1	1	1	1	1	1	river_discharge
1	1	1	1	1	1	1	1	1	1	1	1	river_mud

N.B. Evolution becomes cyclical between steps 6 and 12.

Following the next major intervention, dredging and training of the estuary after 1904 (Table 30), the accommodation space is enlarged and the outer estuary becomes flood-dominant once more. The behaviour in this epoch is not entirely consistent within the documented inner estuary changes, which involved a rather slower transition back to a muddy intertidal and re-establishment of saltmarsh accelerated by planting after the 1950s.

The final epoch sees the cessation of dredging but also the imposition of accelerated sea level rise (Table 31). In the absence of a ‘hold the line’ strategy, the flood defences eventually fail and the system reverts to a more natural state. This comprises elements of the generic funnel-shaped estuary (wave-dominated outer estuary with sandflats; tide-dominated inner estuary with saltmarsh), with cyclicity arising from the narrowing of the space available for saltmarsh.

Table 30. Simulated Evolution of Ribble Estuary for 1904-1980 Epoch

1	2	3	4	5	6	7	8	9	10	11	Step
1	1	1	1	**1**	1	1	1	1	1	**1**	ocean_waves
1	1	1	1	**1**	1	1	1	1	1	**1**	littoral_sand
1	1	1	1	**1**	1	1	1	1	1	**1**	marine_sand
1	1	1	1	**1**	1	1	1	1	1	**1**	marine_mud
1	1	1	1	**1**	1	1	1	1	1	**1**	macrotidal
1	1	1	1	**1**	1	1	1	1	1	**1**	updrift_beach
1	1	1	1	**1**	1	1	1	1	1	**1**	inlet
1	1	1	1	**1**	1	1	1	1	1	**1**	dunes
1	1	1	1	**1**	1	1	1	1	1	**1**	wind
0	1	1	1	**1**	1	1	1	1	1	**1**	accomm_space
1	1	1	1	**1**	1	1	1	1	1	**1**	linear_banks
0	0	1	1	**1**	1	1	1	1	1	**1**	outer_flood_dominance
1	1	1	1	**0**	0	0	0	0	0	**0**	outer_ebb_dominance
1	1	1	0	**0**	0	0	0	0	0	**0**	outer_subtidal_sands
1	1	1	1	**1**	1	1	1	1	1	**1**	outer_estuary_swell
1	1	1	1	**1**	1	1	1	1	1	**1**	outer_sandflat
1	1	1	1	**1**	1	1	1	1	1	**1**	outer_mudflat
0	0	0	1	**1**	1	0	0	0	1	**1**	outer_marsh_low
1	1	1	1	**1**	1	1	1	1	1	**1**	outer_flood_defence
1	1	1	1	**1**	1	1	1	1	1	**1**	outer_floodplain
1	1	1	1	**1**	1	1	1	1	1	**1**	outer_dredging
1	1	1	1	**1**	1	1	1	1	1	**1**	inner_ebb_dominance
1	1	1	0	**0**	0	0	0	0	0	**0**	inner_subtidal_deposits
1	1	1	1	**1**	1	1	1	1	1	**1**	inner_sandflat
1	1	1	1	**1**	1	1	1	1	1	**1**	inner_mudflat
1	1	1	1	**1**	1	1	1	1	1	**1**	inner_marsh_low
1	1	1	1	**1**	1	1	1	1	1	**1**	inner_flood_defence
1	1	1	1	**1**	1	1	1	1	1	**1**	inner_floodplain
1	1	1	1	**1**	1	1	1	1	1	**1**	inner_dredging
1	1	1	1	**1**	1	1	1	1	1	**1**	river_discharge
1	1	1	1	**1**	1	1	1	1	1	**1**	river_mud

N.B. Evolution becomes cyclical between steps 5 and 11.

Table 31. Simulated Evolution of Ribble Estuary for Post-1980s with Imposition of Accelerated SLR

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	Step
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	ocean_waves
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	marine_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	marine_mud
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	macrotidal
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	slr
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	updrift_beach
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inlet
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	dunes
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	wind
0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	prism
1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	accomm_space
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	linear_banks
1	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_flood_dominance
0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	outer_ebb_dominance
0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	outer_subtidal_sands
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_estuary_swell
0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_estuarywaves
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_sandflat
1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	outer_mudflat
1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	outer_marsh_low
1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	outer_flood_defence
1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	outer_floodplain
0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	inner_flood_dominance
1	1	1	1	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	inner_ebb_dominance
0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_subtidal_deposits
1	1	1	1	1	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	inner_sandflat
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_mudflat
1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	1	1	inner_marsh_low
0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	inner_marsh_high
1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	inner_flood_defence
1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	inner_floodplain
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	river_discharge
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	river_mud

N.B. Evolution becomes cyclical between steps 15 and 21.

Southampton Water

Southampton Water, on the south coast of England, is an example of a spit-enclosed estuary (EstSim estuary type 4). A deep and relatively straight estuary channel receives inflows from three rivers, the Itchen and Test towards the head, and the Hamble close to the mouth on the eastern margin (Figure 29).

The system is mesotidal (spring tidal range approximately 4 m at Southampton), with complex tidal propagation from the Solent being associated with double high waters at spring tides. Spring tidal prism is approximately 1 x 10^8 m^3 (Long *et al.*, 2000). In terms of velocity asymmetry, the estuary is ebb dominated throughout, although this diminishes towards the estuary head.

A number of important aspects of estuary geomorphology in Southampton Water can be highlighted:

- The role of Calshot Spit in narrowing the inlet and limiting wave action within the outer estuary.
- A positive sediment budget, with a tendency for the estuary to infill with fine sediment, largely of marine origin.
- Relatively minor contributions to overall estuary hydrodynamics and sediment budget from the fluvial inputs.
- The occurrence of mudflat and saltmarsh in both outer and inner estuary but with evidence of an erosional tendency and some topographic constraint upon the ability of intertidal environments to undergo a natural transgressive migration in response to sea level rise (especially in the outer estuary).
- Historic reclamation of much of the outer and inner estuary intertidal.
- The importance of dredging in maintaining a deep outer estuary channel.

This case study is less suited to a sequential historical analysis of the kind undertaken for the Ribble. However, it presents a useful opportunity to evaluate the generic Boolean functions against a system that is extremely well-documented in terms of its physical processes and which also exhibits some differences from the idealised spit-enclosed estuary considered previously.

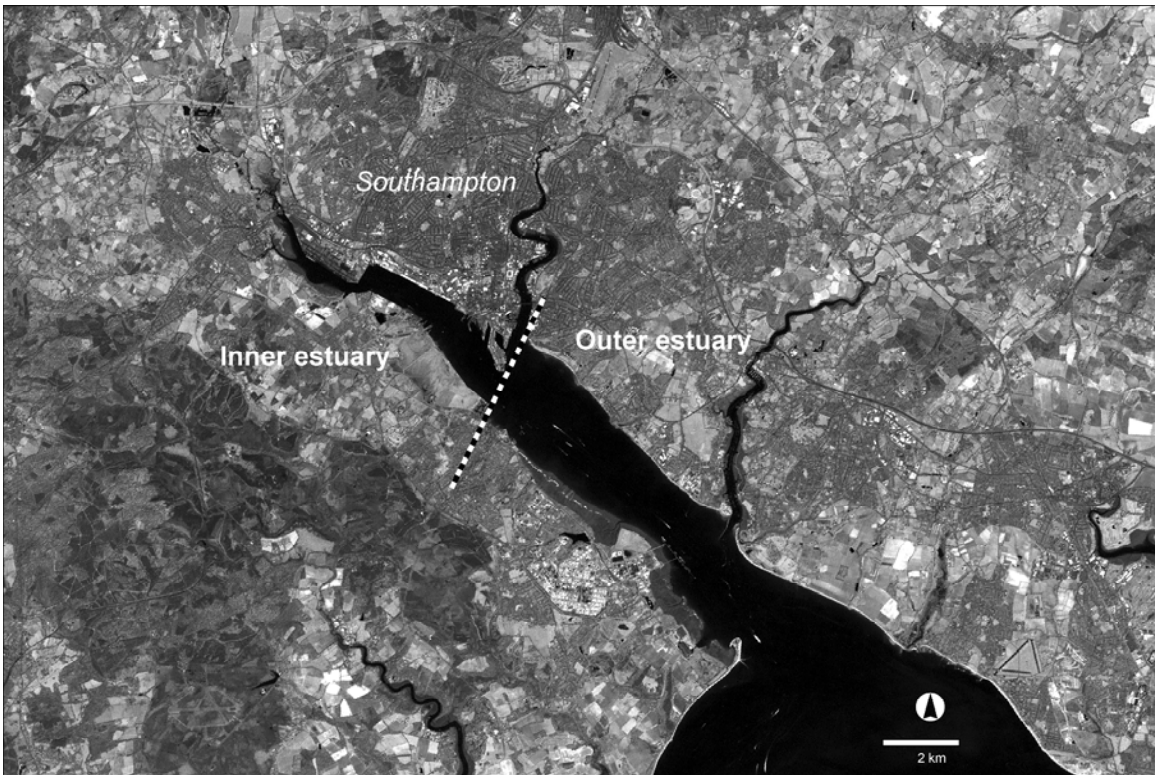
One problem is the presence of steep catchment topography that constrains the long-term adjustment of the outer estuary. This is approximated here by the imposition of bedrock (implying a resistant geology and elevated catchment topography) but without an inherited fluvially-incised channel. This allows the formation of cliffs, which will then lead to ‘coastal squeeze’ under an accelerated sea level rise scenario. In this sense, the system lies someway between the ria and spit-enclosed generic types.

Table 32 shows the evolution of such a system towards a steady state. The littoral drift system leads to the formation of a spit, but the absence of tidal deltas (owing to dredging of the outer estuary) limits sediment bypassing across the inlet such that no downdrift beach forms. The wave action is reduced by the spit and muddy depositional environments that form within the narrowed intertidal accommodation space of both the inner and outer estuary.

The whole system is ebb-dominated, by virtue of the dredging and infilling of the limited intertidal. Both prism and accommodation space are shown as greatly reduced. In the case of the latter, the removal of tidal floodplain by reclamation outweighs the effect of continued outer estuary dredging in the present model formulation.

If accelerated sea level rise is imposed (Table 33), then a characteristic 'coastal squeeze' emerges. In the assumed absence of a 'hold the line' strategy the reclaimed floodplain eventually gives way to tidal flat and a cyclical alternation between wave-dominated sandflat and a low saltmarsh. The estuary also oscillates between ebb and flood dominance under this scenario.

As with the Ribble case study, the analysis of Southampton Water shows that a substantially correct depiction of gross estuary properties can be obtained with an unaltered generic rule base. However, there are subtle estuary-specific aspects of inherited morphology, sediment transport, hydrodynamics, and intervention history that would require customisation of the model functions to be represented more fully. Some features, such as the distinctive tidal hydrodynamics of the Solent - Southampton Water system, are almost certainly beyond the capability of a generalised model to resolve.



(Landsat ETM, 2002)

Broken line indicates suggested division into inner and outer estuary sub-systems.

Figure 29. Aerial view of Southampton Water

Table 32. Simulated Evolution of Southampton Water with No Accelerated SLR

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Step
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	ocean_waves
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	longshore_power
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	marine_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	marine_mud
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	mesotidal
0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	updrift_beach
0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	spit
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inlet
0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	dunes
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	wind
1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	prism
1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	accomm_space
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	bedrock
0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	outer_rock_platform
0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	outer_flood_dominance
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	outer_ebb_dominance
0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	outer_estuary_swell
0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	outer_estuarywaves
0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	outer_sandflat
0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	outer_mudflat
0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	outer_marsh_low
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_flood_defence
1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_floodplain
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	outer_cliff
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_dredging
0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	inner_rockplatform
0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	inner_flood_dominance
0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	inner_ebb_dominance
0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_subtidal_deposits
0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	inner_estuarywaves
0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_mudflat
0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	inner_marsh_low
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_flood_defence
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_floodplain.

N.B. System reaches steady state after 19 steps.

Table 33. Continued Evolution of Southampton Water With Imposition of Accelerated SLR

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	Step
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	ocean_waves
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	longshore_power
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	marine_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	marine_mud
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	mesotidal
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	slr
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	updrift_beach
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	spit
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inlet
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	dunes
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	wind
0	0	0	0	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	prism
0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	1	1	1	1	accomm_space
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	bedrock
0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	1	1	1	1	outer_flood_dominance
1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	1	1	0	0	outer_ebb_dominance
0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	1	1	1	1	outer_estuarywaves
0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	1	outer_sandflat
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_mudflat
1	1	1	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	outer_marsh_low
1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	outer_flood_defence
1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	outer_floodplain
0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	1	1	1	outer_cliff
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_dredging
0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	1	1	1	inner_flood_dominance
1	1	1	1	1	1	1	1	0	0	0	0	0	0	1	1	1	1	0	inner_ebb_dominance
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_subtidal_deposits
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_mudflat
1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	inner_marsh_low
1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	inner_flood_defence
1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	inner_floodplain
0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	inner_cliff

N.B. System becomes cyclical after steps 10 to 19.

5. Pilot Testing of the Prototype Simulator

5.1 Introduction

This section provides details of a series of pilot tests undertaken to evaluate the capabilities of the Prototype Simulator on two UK estuaries. Research has been completed to identify an up to date and relevant list of management questions applicable to UK estuaries, mapped against relevant legislation. These questions were used to derive a series of scenarios for the pilot testing aimed at drawing out the key capabilities and limitations of the approach through application of the Prototype Simulator to the Thames and Teign estuaries.

First the research relating to the identification of management questions is presented. This is followed by the presentation of the results from the two specific pilot tests. A discussion of the capabilities and limitations is provided in Section 6.

5.1.1 Project Context

Within the research, the development of management questions was aimed at ensuring the research was targeted and tested against present and relevant management drivers.

In addition to the specific estuaries chosen for simulator development, two further estuaries were used to provide independent pilot tests to evaluate the capabilities and limitations of the Prototype Simulator. In order to allow extensive and rapid testing two estuaries were chosen, which already have good data sets and have been extensively studied (i.e. the Tames and Teign). The pilot tests were essential in providing a robust evaluation of the Prototype Simulator.

The Management Questions work was completed within Objective 2 and the Pilot Testing within Objective 7. The outputs of these Objectives are reported within EstSim Project Reports 5 (ABPmer, 2007b) and 7 (Rossington *et al.*, 2007) respectively.

5.2 Identification of Management Questions

5.2.1 Management Questions Review

A review of management questions has been completed, based on:

- Previously completed work within ERP1 (EMPHASYS, 2000a; 2000b).
- Updating of a review of legislation relevant to estuary management (ABPmer, 2007b); and
- The results of the end-user consultation (a summary of which is presented in Appendix B) (ABPmer, 2007b).

Interests of estuary users may be at a strategic level such as the development of Coastal Habitat Management Plans or Shoreline Management Plan (SMP) may be local such as the location and impacts of a land-drainage outfall, and there are a variety of estuary management questions, relevant to the whole estuary or separate components of the estuary depending on the user and their interests.

Legislation can place considerable constraint on activities within estuaries, and provide a constantly changing impact on their management. Some legislation affects all sectors, such as the Strategic Environmental Assessment (SEA) Directive and Habitats Directive, whereas some legislation is applicable to limited activities or sectors within the estuary. However, there is a move towards more holistic estuary management both within existing and new legislation. For further details of the review of legislation relevant to estuary management undertaken as part of this study, see ABPmer (2007b).

The consultation exercise, in which a number of people concerned with estuary management were consulted, concluded that estuaries should be managed in a holistic way and as a system where possible, although this is not always the case. The adjacent coast and river(s) should also be considered as part of this system. The consultees also recognised the requirement for whole estuary management as required by current legislation. However, there are various reasons why estuaries are not managed in this way, including limitations in the understanding of the estuary system as well as a lack of suitable tools and models.

An initial interpretation of the consultation in terms of the management questions is presented here, as questions relevant to estuary managers.

General legislative questions:

- How will each of the proposed and adopted legislative measures impact on existing uses and activities within an estuary? (Here proposed and adopted legislative measures include, for example, the EU Water Framework Directive (WFD) and the Floods Directive).
- What impact will there be on estuary morphology as a result of above?

Specific questions relating to climate change:

- How will climate change affect forcing factors, including tidal range, storm intensity and frequency, wave heights and direction, within an estuary?
- How will climate change affect existing uses and activities within an estuary?
- How will climate change affect the individual estuary components?
    - e.g. for ports, how will access to docks be affected?
    - What impact will there be on habitats?
    - What changes will there be to sedimentation patterns and supply?

Specific management questions, related to an activity and legislation:

- How will an activity affect the ecological status of an estuary (under the WFD)?
- How will an activity affect sedimentation patterns / habitats (under the Habitats Regulations, WFD, Floods Directive)?
- How will an activity affect flood risk (under the Floods Directive)?
- What will the cumulative impacts be of activities within the estuary (under the SEA Directive, WFD)?

5.2.2 Management Questions and Pilot Testing Scenarios

These initial results of the management issues, legislation summary and the consultation exercise have been further developed into the scenarios used within the pilot testing of the Prototype Simulator. The main issues can be thought of under the Drivers - Pressures - State - Impact - Response framework, where the scenario to be tested will affect the Response of the estuary. The scenarios that have been produced in this Task are presented in Table 34. These scenarios are considered to both ensure that the testing of the Prototype Simulator is against a series of relevant issues and suitable to determine the capabilities of the approach. This study has found that the main drivers for estuary management currently are climate change, flood and coastal erosion risk management and development pressures. Each of these drivers has a pressure or limiting factor in the form of the relevant legislation or planning process, including the Habitats Regulations, Shoreline Management Plans (SMPs), the WFD and the SEA Directive.

The state under each scenario can be thought of as the geomorphic state of the whole estuary, or of certain components, such as the habitat area. The impacts are those that the driver and pressure exert on the state, for example, the impact of sea level rise on habitats designated under the Habitats Regulations within an estuary; the response of the estuary to a SMP policy such as 'hold the line', or the impact on the estuary system of a development, such as a barrage or bridge. The range of scenarios presented in Table 34 have been used as a guide within the Pilot Testing exercise. In applying these scenarios, the pilot testing was used to address a number of generic issues regarding capabilities and limitations, as discussed within Section 6 of this report.

Table 34. Suggested Generic Scenarios for Pilot Testing the Prototype Simulator

Scenario	Driver	Pressures	State	Impact	Scenario
1	Climate Change	Habitats Regulations	Habitat area / balance.	Impact of sea level rise on designated habitats	Impose sea level rise on estuary system and assess response in terms of habitat change.
2	Climate Change	Habitats Regulations Flood Risk	State of individual estuary components.	Sensitivities of each component of estuary system	Impose sea level rise on estuary system and assess response to each estuary component.
3	Flood and coastal erosion risk management	Chosen Shoreline Management Plan policies, (Habitats Regulations)	Estuary geomorphic state, habitat area / balance, sedimentation / erosion.	Response of estuary to the SMP policies	Remove flood and coastal defences throughout estuary and assess response; a 'do nothing' scenario.
4	Flood and coastal erosion risk management	Shoreline Management Planning, (Habitats Regulations)	Estuary geomorphic state, evolution.	Response of estuary to 'hold the line' SMP policies	Apply 'hold the line' throughout estuary to assess impact of constraining evolution.
5a	Development - individual impacts	WFD, consenting/ licensing process	Estuary geomorphic state, habitat area/ balance, sedimentation / erosion.	Impact on system as a result of development / ability of system to respond.	Apply port development to estuary in the form of dredging and assess changes to estuary.
5b	Development - individual impacts	WFD, consenting / licensing process	Estuary geomorphic state, habitat area / balance, sedimentation / erosion.	Impact on system as a result of development / ability of system to respond.	Apply port development to estuary in the form of reclamation, and assess changes to estuary.
5c	Development - cumulative impacts	SEA Directive	Estuary geomorphic state, habitat area / balance, sedimentation / erosion.	Cumulative impact on system as a result of multiple developments.	Apply both dredging and reclamation to estuary and assess cumulative changes.

5.3 Pilot Testing: Thames Estuary

5.3.1 Generic Funnel-Shaped Estuary

The Thames estuary is described as a funnel shaped estuary in Futurecoast (Dyer, 2002), a coastal plain estuary by JNCC (1997), and based on the typology applied within Section 3 of this report the Thames is defined as a funnel-shaped estuary.

The evolution of a generic funnel-shaped estuary in the Prototype Simulator is shown in Table 35. The estuary evolves from starting conditions of ocean waves, littoral sand, marine sand, marine mud, macro-tidal (tidal range), inlet, wind, prism, accommodation space, river discharge, river sand and river mud. It takes 13 steps to reach a steady state with numerous features emerging from the starting conditions and feedback altering some states. The steps represent an evolutionary path but are not intended to represent a specific duration of time (French & Burningham, 2007).

The steady state condition for the generic funnel-shaped estuary includes an updrift beach, dunes, linear banks, outer flood dominance, outer subtidal sands, outer estuary swell, outer estuary waves, outer sand flat, inner ebb-dominance, inner subtidal deposits, inner sandflat, inner mudflat and inner marshes. Accommodation space is lost because it is taken up by intertidal features in the outer estuary and in the inner estuary there is a switch between flood and ebb dominance as intertidal features appear.

Table 35. Evolution of a Generic Funnel Shaped Estuary Towards Steady State

1	2	3	4	5	6	7	8	9	10	11	12	13	Step
1	1	1	1	1	1	1	1	1	1	1	1	1	ocean_waves
1	1	1	1	1	1	1	1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	marine_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	marine_mud
1	1	1	1	1	1	1	1	1	1	1	1	1	macrotidal
0	0	0	1	1	1	1	1	1	1	1	1	1	updrift_beach
1	1	1	1	1	1	1	1	1	1	1	1	1	inlet
0	0	0	0	0	0	0	0	1	1	1	1	1	dunes
1	1	1	1	1	1	1	1	1	1	1	1	1	wind
1	1	1	1	1	1	1	1	1	1	1	1	1	prism
1	1	1	1	1	1	1	0	0	0	0	0	0	accomm_space
0	0	0	1	1	1	1	1	1	1	1	1	1	linear_banks
0	1	1	1	1	1	1	1	1	1	1	1	1	outer_flood_dominance
0	0	0	0	0	0	1	1	1	1	1	1	1	outer_subtidal_sands
0	1	1	1	1	1	1	1	1	1	1	1	1	outer_estuary_swell
0	1	1	1	1	1	1	1	1	1	1	1	1	outer_estuarywaves
0	0	0	1	1	1	1	1	1	1	1	1	1	outer_sandflat
0	1	1	1	1	1	1	1	0	0	0	0	0	inner_flood_dominance
0	0	0	0	0	0	0	0	0	0	1	1	1	inner_ebb_dominance
0	0	0	1	1	1	1	1	1	1	1	1	1	inner_subtidal_deposits
0	0	1	1	0	0	0	0	0	0	0	0	0	inner_estuarywaves
0	0	0	0	0	0	1	1	1	1	1	1	1	inner_sandflat
0	0	0	1	1	1	1	1	1	1	1	1	1	inner_mudflat
0	0	0	0	0	0	0	0	0	0	0	0	1	inner_marsh_low
0	0	0	0	0	0	0	0	0	1	1	1	1	inner_marsh_high
1	1	1	1	1	1	1	1	1	1	1	1	1	river_discharge
1	1	1	1	1	1	1	1	1	1	1	1	1	river_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	river_mud

The Thames differs from the generic funnel shaped estuary defined previously in the Prototype Simulator (French & Burningham, 2007) in a number of ways. The Thames has very limited intertidal area in the inner estuary, with no inner sandflat, inner mud flat, inner marsh low or inner marsh high which develops in the generic funnel shaped estuary. Changes to the generic funnel-shaped estuary are necessary to better represent the Thames and these are described below.

5.3.2 Adjusting the Generic Estuary Type for the Thames in the Prototype Simulator

The Thames estuary lacks the intertidal features in the inner estuary that evolve in the generic funnel-shaped estuary. In order to test the effects of management interventions in the Thames, it is necessary to first develop a starting estuary that resembles the Thames in terms of features and processes present. A number of changes need to be made to the funnel-shaped estuary template to achieve this. In this simulation, inner and outer flood defences have been included in an attempt to limit the development of intertidal areas (Table 36).

Table 36. Funnel-Shaped Estuary with Inner Flood Defences and Outer Flood Defences

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Step
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	ocean_waves
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	marine_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	marine_mud
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	Macrotidal
0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	updrift_beach
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	Inlet
0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	Dunes
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	Wind
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Prism
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	accomm_space
0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	linear_banks
0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	outer_flood_dominance
0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	outer_ebb_dominance
0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_estuary_swell
0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	outer_estuarywaves
0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	outer_sandflat
0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	outer_mudflat
0	0	0	0	0	0	1	1	1	0	0	0	1	1	1	outer_marsh_low
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_flood_defence
0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_floodplain
0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	inner_flood_dominance
0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	inner_ebb_dominance
0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	inner_subtidal_deposits
0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	inner_estuarywaves
0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	inner_sandflat
0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	inner_mudflat
0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	inner_marsh_low
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_flood_defence
0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_floodplain
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	river_discharge
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	river_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	river_mud

The starting conditions are the same as the generic funnel-shaped estuary but with inner and outer flood defences added. In this case, the simulated estuary reaches a cyclic equilibrium between steps 9 and 15.

In the outer estuary, the addition of the outer flood defence causes the development of outer mud flats and outer marsh low (cyclic), which were not present in the generic funnel-shaped estuary and are not seen in the Thames. There is a switch between outer flood dominance and outer ebb dominance and a flood plain develops behind the flood defence. In the inner estuary, the presence of inner flood defences prevents high marsh from forming. Low marsh and mud and sand flats still develop. As with the outer estuary, a flood plain develops behind the inner flood defences. In addition, tidal prism is turned off which it did not do in the simulation of the generic estuary (Table 35).

The development of mudflats and marshes in the outer estuary is not realistic for the Thames estuary. The Outer Thames has broad sand flats at this point and very little saltmarsh, suggesting that the Prototype Simulator use of outer flood defences may not be appropriate here. Table 37 shows the evolution of a funnel-shaped estuary with inner flood defences only.

Table 37. Funnel-Shaped Estuary with Inner Flood Defence Only

1	2	3	4	5	6	7	8	9	10	11	Step
1	1	1	1	1	1	1	1	1	1	1	ocean_waves
1	1	1	1	1	1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	1	1	1	1	1	marine_sand
1	1	1	1	1	1	1	1	1	1	1	marine_mud
1	1	1	1	1	1	1	1	1	1	1	Macrotidal
0	0	0	1	1	1	1	1	1	1	1	updrift_beach
1	1	1	1	1	1	1	1	1	1	1	Inlet
0	0	0	0	0	0	0	0	1	1	1	Dunes
1	1	1	1	1	1	1	1	1	1	1	Wind
1	1	1	1	1	1	1	1	1	1	1	Prism
1	1	1	1	1	1	1	0	0	0	0	accomm_space
0	0	0	1	1	1	1	1	1	1	1	linear_banks
0	1	1	1	1	1	1	1	1	1	1	outer_flood_dominance
0	0	0	0	0	0	1	1	1	1	1	outer_subtidal_sands
0	1	1	1	1	1	1	1	1	1	1	outer_estuary_swell
0	1	1	1	1	1	1	1	1	1	1	outer_estuarywaves
0	0	0	1	1	1	1	1	1	1	1	outer_sandflat
0	1	1	1	1	1	1	1	0	0	0	inner_flood_dominance
0	0	0	0	0	0	0	0	0	0	1	inner_ebb_dominance
0	0	0	1	1	1	1	1	1	1	1	inner_subtidal_deposits
0	0	1	1	0	0	0	0	0	0	0	inner_estuarywaves
0	0	0	0	0	0	1	1	1	1	1	inner_sandflat
0	0	0	1	1	1	1	1	1	1	1	inner_mudflat
0	0	0	0	0	0	0	1	1	1	1	inner_marsh_low
1	1	1	1	1	1	1	1	1	1	1	inner_flood_defence
0	1	1	1	1	1	1	1	1	1	1	inner_floodplain
1	1	1	1	1	1	1	1	1	1	1	river_discharge
1	1	1	1	1	1	1	1	1	1	1	river_sand
1	1	1	1	1	1	1	1	1	1	1	river_mud

Removing the outer flood defences gives outer estuary morphologies more like those expected for the Thames but does not affect the inner estuary morphology. In a further simulation (Table 38) sea level rise is included to simulate the process of coastal squeeze with flood defences. When imposing sea level rise, it is necessary to also select 'hold the line' to prevent sea defences and other interventions breaking down over time.

Under this condition (inner flood defence, sea level rise and 'hold the line') the inner marsh low is now lost, but inner sand and mudflats remain. This differs from the situation in the real Thames where all intertidal area in the inner estuary has been protected and reclaimed as the city expanded. To include this effect in the simulator it is necessary to introduce an "encroachment" term to the function libraries. This is described in the next section.

In addition, it was noted that outer estuary swell is not present in the Thames and ocean waves were switched off to reflect this. This caused high and low marsh to develop in the outer estuary. After reviewing the Boolean statements it was considered that the presence of outer estuary swell OR outer estuary waves should inhibit the development of outer marsh, rather than outer estuary swell AND outer estuary waves, and this change was also made to the Prototype Simulator.

Table 38. Funnel-Shaped Estuary with Inner Flood Defences, 'Hold The Line' and slr

1	2	3	4	5	6	7	8	9	10	11	Step
1	1	1	1	1	1	1	1	1	1	1	ocean_waves
1	1	1	1	1	1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	1	1	1	1	1	marine_sand
1	1	1	1	1	1	1	1	1	1	1	marine_mud
1	1	1	1	1	1	1	1	1	1	1	macrotidal
1	1	1	1	1	1	1	1	1	1	1	slr
0	0	0	1	1	1	1	1	1	1	1	updrift_beach
1	1	1	1	1	1	1	1	1	1	1	inlet
0	0	0	0	0	0	0	0	1	1	1	dunes
1	1	1	1	1	1	1	1	1	1	1	wind
1	1	1	1	1	1	1	1	1	1	1	hold_the_line
1	1	1	1	1	1	1	1	1	1	1	prism
1	1	1	1	1	1	1	0	0	0	0	accomm_space
0	0	0	1	1	1	1	1	1	1	1	linear_banks
0	1	1	1	1	1	1	1	1	1	1	outer_flood_dominance
0	0	0	0	0	0	1	1	1	1	1	outer_subtidal_sands
0	1	1	1	1	1	1	1	1	1	1	outer_estuary_swell
0	1	1	1	1	1	1	1	1	1	1	outer_estuarywaves
0	0	0	1	1	1	1	1	1	1	1	outer_sandflat
0	1	1	1	1	1	1	1	0	0	0	inner_flood_dominance
0	0	0	0	0	0	0	0	0	0	1	inner_ebb_dominance
0	0	0	1	1	1	1	1	1	1	1	inner_subtidal_deposits
0	0	1	1	0	0	0	0	0	0	0	inner_estuarywaves
0	0	0	0	0	0	1	1	1	1	1	inner_sandflat
0	0	0	1	1	1	1	1	1	1	1	inner_mudflat
1	1	1	1	1	1	1	1	1	1	1	inner_flood_defence
0	1	1	1	1	1	1	1	1	1	1	inner_floodplain
1	1	1	1	1	1	1	1	1	1	1	river_discharge
1	1	1	1	1	1	1	1	1	1	1	river_sand
1	1	1	1	1	1	1	1	1	1	1	river_mud

5.3.3 Changes to Function Libraries for the Thames

Addition of "encroachment" term

New terms can be added to the function libraries to allow morphologies for specific estuaries to be represented more accurately. For the Thames an encroachment term was added to prevent intertidal morphologies developing in the upper estuary:

INNER_ENCROACHMENT = (inner_encroachment & inner_flood_defence)

When INNER_ENCROACHMENT is turned on, it prevents mud and sand flats developing in the inner estuary. It requires both inner_encroachment and inner_flood_defence to be on. In the case of managed realignment (i.e. removal of flood defences) inner_encroachment is turned off and intertidal features can develop.

Once a new term has been added to the function library it can be used in the estuary definition file.

Change to conditions for outer marsh high

Following some initial testing, the Outer marsh high logic statement was changed from:

OUTER_MARSH_HIGH = (~outer_marsh_high & (marine_mud | (cliff_mud & coastal_cliff_erosion)) & ~bedrock & ~outer_flood_defence & ~(outer_estuary_swell **&** outer_estuarywaves)) | (outer_marsh_high & ~outer_flood_defence & ~(slr & ~(marine_mud | (cliff_mud & coastal_cliff_erosion))) & ~outer_estuarywaves)
To:
OUTER_MARSH_HIGH = (~outer_marsh_high & (marine_mud | (cliff_mud & coastal_cliff_erosion)) & ~bedrock & ~outer_flood_defence & ~(outer_estuary_swell **|** outer_estuarywaves)) | (outer_marsh_high & ~outer_flood_defence & ~(slr & ~(marine_mud | (cliff_mud & coastal_cliff_erosion))) & ~outer_estuarywaves)

5.3.4 Thames Specific Setup

Using the changes to the generic funnel-shaped estuary derived from experience with initial testing described in the previous sections (i.e. inner flood defences, inner encroachment, no ocean waves and outer estuary swell or outer estuary waves preventing outer marsh high developing) it was possible to simulate an estuary that represented the Thames estuary satisfactorily (Table 39). This model set up is used for all modelling tests of the Thames estuary reported in the remainder of this report.

5.3.5 Thames Estuary Pilot Tests

Various pilot tests were carried out to simulate the response of the Thames estuary to management interventions such as a barrage, dredging, reclamation and managed realignment. The affect of accelerated sea level rise was also simulated.

Barrage

The effect of including a barrage on the Thames was simulated using the steady state condition for Thames specific setup with the addition of a barrage feature in the Outer Estuary (Table 40).

Table 39. Set Up and Evolution for the Thames Estuary

1	2	3	4	5	6	7	8	9	10	11	Step
1	1	1	1	1	1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	1	1	1	1	1	marine_sand
1	1	1	1	1	1	1	1	1	1	1	marine_mud
1	1	1	1	1	1	1	1	1	1	1	macrotidal
1	1	1	1	1	1	1	1	1	1	1	slr
1	1	1	1	1	1	1	1	1	1	1	inlet
1	1	1	1	1	1	1	1	1	1	1	wind
1	1	1	1	1	1	1	1	1	1	1	hold_the_line
1	1	1	1	1	1	1	1	1	1	1	prism
1	1	1	1	1	1	1	0	0	0	0	accomm_space
0	0	0	1	1	1	1	1	1	1	1	linear_banks
0	1	1	1	1	1	1	1	1	1	1	outer_flood_dominance
0	0	0	0	0	0	1	1	1	1	1	outer_subtidal_sands
0	1	1	1	1	1	1	1	1	1	1	outer_estuarywaves
0	0	0	1	1	1	1	1	1	1	1	outer_sandflat
0	0	0	1	1	1	1	1	1	1	1	outer_mudflat
0	1	1	1	1	1	1	1	0	0	0	inner_flood_dominance
0	0	0	0	0	0	0	0	0	0	1	inner_ebb_dominance
0	0	0	1	1	1	1	1	1	1	1	inner_subtidal_deposits
0	0	1	1	1	1	1	1	1	1	1	inner_estuarywaves
1	1	1	1	1	1	1	1	1	1	1	inner_flood_defence
0	1	1	1	1	1	1	1	1	1	1	inner_floodplain
1	1	1	1	1	1	1	1	1	1	1	inner_encroachment
1	1	1	1	1	1	1	1	1	1	1	river_discharge
1	1	1	1	1	1	1	1	1	1	1	river_sand
1	1	1	1	1	1	1	1	1	1	1	river_mud

Table 40. Evolution of the Thames Estuary with a Barrage

1	2	3	4	5	6	7	8	9	10	11	12	13	14	Step
1	1	1	1	1	1	1	1	1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	marine_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	marine_mud
1	0	0	0	0	0	0	0	0	0	0	0	0	0	Macrotidal
0	1	1	1	1	1	1	1	1	1	1	1	1	1	Mesotidal
1	1	1	0	0	0	0	0	0	0	0	0	0	0	Inlet
1	1	1	1	1	1	1	1	1	1	1	1	1	1	Wind
1	1	1	1	1	1	1	1	1	1	1	1	1	1	Barrage
1	1	1	1	1	1	1	1	1	1	1	1	1	1	hold_the_line
1	1	1	1	0	0	0	0	0	0	0	0	0	0	Prism
0	0	0	0	0	0	0	1	1	1	1	1	1	1	flood_delta
1	1	1	1	0	0	0	0	0	0	0	0	0	0	linear_banks
1	1	1	0	0	0	0	0	0	0	0	0	0	0	outer_flood_dominance
1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_subtidal_sands
1	1	1	1	1	0	0	0	0	0	0	0	0	0	outer_estuarywaves
1	1	1	1	1	1	1	1	0	0	0	0	0	0	outer_sandflat
1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_mudflat
0	0	0	0	0	0	0	0	0	0	0	0	0	1	outer_marsh_low
0	0	0	0	0	0	0	0	0	0	1	1	1	1	outer_marsh_high
1	1	1	1	1	0	0	0	0	0	0	0	0	0	inner_ebb_dominance
1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_subtidal_deposits
1	1	1	1	1	1	0	0	0	0	0	0	0	0	inner_estuarywaves
1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_flood_defence
1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_floodplain
1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_encroachment
1	1	1	1	1	1	1	1	1	1	1	1	1	1	river_discharge
1	1	1	1	1	1	1	1	1	1	1	1	1	1	river_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	river_mud

The addition of a barrage reduced the tidal range from macrotidal to mesotidal and resulted in the system no longer being an “inlet” which in turn caused the “prism” to be turned off. A flood delta develops, as do muddy features in the outer estuary. The outer estuary sandflats and linear banks present before for the barrage was added are predicted to disappear. Intertidal morphologies do not develop in the inner estuary in this case because inner encroachment prevents this.

How realistic the predictions relating to the barrage are dependent on the assumptions made about the barrage. If it is assumed to almost entirely close the estuary, the above predictions may be realistic as the inlet is effectively closed, removing tidal prism and allowing the estuary to infill with fluvial mud. However, the existing Thames barrier does not have such an extreme effect on the processes and morphologies of the Thames. It is possible that different kinds of barrages could be defined, having differing effects on estuary processes and morphologies. This would require functional definitions of the barrage being added to the existing libraries to handle specific cases.

In the face of accelerated sea level rise, in absence of a hold the line policy, the evolution following the imposition of a barrage (Table 41) is similar. However, the inner flood defences break down, allowing sand and mudflats and marshes to develop. This draws attention to the use of management intervention policies in the function library; each policy applies everywhere in the system. Separate policies for the inner and outer estuary and coastal sub-systems could be applied in a revised version of the Prototype Simulator.

Table 41. Evolution of the Thames Estuary with a Barrage and Sea Level Rise

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	Step
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	marine_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	marine_mud
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	macrotidal
0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	mesotidal
0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	microtidal
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	slr
1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	inlet
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	wind
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	barrage
1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	prism
0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	flood_delta
1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	linear_banks
1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	outer_flood_dominance
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_subtidal_sands
1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	outer_estuarywaves
1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	outer_sandflat
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_mudflat
0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	1	1	outer_marsh_low
0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	outer_marsh_high
1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	inner_ebb_dominance
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_subtidal_deposits
1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	inner_estuarywaves
0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	inner_sandflat
0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	inner_mudflat
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	inner_marsh_low
0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	inner_marsh_high
1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	inner_flood_defence
1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	inner_floodplain
1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	inner_encroachment
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	river_discharge
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	river_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	river_mud

Dredging

The effects of dredging on the Thames estuary were simulated using the steady state conditions for the Thames specific setup with outer dredging only (Table 42) and outer and inner dredging (Table 43).

It should be noted that the binary “all or nothing” nature of the model means that dredging is always represented as removing most of the subtidal deposit. In the case of the Thames, dredging in the outer estuary represents removal of a minute fraction of the subtidal deposit (because the outer estuary is so wide) while dredging in the inner estuary, whilst significant to the sediment regime, only removes a small proportion of the subtidal deposit. The effects predicted by the Simulator should therefore be taken in context.

In the outer dredging only case (Table 42), the Simulator predicts that a new steady state will be reached in eight steps. The main differences between the steady state condition with outer dredging and the undisturbed Thames specific case (Table 39) are that there is accommodation space with outer dredging and outer subtidal sands are lost. The inner estuary starts as ebb dominant but becomes flood dominant by step 6.

Table 42. Evolution of the Thames Estuary with Outer Dredging

1	2	3	4	5	6	7	8	Step
1	1	1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	1	1	marine_sand
1	1	1	1	1	1	1	1	marine_mud
1	1	1	1	1	1	1	1	macrotidal
1	1	1	1	1	1	1	1	inlet
1	1	1	1	1	1	1	1	wind
1	1	1	1	1	1	1	1	hold_the_line
1	1	1	1	1	1	1	1	prism
0	0	0	0	1	1	1	1	accomm_space
1	1	1	1	1	1	1	1	linear_banks
1	1	1	1	1	1	1	1	outer_flood_dominance
1	1	1	0	0	0	0	0	outer_subtidal_sands
1	1	1	1	1	1	1	1	outer_estuarywaves
1	1	1	1	1	1	1	1	outer_sandflat
1	1	1	1	1	1	1	1	outer_mudflat
1	1	1	1	1	1	1	1	outer_dredging
0	0	0	0	0	1	1	1	inner_flood_dominance
1	1	1	1	1	1	1	0	inner_ebb_dominance
1	1	1	1	1	1	1	1	inner_subtidal_deposits
1	1	1	1	1	1	1	1	inner_estuarywaves
1	1	1	1	1	1	1	1	inner_flood_defence
1	1	1	1	1	1	1	1	inner_floodplain
1	1	1	1	1	1	1	1	inner_encroachment
1	1	1	1	1	1	1	1	river_discharge
1	1	1	1	1	1	1	1	river_sand
1	1	1	1	1	1	1	1	river_mud

With inner and outer dredging (Table 43), accommodation space responds quickly and is turned on in step 2. Outer subtidal sands and inner subtidal deposits are lost. The inner estuary quickly becomes flood dominant. In general, dredging removes subtidal deposits from the inner and outer estuary and maintains accommodation space by removing subtidal sediment. In the present simulations, dredging does not affect the outer sand and mud flats.

Table 43. Evolution of the Thames Estuary with Inner Dredging and Outer Dredging

1	2	3	4	5	Step
1	1	1	1	1	littoral_sand
1	1	1	1	1	marine_sand
1	1	1	1	1	marine_mud
1	1	1	1	1	macrotidal
1	1	1	1	1	Inlet
1	1	1	1	1	Wind
1	1	1	1	1	Hold_the_line
1	1	1	1	1	prism
0	1	1	1	1	accomm_space
1	1	1	1	1	linear_banks
1	1	1	1	1	outer_flood_dominance
1	1	1	0	0	outer_subtidal_sands
1	1	1	1	1	outer_estuarywaves
1	1	1	1	1	outer_sandflat
1	1	1	1	1	outer_mudflat
1	1	1	1	1	outer_dredging
0	0	1	1	1	inner_flood_dominance
1	1	1	1	0	inner_ebb_dominance
1	1	1	0	0	inner_subtidal_deposits
1	1	1	1	1	inner_estuarywaves
1	1	1	1	1	inner_flood_defence
1	1	1	1	1	inner_floodplain
1	1	1	1	1	inner_dredging
1	1	1	1	1	inner_encroachment
1	1	1	1	1	River_discharge
1	1	1	1	1	River_sand
1	1	1	1	1	River_mud

Reclamation

The Thames has undergone extensive reclamations in the past, particularly in the inner estuary, making it necessary to include the inner encroachment term (Section 5.3.3) to simulate the observed effects. Further reclamation in the Thames is likely to reduce the tidal prism, possibly without removing the remaining intertidal area. To simulate this, the Thames specific setup was used, with prism initially set to 0. It should be noted that tidal prism is a state variable and is therefore not intended as a valid change to forcing. However this provides a useful test of the models robustness to unintended changes.

Table 44 shows that the prism was turned back on quickly (by step 2) and the estuary evolved towards steady state in four steps, ending with the same morphology as the undisturbed Thames specific setup. This suggests that simply removing tidal prism is not sufficient to simulate the effects of reclamation. The rapid recovery to steady state also suggests the model is robust to misuses of the state variables.

In the examples given by French & Burningham (2007), flood defences are used to simulate land reclamation. The addition of flood defences removes high marsh and creates a flood plain behind the defence that can be flooded if the defence is removed. This is difficult to implement in the Thames, where it has already been shown that flood defences are not sufficient in the Boolean function library to reproduce the observed intertidal loss in the inner estuary, which has been caused by the encroachment of the city onto reclaimed lands. In principle, more complex situations could be included by including additional zones of reclamation in the function libraries. However, due to interactions with other morphologies and processes this will be a complex task and has not been attempted in the present pilot testing exercise.

Table 44. Evolution of the Thames with Prism Initially Turned off to Represent the Effects of Land Reclamation

1	2	3	4	Step
1	1	1	1	littoral_sand
1	1	1	1	marine_sand
1	1	1	1	marine_mud
1	1	1	1	macrotidal
1	1	1	1	inlet
1	1	1	1	wind
1	1	1	1	hold_the_line
0	1	1	1	prism
1	1	1	1	linear_banks
1	0	1	1	outer_flood_dominance
1	1	1	1	outer_subtidal_sands
1	0	1	1	outer_estuarywaves
1	1	1	1	outer_sandflat
1	1	1	1	outer_mudflat
1	1	1	1	inner_ebb_dominance
1	1	1	1	inner_subtidal_deposits
1	1	0	1	inner_estuarywaves
1	1	1	1	inner_flood_defence
1	1	1	1	inner_floodplain
1	1	1	1	inner_encroachment
1	1	1	1	river_discharge
1	1	1	1	river_sand
1	1	1	1	river_mud

Realignment

The effect of managed realignment is simulated by removing the flood defences, and in Table 45 the effect of removing flood defences has been simulated using the steady state conditions for the undisturbed Thames specific setup (step 11, Table 39) as the starting conditions. This can also be done using a realign policy, although this causes a delay of 6 time steps before the flood defences are removed.

Removing the inner flood defences turns off inner encroachment and inner flood plain. At step 5, inner sand and mud flats develop, causing inner estuary waves to turn off. Later, inner marsh high and inner marsh low develop, completing evolution to a new steady state. The outer estuary is unaffected by the removal of the inner flood defences.

The removal of flood defences in the Boolean function library produces behaviour that could well be expected in a real estuary. However it is considered extremely unlikely that large areas of flood defence will be removed as was simulated here, and the actual development of intertidal morphologies following realignment will depend on much more than the removal of flood walls. Sediment supply, elevation of flood plain and management of the realigned area will all affect the morphologies that develop following a realignment intervention.

Table 45. Evolution of the Thames Following Realignment of Flood Defences (Starting from Steady State Morphology)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	Step
1	1	1	1	1	1	1	1	1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	marine_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	marine_mud
1	1	1	1	1	1	1	1	1	1	1	1	1	1	Macrotidal
1	1	1	1	1	1	1	1	1	1	1	1	1	1	Inlet
1	1	1	1	1	1	1	1	1	1	1	1	1	1	Wind
1	1	1	1	1	1	1	1	1	1	1	1	1	1	hold_the_line
1	1	1	1	1	1	1	1	1	1	1	1	1	1	Prism
1	1	1	1	1	1	1	1	1	1	1	1	1	1	linear_banks
1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_flood_dominance
1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_subtidal_sands
1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_estuarywaves
1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_sandflat
1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_mudflat
1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_ebb_dominance
1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_subtidal_deposits
1	1	1	1	1	0	0	0	0	0	0	0	0	0	inner_estuarywaves
0	0	0	0	1	1	1	1	1	1	1	1	1	1	inner_sandflat
0	0	0	0	1	1	1	1	1	1	1	1	1	1	inner_mudflat
0	0	0	0	0	0	0	0	0	0	0	0	0	1	inner_marsh_low
0	0	0	0	0	0	0	0	0	0	1	1	1	1	inner_marsh_high
1	0	0	0	0	0	0	0	0	0	0	0	0	0	inner_floodplain
1	0	0	0	0	0	0	0	0	0	0	0	0	0	inner_encroachment
1	1	1	1	1	1	1	1	1	1	1	1	1	1	river_discharge
1	1	1	1	1	1	1	1	1	1	1	1	1	1	river_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	river_mud

Sea level rise

The effect of accelerated sea level rise was simulated from the steady state condition of the Thames specific setup and the results are shown in Table 46. Adding sea-level rise for the Thames estuary has no impact on the processes or on the steady state morphology.

Table 46. The evolution of the Thames under accelerated sea level rise

1	2	Step
1	1	littoral_sand
1	1	marine_sand
1	1	marine_mud
1	1	Macrotidal
1	1	slr
1	1	inlet
1	1	wind
1	1	hold_the_line
1	1	prism
1	1	linear_banks
1	1	outer_flood_dominance
1	1	outer_subtidal_sands
1	1	outer_estuarywaves
1	1	outer_sandflat
1	1	outer_mudflat
1	1	inner_ebb_dominance
1	1	inner_subtidal_deposits
1	1	inner_estuarywaves
1	1	inner_flood_defence
1	1	inner_floodplain
1	1	inner_encroachment
1	1	river_discharge
1	1	river_sand
1	1	river_mud

When sea level rise and managed realignment are simulated (Table 47) the evolution is similar to the simple realignment scenario (Table 44) except that inner marsh low now shows cyclical behaviour.

It should be noted that the ‘realign’ policy gives the same behaviour in response to sea level rise as the absence of ‘hold the line’. Both are subject to a delay in the breakdown of flood defence. If instant removal of flood defences is required this can be implemented by setting the flood defences to zero in the estuary definition file.

Table 47. Evolution of the Thames with Accelerated Sea Level Rise and a Policy to Realign

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	Step
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	marine_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	marine_mud
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	macrotidal
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	slr
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inlet
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	wind
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	realign
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	prism
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	linear_banks
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_flood_dominance
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_subtidal_sands
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_estuarywaves
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_sandflat
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_mudflat
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_ebb_dominance
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_subtidal_deposits
1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	inner_estuarywaves
0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_sandflat
0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_mudflat
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	inner_marsh_low
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	inner_marsh_high
1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	inner_flood_defence
1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	inner_floodplain
1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	inner_encroachment
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	river_discharge
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	river_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	river_mud

5.4 Pilot Testing: Teign Estuary

5.4.1 Generic Spit-Enclosed Estuary

The Teign Estuary is described as a single spit-enclosed estuary in Futurecoast (Dyer, 2002) and as a ria by JNCC (1997). It is similar to the generic spit-enclosed estuary defined in Section 3, with the main differences being the presence of reed beds in the inner estuary, a sea wall on the updrift coast and absence of a marine mud supply.

The starting conditions and evolution for a generic spit-enclosed estuary are shown in Table 48. Starting conditions include ocean waves, longshore power, littoral sand, marine sand, marine mud, meso-tidal, inlet, wind, prism, accommodation space, river discharge and river sand and mud. The generic spit-enclosed estuary evolves to steady state in 13 steps. Morphological features at steady state include an updrift beach, a spit, downdrift beach, dunes, ebb and flood deltas, outer subtidal sands, outer sand and mudflats, inner subtidal deposits, inner sand and mudflats and inner marshes (high and low). Accommodation space is lost at step 8 and the outer estuary is flood dominant. The inner estuary is ebb dominant.

Table 48. Evolution of a Generic Spit-Enclosed Estuary

1	2	3	4	5	6	7	8	9	10	11	12	13	Step
1	1	1	1	1	1	1	1	1	1	1	1	1	ocean_waves
1	1	1	1	1	1	1	1	1	1	1	1	1	longshore_power
1	1	1	1	1	1	1	1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	marine_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	marine_mud
1	1	1	1	1	1	1	1	1	1	1	1	1	mesotidal
0	0	0	1	1	1	1	1	1	1	1	1	1	updrift_beach
0	0	0	0	0	0	1	1	1	1	1	1	1	spit
1	1	1	1	1	1	1	1	1	1	1	1	1	inlet
0	0	0	0	0	0	0	0	0	1	1	1	1	downdrift_beach
0	0	0	0	0	0	0	0	1	1	1	1	1	dunes
1	1	1	1	1	1	1	1	1	1	1	1	1	wind
1	1	1	1	1	1	1	1	1	1	1	1	1	prism
1	1	1	1	1	1	1	0	0	0	0	0	0	accomm_space
0	0	0	1	1	1	1	1	1	1	1	1	1	ebb_delta
0	0	0	1	1	1	1	1	1	1	1	1	1	flood_delta
0	1	1	1	1	1	1	1	1	1	1	1	1	outer_flood_dominance
0	0	0	0	0	0	1	1	1	1	1	1	1	outer_subtidal_sands
0	1	1	1	1	1	1	0	0	0	0	0	0	outer_estuary_swell
0	1	1	1	1	1	1	1	1	1	1	1	1	outer_estuarywaves
0	0	0	0	1	1	1	1	1	1	1	1	1	outer_sandflat
0	0	0	0	0	0	0	0	0	0	1	1	1	outer_mudflat
0	0	1	1	1	1	1	1	1	1	1	1	1	inner_ebb_dominance
0	0	0	1	1	1	1	1	1	1	1	1	1	inner_subtidal_deposits
0	0	1	1	0	0	0	0	0	0	0	0	0	inner_estuarywaves
0	0	0	0	0	0	1	1	1	1	1	1	1	inner_sandflat
0	0	0	1	1	1	1	1	1	1	1	1	1	inner_mudflat
0	0	0	0	0	0	0	0	0	0	0	0	1	inner_marsh_low
0	0	0	0	0	0	0	0	0	1	1	1	1	inner_marsh_high
1	1	1	1	1	1	1	1	1	1	1	1	1	river_discharge
1	1	1	1	1	1	1	1	1	1	1	1	1	river_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	river_mud

5.4.2 Teign-Specific Setup

A Teign-specific estuary definition file was created based on the generic spit-enclosed estuary. It was adapted (Table 49) to include:

- An illustrative function for inner reed beds;
- An updrift seawall; and,
- No marine mud supply.

In the Teign-specific case reed beds form in the inner estuary and the absence of marine mud prevents outer mudflats from forming, in line with observed morphology of the estuary. This is found to be a realistic representation of the Teign estuary, except for the outer flood dominance, as the Teign estuary is known to be strongly ebb dominant.

It should be noted that there are no obvious “inner” and “outer” sections within the Teign and this adds some uncertainty to the conclusions arising from the application of the generic estuary template.

Table 49. Evolution of Teign Estuary (Based on Spit-Enclosed Generic Type, With Inner Reed Bed, a Seawall and no Marine Mud)

1	2	3	4	5	6	7	8	9	10	11	12	13	Step
1	1	1	1	1	1	1	1	1	1	1	1	1	ocean_waves
1	1	1	1	1	1	1	1	1	1	1	1	1	longshore_power
1	1	1	1	1	1	1	1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	marine_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	mesotidal
0	0	0	1	1	1	1	1	1	1	1	1	1	updrift_beach
0	0	0	0	0	0	1	1	1	1	1	1	1	spit
1	1	1	1	1	1	1	1	1	1	1	1	1	inlet
0	0	0	0	0	0	0	0	0	1	1	1	1	downdrift_beach
0	0	0	0	0	0	0	0	1	1	1	1	1	dunes
1	1	1	1	1	1	1	1	1	1	1	1	1	wind
1	1	1	1	1	1	1	1	1	1	1	1	1	seawall
1	1	1	1	1	1	1	1	1	1	1	1	1	prism
1	1	1	1	1	1	1	0	0	0	0	0	0	accomm_space
0	0	0	1	1	1	1	1	1	1	1	1	1	ebb_delta
0	0	0	1	1	1	1	1	1	1	1	1	1	flood_delta
0	1	1	1	1	1	1	1	1	1	1	1	1	outer_flood_dominance
0	0	0	0	0	0	1	1	1	1	1	1	1	outer_subtidal_sands
0	1	1	1	1	1	1	0	0	0	0	0	0	outer_estuary_swell
0	1	1	1	1	1	1	1	1	1	1	1	1	outer_estuarywaves
0	0	0	0	1	1	1	1	1	1	1	1	1	outer_sandflat
0	0	1	1	1	1	1	1	1	1	1	1	1	inner_ebb_dominance
0	0	0	1	1	1	1	1	1	1	1	1	1	inner_subtidal_deposits
0	0	1	1	0	0	0	0	0	0	0	0	0	inner_estuarywaves
0	0	0	0	0	0	1	1	1	1	1	1	1	inner_sandflat
0	0	0	1	1	1	1	1	1	1	1	1	1	inner_mudflat
0	0	0	0	0	0	0	0	0	0	0	0	1	inner_marsh_low
0	0	0	0	0	0	0	0	0	1	1	1	1	inner_marsh_high
0	0	0	0	0	0	0	0	0	1	1	1	1	inner_reed_bed
1	1	1	1	1	1	1	1	1	1	1	1	1	river_discharge
1	1	1	1	1	1	1	1	1	1	1	1	1	river_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	river_mud

5.4.3 Teign Estuary Pilot Tests

A number of modelling tests were performed to investigate the effect of management interventions and sea-level rise on the Teign estuary. These were based on the Teign specific setup and all experiments were run from the steady state condition (Section 5.4.2, Table 49), unless otherwise stated.

Flood defence

Flood defences were imposed in the outer estuary (Table 50), inner estuary (Table 51) and both outer and inner estuary (Table 52). Outer flood defences cause the prism to be turned off at step 2. Ebb and flood deltas remain as in the undisturbed case. The outer estuary initially has flood dominance, but this switches to ebb dominance at step 5. Outer estuary waves and outer sandflats are lost at the completion of the evaluation to a new steady state. The inner estuary is unaffected by the outer flood defences.

Flood defences in the inner Teign estuary had less effect on the overall morphology of the estuary (Table 51). The outer estuary remains the same as the undisturbed case. In the inner estuary, inner marsh high and the inner reed bed are lost.

Table 50. Evolution of the Teign Estuary with Outer Flood Defences

1	2	3	4	5	6	Step
1	1	1	1	1	1	ocean_waves
1	1	1	1	1	1	longshore_power
1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	marine_sand
1	1	1	1	1	1	Mesotidal
1	1	1	1	1	1	updrift_beach
1	1	1	1	1	1	Spit
1	1	1	1	1	1	Inlet
1	1	1	1	1	1	downdrift_beach
1	1	1	1	1	1	Dunes
1	1	1	1	1	1	Wind
1	1	1	1	1	1	Seawall
1	0	0	0	0	0	Prism
1	1	1	1	1	1	ebb_delta
1	1	1	1	1	1	flood_delta
1	1	0	0	0	0	outer_flood_dominance
0	0	0	0	1	1	outer_ebb_dominance
1	1	1	1	1	1	outer_subtidal_sands
1	1	0	0	0	0	outer_estuarywaves
1	1	1	1	1	0	outer_sandflat
1	1	1	1	1	1	outer_flood_defence
0	1	1	1	1	1	outer_floodplain
1	1	1	1	1	1	inner_ebb_dominance
1	1	1	1	1	1	inner_subtidal_deposits
1	1	1	1	1	1	inner_sandflat
1	1	1	1	1	1	inner_mudflat
1	1	1	1	1	1	inner_marsh_low
1	1	1	1	1	1	inner_marsh_high
1	1	1	1	1	1	inner_reed_bed
1	1	1	1	1	1	river_discharge
1	1	1	1	1	1	river_sand
1	1	1	1	1	1	river_mud

Table 51. Evolution of the Teign Estuary with Inner Estuary Defences

1	2	3	4	5	6	Step
1	1	1	1	1	1	ocean_waves
1	1	1	1	1	1	longshore_power
1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	marine_sand
1	1	1	1	1	1	Mesotidal
1	1	1	1	1	1	updrift_beach
1	1	1	1	1	1	Spit
1	1	1	1	1	1	Inlet
1	1	1	1	1	1	downdrift_beach
1	1	1	1	1	1	Dunes
1	1	1	1	1	1	Wind
1	1	1	1	1	1	Seawall
1	1	1	1	1	1	Prism
1	1	1	1	1	1	ebb_delta
1	1	1	1	1	1	flood_delta
1	1	1	1	1	1	outer_flood_dominance
1	1	1	1	1	1	outer_subtidal_sands
1	1	1	1	1	1	outer_estuarywaves
1	1	1	1	1	1	outer_sandflat
1	1	1	1	1	1	inner_ebb_dominance
1	1	1	1	1	1	inner_subtidal_deposits
1	1	1	1	1	1	inner_sandflat
1	1	1	1	1	1	inner_mudflat
1	1	1	1	1	1	inner_marsh_low
1	1	1	1	1	0	inner_marsh_high
1	1	1	1	1	0	inner_reed_bed
1	1	1	1	1	1	inner_flood_defence
0	1	1	1	1	1	inner_floodplain
1	1	1	1	1	1	river_discharge
1	1	1	1	1	1	river_sand
1	1	1	1	1	1	river_mud

Table 52 shows the combined effects of inner and outer flood defences. Again, the main changes are in the outer estuary, and are similar to those described for outer flood defences only.

Table 52. Evolution of the Teign Estuary With Inner and Outer Flood Defences

1	2	3	4	5	6	Step
1	1	1	1	1	1	ocean_waves
1	1	1	1	1	1	longshore_power
1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	marine_sand
1	1	1	1	1	1	Mesotidal
1	1	1	1	1	1	updrift_beach
1	1	1	1	1	1	Spit
1	1	1	1	1	1	Inlet
1	1	1	1	1	1	downdrift_beach
1	1	1	1	1	1	Dunes
1	1	1	1	1	1	Wind
1	1	1	1	1	1	Seawall
1	0	0	0	0	0	Prism
1	1	1	1	1	1	ebb_delta
1	1	1	1	1	1	flood_delta
1	1	0	0	0	0	outer_flood_dominance
0	0	0	0	1	1	outer_ebb_dominance
1	1	1	1	1	1	outer_subtidal_sands
1	1	0	0	0	0	outer_estuarywaves
1	1	1	1	1	0	outer_sandflat
1	1	1	1	1	1	outer_flood_defence
0	1	1	1	1	1	outer_floodplain
1	1	1	1	1	1	inner_ebb_dominance
1	1	1	1	1	1	inner_subtidal_deposits
1	1	1	1	1	1	inner_sandflat
1	1	1	1	1	1	inner_mudflat
1	1	1	1	1	1	inner_marsh_low
1	1	1	1	1	0	inner_marsh_high
1	1	1	1	1	0	inner_reed_bed
1	1	1	1	1	1	inner_flood_defence
0	1	1	1	1	1	inner_floodplain
1	1	1	1	1	1	river_discharge
1	1	1	1	1	1	river_sand
1	1	1	1	1	1	river_mud

Dredging

The effect of dredging in the outer estuary (Table 53), inner estuary (Table 54) and both inner and outer estuary (Table 55) was simulated using the Teign-specific setup. The comments made in Section 4.2.5 regarding the representation of dredging in the present version of the simulator should be re-iterated here. The binary “all or nothing” nature of the model means that dredging is always represented as removing most of the subtidal deposit, and in general, this greatly over-emphasises the effects of dredging.

The predicted effects of outer dredging (Table 53) include increased accommodation space, loss of the ebb and flood deltas and loss of the outer subtidal sands. The inner estuary was unaffected. As mentioned in Section 5.4.2 there is some uncertainty in the interpretation of these results due to the problems of identifying the inner and outer sections of the Teign estuary.

With inner dredging only (Table 54), the evolution of the outer estuary is the same as for the undisturbed case. The downdrift beach, accommodation space, and flood and ebb deltas are unaffected by inner dredging. In the inner estuary, inner subtidal deposits are removed, however, the inner mud flats, marshes and reed beds remain.

Table 53. Evolution of the Teign Estuary with Outer Dredging

1	2	3	4	5	Step
1	1	1	1	1	ocean_waves
1	1	1	1	1	longshore_power
1	1	1	1	1	littoral_sand
1	1	1	1	1	marine_sand
1	1	1	1	1	Mesotidal
1	1	1	1	1	updrift_beach
1	1	1	1	1	Spit
1	1	1	1	1	Inlet
1	1	1	1	1	downdrift_beach
1	1	1	1	1	Dunes
1	1	1	1	1	Wind
1	1	1	1	1	Seawall
1	1	1	1	1	Prism
0	0	0	0	1	accomm_space
1	1	1	0	0	ebb_delta
1	1	1	0	0	flood_delta
1	1	1	1	1	outer_flood_dominance
1	1	1	0	0	outer_subtidal_sands
1	1	1	1	1	outer_estuarywaves
1	1	1	1	1	outer_sandflat
1	1	1	1	1	outer_dredging
1	1	1	1	1	inner_ebb_dominance
1	1	1	1	1	inner_subtidal_deposits
1	1	1	1	1	inner_sandflat
1	1	1	1	1	inner_mudflat
1	1	1	1	1	inner_marsh_low
1	1	1	1	1	inner_marsh_high
1	1	1	1	1	inner_reed_bed
1	1	1	1	1	river_discharge
1	1	1	1	1	river_sand
1	1	1	1	1	river_mud

Table 54. Evolution of the Teign with Inner Dredging

1	2	3	4	Step
1	1	1	1	ocean_waves
1	1	1	1	longshore_power
1	1	1	1	littoral_sand
1	1	1	1	marine_sand
1	1	1	1	Mesotidal
1	1	1	1	updrift_beach
1	1	1	1	Spit
1	1	1	1	Inlet
1	1	1	1	downdrift_beach
1	1	1	1	Dunes
1	1	1	1	Wind
1	1	1	1	Seawall
1	1	1	1	Prism
1	1	1	1	ebb_delta
1	1	1	1	flood_delta
1	1	1	1	outer_flood_dominance
1	1	1	1	outer_subtidal_sands
1	1	1	1	outer_estuarywaves
1	1	1	1	outer_sandflat
1	1	1	1	inner_ebb_dominance
1	1	1	0	inner_subtidal_deposits
1	1	1	1	inner_sandflat
1	1	1	1	inner_mudflat
1	1	1	1	inner_marsh_low
1	1	1	1	inner_marsh_high
1	1	1	1	inner_reed_bed
1	1	1	1	inner_dredging
1	1	1	1	river_discharge
1	1	1	1	river_sand
1	1	1	1	river_mud

Table 55 shows the evolution of the Teign estuary with both inner and outer estuary dredging. For the outer estuary, evolution is the same as for outer dredging only. Similarly, the inner estuary is the same as for inner estuary only.

Table 55. Evolution of the Teign Estuary With Inner Dredging and Outer Dredging

1	2	3	4	Step
1	1	1	1	ocean_waves
1	1	1	1	longshore_power
1	1	1	1	littoral_sand
1	1	1	1	marine_sand
1	1	1	1	Mesotidal
1	1	1	1	updrift_beach
1	1	1	1	Spit
1	1	1	1	Inlet
1	1	1	1	downdrift_beach
1	1	1	1	Dunes
1	1	1	1	Wind
1	1	1	1	Seawall
1	1	1	1	Prism
0	1	1	1	accomm_space
1	1	1	0	ebb_delta
1	1	1	0	flood_delta
1	1	1	1	outer_flood_dominance
1	1	1	0	outer_subtidal_sands
1	1	1	1	outer_estuarywaves
1	1	1	1	outer_sandflat
1	1	1	1	outer_dredging
1	1	1	1	inner_ebb_dominance
1	1	1	0	inner_subtidal_deposits
1	1	1	1	inner_sandflat
1	1	1	1	inner_mudflat
1	1	1	1	inner_marsh_low
1	1	1	1	inner_marsh_high
1	1	1	1	inner_reed_bed
1	1	1	1	inner_dredging
1	1	1	1	river_discharge
1	1	1	1	river_sand
1	1	1	1	river_mud

Realignment

This simulation uses the steady state conditions from simulation with inner and outer flood defences as the starting point (step 11, Table 52), and the defences are then removed to simulate realignment. Following the removal of flood defences, the simulator predicts that the Teign estuary would evolve in 7 steps towards a steady state morphology that is the same as the undisturbed morphology (Table 56).

Table 56. Evolution of the Teign Estuary From a Defended Steady State Following Removal Of Flood Defences

1	2	3	4	5	6	7	Step
1	1	1	1	1	1	1	Ocean_waves
1	1	1	1	1	1	1	longshore_power
1	1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	1	Marine_sand
1	1	1	1	1	1	1	mesotidal
1	1	1	1	1	1	1	Updrift_beach
1	1	1	1	1	1	1	Spit
1	1	1	1	1	1	1	Inlet
1	1	1	1	1	1	1	downdrift_beach
1	1	1	1	1	1	1	Dunes
1	1	1	1	1	1	1	Wind
1	1	1	1	1	1	1	seawall
0	1	1	1	1	1	1	Prism
0	0	1	1	1	1	0	accomm_space
1	1	1	1	1	1	1	ebb_delta
1	1	1	1	1	1	1	flood_delta
0	0	1	1	1	1	1	outer_flood_dominance
1	1	1	1	0	0	0	outer_ebb_dominance
0	0	0	0	0	1	1	outer_subtidal_sands
0	0	1	1	1	1	1	outer_estuarywaves
0	0	0	0	0	1	1	outer_sandflat
1	1	1	1	1	1	1	inner_ebb_dominance
1	1	1	1	1	1	1	inner_subtidal_deposits
1	1	1	1	1	1	1	inner_sandflat
1	1	1	1	1	1	1	inner_mudflat
1	1	1	1	1	1	1	inner_marsh_low
0	0	0	0	0	1	1	inner_marsh_high
0	0	0	0	0	1	1	inner_reed_bed
1	1	1	1	1	1	1	river_discharge
1	1	1	1	1	1	1	river_sand
1	1	1	1	1	1	1	river_mud

Groynes

The effect of groynes on the updrift coast was investigated by adding groynes to the Teign specific steady state conditions. Table 57 shows that there is no response to adding groynes in the absence of additional forcing.

Table 57. Evolution of the Teign Estuary from Steady State Following the Addition of Groynes on the Updrift Coast

1	2	Step
1	1	ocean_waves
1	1	longshore_power
1	1	littoral_sand
1	1	marine_sand
1	1	mesotidal
1	1	updrift_beach
1	1	spit
1	1	inlet
1	1	downdrift_beach
1	1	dunes
1	1	wind
1	1	groynes
1	1	seawall
1	1	hold_the_line
1	1	prism
1	1	ebb_delta
1	1	flood_delta
1	1	outer_flood_dominance
1	1	outer_subtidal_sands
1	1	outer_estuarywaves
1	1	outer_sandflat
1	1	inner_ebb_dominance
1	1	inner_subtidal_deposits
1	1	inner_sandflat
1	1	inner_mudflat
1	1	inner_marsh_low
1	1	inner_marsh_high
1	1	inner_reed_bed
1	1	river_discharge
1	1	river_sand
1	1	river_mud

Table 58 shows the evolution of the Teign from steady state following the addition of groynes under conditions of accelerated sea-level rise and a hold the line policy.

In response to the presence of groynes and accelerated sea level rise, the updrift beach and spit are lost, followed by the downdrift beach and dunes. Ocean waves now penetrate the estuary resulting in outer estuary swell. The behaviour of the inner marsh becomes cyclic.

Table 58. **Evolution of the Teign Estuary from Steady State Following the Addition of Groynes on the Updrift Coast Under the Influence of Sea Level Rise (13-18 Shows Cyclical Behaviour)**

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Step
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	ocean_waves
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	longshore_power
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	marine_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	mesotidal
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	slr
1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	updrift_beach
1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	spit
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inlet
1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	downdrift_beach
1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	dunes
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	wind
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	groynes
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	seawall
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	hold_the_line
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	prism
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	ebb_delta
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	flood_delta
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_flood_dominance
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_subtidal_sands
0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_estuary_swell
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_estuarywaves
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_sandflat
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_ebb_dominance
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_subtidal_deposits
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_sandflat
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_mudflat
1	1	1	0	0	0	1	1	1	0	0	0	1	1	1	0	0	0	inner_marsh_low
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_marsh_high
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_reed_bed
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	river_discharge
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	river_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	river_mud

Sea level rise

Table 59 shows the predicted evolution of the Teign Estuary under accelerated sea-level rise with a 'hold the line' strategy. Under this condition, the seawall is maintained and no beaches or spits form. Running the same simulation from the Teign specific steady state starting configuration leads to the deterioration of the beaches, spit and dunes if 'hold the line' is selected (Table 60). These results suggest that eventual loss of the beach and spit can be expected if seawalls or groynes are used to permanently 'hold the line' on the updrift coast.

Table 59. Evolution of the Teign Estuary Under Sea Level Rise with ‘Hold the Line’ Policy

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Step
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	ocean_waves
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	longshore_power
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	marine_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	mesotidal
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	slr
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inlet
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	wind
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	seawall
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	hold_the_line
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	prism
1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	accomm_space
0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	ebb_delta
0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	flood_delta
0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_flood_dominance
0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	outer_subtidal_sands
0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_estuary_swell
0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_estuarywaves
0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	outer_sandflat
0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_ebb_dominance
0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_subtidal_deposits
0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	inner_estuarywaves
0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	inner_sandflat
0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_mudflat
0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	inner_marsh_low
0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	inner_marsh_high
0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	inner_reed_bed
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	river_discharge
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	river_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	river_mud

Table 60. Evolution of Teign Estuary From Steady State Under Accelerated Sea Level Rise With a ‘Hold the Line’ Policy

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Step
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	ocean_waves
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	longshore_power
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	marine_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	mesotidal
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	slr
1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	updrift_beach
1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	spit
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inlet
1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	downdrift_beach
1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	dunes
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	wind
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	seawall
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	hold_the_line
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	prism
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	ebb_delta
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	flood_delta
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_flood_dominance
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_subtidal_sands
0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	outer_estuary_swell
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_estuarywaves
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_sandflat
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_ebb_dominance
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_subtidal_deposits
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_sandflat
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_mudflat
1	1	1	0	0	0	1	1	1	0	0	0	1	1	1	0	0	0	inner_marsh_low
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_marsh_high
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_reed_bed
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	river_discharge
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	river_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	river_mud

If ‘hold the line’ is not selected, sea defences break down under accelerated sea level rise, restoring natural processes (Table 61). Following the breakdown of the seawalls, updrift beach, spit, downdrift beaches and dunes form. The final morphology is similar to the undisturbed Teign-specific case, except that inner marsh low now shows cyclic behaviour.

Table 61. Predicted Evolution of the Teign From Steady State Under Rapid Sea Level Rise Without Hold the Line Policy

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	Step
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	ocean_waves
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	longshore_power
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	littoral_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	marine_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	mesotidal
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	Slr
1	1	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	updrift_beach
1	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1	1	Spit
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	Inlet
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	downdrift_beach
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	dunes
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	Wind
1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	seawall
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	prism
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	Ebb_delta
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	flood_delta
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_flood_dominance
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_subtidal_sands
0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	outer_estuary_swell
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_estuarywaves
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	outer_sandflat
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_ebb_dominance
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_subtidal_deposits
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_sandflat
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_mudflat
1	1	1	0	0	0	1	1	1	0	0	0	1	1	1	0	0	0	1	inner_marsh_low
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_marsh_high
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	inner_reed_bed
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	River_discharge
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	River_sand
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	River_mud

6. Capabilities and Limitations

6.1 Introduction

Research within the development phase of the Prototype Simulator (reported in Section 4) and the pilot testing undertaken (reported in Section 5) has allowed assessment of the key capabilities and limitations of the approach. These are discussed in detail within this section.

Firstly, a discussion is provided of the emerging strengths and weaknesses of the Boolean network approach. The capabilities and limitations emerging from the pilot testing are then discussed under a number of specific headings. This section then concludes with a series of overall statements drawing out some of the key points regarding the applicability of the prototype simulator.

6.1.1 Project Context

This section draws together the experience gained during various stages of the overall project to provide assessment and guidance regarding the applicability of the prototype simulator. Specifically in the context of the project, the capabilities and limitations of the approach presented here draw on those determined within Objectives 5 and 7 (‘System Simulation’ and ‘Pilot Testing’ respectively) and presented within Project Reports 4 (French & Burningham, 2007) and 7 (Rossington *et al*, 2007).

6.2 Strengths and Weaknesses of Network Models Formulated Using Boolean Functions

A major advantage of network-based models is that they allow inferences concerning the behaviour of large and complex geomorphic systems that can be reasonably well defined in terms of a set of components, but which remain ill defined in terms of the mechanistic interactions between these components. This is very much in accordance with the arguments advanced by Capobianco *et al.* (1999). However, the Qualitative Reasoning (QR) methodologies that they advocate depend on rigorous analysis of the feedbacks (or ‘causal loops’) in a system and this demands considerable expertise in quantitative as well as qualitative modelling (e.g. Wolstenholme, 1999). In contrast, a Boolean approach makes few assumptions about the underlying system behaviour and only requires the modeller to have sufficient experience to translate geomorphological understanding into a series of logical functions. Aspects of system behaviour are computed directly from the Boolean expressions using any numerical computation software or programming language that supports the small set of standard logical operators. The emphasis is placed very firmly on the formalisation of qualitative knowledge through system and influence diagrams, and the consensus (or otherwise) amongst experts regarding the translation of the latter into functional form. A Boolean network model thus provides a good basis for comparative evaluation of alternative conceptual models and for identifying aspects of system behaviour that are sensitive to differences in interpretation or scientific opinion.

Like all modelling methodologies, the Boolean network approach also has its limitations. Some of the consequences of adopting a discrete binary logic have been touched upon in section 4.2 of this report. In particular, the assumption that a threshold can be applied to the influences between system variables to yield meaningful binary states, and that these influences act together with a similar weight and in synchrony, is clearly restrictive and sometimes difficult to justify in terms of what is known of the underlying physical or biological processes. The introduction of decay terms for morphological components is shown here to yield more realistic evolutionary behaviour.

Conversion of qualitative geomorphological understanding into Boolean function form can also be problematic. The functions chosen must be complex enough to accommodate a worthwhile range of system behaviours, yet they must also be consistent in their implementation in order that the predicted behaviour constitutes an emergent property of the system, rather than a consequence of logical inconsistency in some of its defining functions. For interactions of a few components, recourse can be made to the logical truth table or binary decision tree and potentially undesirable behaviour identified at the level of the individual function. Larger variable sets bring the potential for more complex functions, however, and the resulting truth tables may be quite large (recalling that there will be 2^N potential states where N is the number of components). Techniques such as ordering of the variables, deletion of redundant nodes and sharing of equivalent sub-graphs can help here. However, there is likely to be a trade-off between the complexity with which we define a system in terms of a finite set of components and the tractability of defining a logically consistent set of constituent functions. Further experimentation would be required to find this optimum.

6.3 Assessment of Capabilities of Prototype Simulator

The Prototype Simulator is assessed in the following sub-sections according to a series of topics, which largely draw upon the Pilot Testing undertaken on the Thames and Teign estuaries.

- Overall performance and Emergent Properties;
- Assessing Sensitivities to Change;
- Determining Constraints upon Estuary Evolution;
- Evaluating Quantitative Models.

A major benefit of the Prototype Simulator is that it is straightforward to use from the MATLAB code with the generic estuary definitions and existing rule-based function library. As part of the pilot testing study (section 5) application of the code to the Thames and Teign is investigated. In general, minor modifications to the generic estuary definitions allow the observed features of the Thames and Teign estuaries to emerge. For the Thames, this requires changes to the generic funnel-shaped estuary specification, and an addition and modification to the function libraries to reproduce the observed morphologies. These changes in the code are relatively simple to make but require a good understanding of estuary processes and morphology. With these modifications, the simulation produces a morphology that represents the Thames reasonably well.

For the Teign, changes are limited to minor alterations to the estuary specification to make it case-specific. In general, the results are satisfactory with morphologies resembling those found in the results; however the simulator predicts outer flood dominance for the Teign, whilst ebb dominance (at least in terms of peak velocity) is the observed behaviour (ABP, 2002).

The use of Boolean logic (1 or 0) to define the relationships within the estuary system means that morphologies and processes are represented as either being “on” or “off” (or “lots” or “little” depending on interpretation). This can make it difficult to decide whether a particular feature or process should be 1 or 0 in the model, as there may be “some” present. For example, the Thames estuary has some outer sea defences, but including these sea defences in the model caused other effects which in turn lead to morphologies that are not seen to develop in the real system. This problem could be overcome with an increase in the model complexity.

It is clear from the testing that as processes and morphological features are represented either as “on” or “off”, the user needs to be clear on what the processes/morphologies are and when they should be on/off (i.e. to look at the results in the context of experience and observations of a particular estuary) in order to interpret the results correctly. In the present study this is assessed largely by trial and error and the interpretation of the Simulator performance requires a high level of expert knowledge to know what the expected outcomes should be and how these differ from the Simulator assessment. Therefore the initial stages of the Simulator application are similar to any modelling exercise, namely that performance is validated against data for the system in question and parameters and coefficients are tuned to obtain the required level of confidence in applying the Simulator to answer specific questions about the system function.

A number of the logical relationships within the Prototype Simulator, as it currently stands, appear to require modification. This report has not sought to modify these aspects unless absolutely necessary (as in Section 5), so that the results are as objective as possible. However, the logical relationships in question can result in a misunderstanding of the relevance of the results predicted by the model. These issues are not a criticism of the method but an acknowledgement that the development of this type of model is an ongoing process. Prior to “off-the-shelf” use the following aspects require consideration:

- The negative feedback that some elements, in particular saltmarsh elements, have on themselves appears to be the cause of the cyclical behaviour observed in sections 4 and 5.

- The way that waves are characterised in the inner estuary means that the presence of saltmarsh can switch off the effect of waves on mud and sand flats. Although the reverse is reasonable as the presence of extensive mud and sandflats should be able to switch off wave action on saltmarsh, since saltmarsh is by definition “behind” the mud and sandflats it should not be able to switch off wave action from these elements.

- With the code as it stands it is possible for the estuary to be both ebb dominant and flood dominant at the same time and for the estuary to be both micro-tidal and meso-tidal as a response to a tidal barrage.

The Prototype Simulator can be used to determine emergent properties of an estuary system through representation of characteristic and broad-scale behaviour. It is also able to capture behaviour at the level of sub-systems, presently defined as the outer estuary, inner estuary and coastal regions.

6.3.1 Assessing Sensitivities to Change

The Prototype Simulator is able to describe an evolutionary path for the estuary given the present rule-base and associated function library. It can indicate whether the system displays monotonic or cyclical behaviour, as moderated by the lag/decay term in the code. However, it is not able to determine the sensitivities of an estuary system to change. This is partly due to its binary nature, which, as discussed above, is not a sensitive method to describe an estuary.

In some cases the Simulator predicts the estuary system to be insensitive to particular changes in forcing, for example accelerated sea level rise in the Thames and addition of updrift groynes in the Teign both have no impact on the estuary configuration. In reality, these changes are likely to cause responses within the system. In others, the Simulator predicts the estuary to be highly sensitive to changes. For example, the addition of flood defences in the outer estuary causes large-scale changes in both processes and morphology. Changes caused by adding outer defences in the Thames estuary led to removal of tidal prism, a switch from flood to ebb dominance and development of outer mudflats and saltmarsh. In the Teign, the response to outer flood defences was slightly different; the loss of tidal prism and switch to ebb-dominance was similar to in the Thames, but intertidal sandflats were also lost.

6.3.2 Determining Constraints on Estuary Evolution

The Prototype Simulator may have some capability to determine the system response to constraints on estuary evolution. The constraints are specified by the user, in terms of forcing such as waves, sediment supply, fluvial effects and management policies and in terms of geological constraints such as the presence of bedrock and fluvial channels. From these specifications the simulator can predict what morphologies will develop based on the constraints supplied by the user and therefore gives some indication as to what constrains the development of certain features.

Some of the constraints are implemented at a broad level in the present version of the Simulator; for example, management policies apply equally to the inner, outer and coastal sub-systems.

6.3.3 Evaluating Quantitative Models

The ability of the Prototype Simulator to provide an exploratory tool for examining broad-scale estuary evolution for evaluating quantitative models is uncertain. Whilst the Simulator captures general features of estuary evolution, it lacks sensitivity and the “all or nothing” binary approach may make it an unsuitable basis for evaluating quantitative models. The Simulator provides a reasonable guide to the direction of change of the estuary system following a change in forcing, but it does not capture the complexities of real estuary systems. In fact a major strength of the Simulator is its simplicity but this means that it cannot determine whether the associated change resulting from intervention is negligible or considerable. In addition, the estuary evolution is modelled as a series of steps but these are not linked to any real time scales, which makes it difficult to make comparisons with quantitative models.

6.3.4 Other Remarks

From the pilot testing described, it is apparent that the Prototype Simulator can be used to evaluate generic estuary behaviour and can capture the emergent properties of specific estuary systems. The latter requires prior knowledge of the geomorphology and processes likely to be important in the system being considered. Exploratory modelling using the Simulator enables the results to be evaluated against what is already known about that specific system, and the Simulator can be refined until it captures the essential elements.

The simplicity of the Prototype Simulator is attractive. It combines multiple complex (subjective) geomorphological concepts and is quick to run; both of these aspects are major advantages. The Simulator is therefore able to provide a resource for development of a conceptual model of a specific estuary or estuaries in general. As such it could prove beneficial as both an educational tool, in terms of disseminating the concepts of the systems based approach and as a geomorphological resource to guide the conceptual development of modelling studies. However, it is considered that the present version of the Simulator will require some alterations to the code and an enhancement of the general level of complexity. In addition, more extensive testing with specific estuary setups is necessary to determine the range of behaviours that may be experienced.

As with any model, the Prototype Simulator requires good/expert knowledge of estuary morphology both to set it up for specific estuaries and to interpret the results. This limits the range of users that can apply it in estuary studies. As with the output of any modelling exercise it is necessary to verify the output state in context and against observations or objective judgments.

6.4 Summary of Capabilities and Limitations

From the assessment and discussion provided in the preceding sections a series of concluding statements are made below regarding the capabilities and limitations of the Prototype Simulator.

- The Simulator can be used to explore the behaviour of generic UK estuaries based on a set of rule-based functions. Also, in general, the Simulator was able to reproduce the observed features of two UK estuaries (the Thames and Teign) following specific modifications to the generic estuary specifications and small changes to the code. It is quite likely that other interpretations are possible and may be required for specific purposes.

- In some cases the Simulator was not able to determine sensitivities of the estuary system to change due to its “all or nothing” binary approach. Some processes unexpectedly caused no changes, while others prompted large changes. The pilot testing identified a number of shortcomings with the existing model, which means that further improvement, possibly including increased complexity, and validation of the Simulator is required.

- The Simulator was found to have some capability to determine the system response to constraints on the evolution of estuaries. In order to investigate the system response in these conditions, prior knowledge of estuary morphology and functioning is needed as well as prior knowledge of the constraints, such as the influence of geology and variations in the erodibility of the bed.

- The Simulator may be useful for evaluating quantitative models by providing information on the direction of change. The Simulator is capable of predicting an evolutionary path but the “all or nothing” binary approach and inherent lack of time scale makes comparison difficult. The Simulator outputs require expert knowledge to interpret them and as with all studies, confidence in results comes from the application of a number of relevant tools.

- The Simulator performs well in some areas, and less well in others, and hence it requires more effort and expertise to exploit the potential benefits. In our opinion, in isolation the Simulator in its present form is not a suitable tool for evaluating estuary management options. This is because of the inability of the Simulator to distinguish between large and minor effects, which is a result of the Boolean architecture. This makes it inappropriate for use as the only source of information with which to inform decisions regarding regulation and development.

- The Simulator could provide benefits as both an educational tool and as a geomorphological resource to guide the conceptual development of modelling studies. However, it requires some knowledge of estuary morphology, both to set up the Simulator for specific estuaries and to interpret the results, which places a constraint on its use. In order to realise the potential of the Simulator the complexity needs to be extended further and extensive testing for a wider range of specific estuaries is necessary to determine the behaviours that may be present in real estuaries.

7. The Prototype Simulator Interface

7.1 Introduction

This section documents the development of a web-based interface to host the prototype simulator. A review of the advantages and disadvantages of a number of alterative architectures to host the Prototype Simulator are presented in Section 7.2, along with details of the selection of an approach for development. An overview is provided of the development of the Interface in Section 7.3. In addition to the Interface developed, a 'Research Code web page' has also been developed, to provide researchers with access to the underlying Prototype Simulator MATLAB code (See Section 7.4).

7.1.1 Project Context

During the further development of the Boolean Approach within the System Simulation Objective, a review was undertaken to evaluate the various options to develop an architecture for the Prototype Simulator within the Manager-System Interface Objective. The outputs of the review were carried into the Manager-System interface Objective and a preferred option was selected for development.

Initially, the Manager-System Interface Objective was intended to investigate a selection of visualisation tools to assess their suitability for use alongside the simulator. In practice, the work completed in this objective has exceeded this requirement through the development of a preferred option. In addition to providing access to the Prototype Simulator, the interface also facilitates knowledge exchange regarding the wider application of a systems based approach to estuaries and the developments within the EstSim project. Alongside this, the 'Research Code web page' ensures full open access to the Prototype Simulator code. Developments within the Manager System Interface are reported within Project Report 6 (Morris, 2007).

7.2 Review of Alternative Architectures for Prototype Simulator

Implementation of a fully featured web-interfaced estuary behavioural system simulation package is beyond the immediate scope of EstSim. However, it has been possible to produce prototype software that provides valuable R&D experience (including proof of concept testing and evaluation of system conceptualisation) as well as dissemination of the behavioural systems concept.

Alternative architectures for an EstSim tool were envisaged based around combinations of functionality and delivery. In terms of *functionality*, simulation of estuary system behaviour could take the form of interactive selection from a fixed set of scenarios interfaced to pre-computed model outcomes, whereas the ability for the user to define custom scenarios and/or system structures would require on-demand computation and a more fully featured software tool. The highest level of functionality would also allow 'research-level' uses, such as exploration of a system's state variable space, to analyse more specific aspects of its behaviour.

There is, likewise, a range of options for *delivery*. These include distribution of a standalone software application (either on CD or via the World Wide Web); implementation of a web-based decision support system; or implementation of a more sophisticated web-based decision support and analysis tool interfaced to server-side computation facilities, which could support a full spectrum of interactive analyses into system behaviour.

Variations on these options are also possible including a web-based decision support system, which could be supplemented by downloadable tools and/or customisable models (either standalone or compatible with one of the leading proprietary system simulation packages).

A review has been undertaken to explore the relative merits of these different options and inform the decision as to which development option is most appropriate. This review is documented in the following sub-sections:

7.2.1 Approach 1: Web-Based Estuary Simulator and Prototype Decision Support System

A model for this is ABPmer's online Estuary Guide (www.estuary-guide.net), which is currently being further developed in Defra/Environment Agency R&D Project FD2119. This essentially constitutes a web-linked interactive database with no computational capability that could support editable system diagrams or user-specified scenarios. However, it represents a valuable demonstration and proof of concept tool.

7.2.2 Approach 2: A Web-Based Estuary Simulator with Server-Side Computational Capabilities

This approach is similar to Approach 1 but with the added functionality of:

- Server-based computation of user-specific scenarios, possibly with support for customisation of estuary system diagrams to allow investigation of management questions for particular estuaries.

The intention of this option is to produce a powerful web-based application that is a valuable addition to the existing suite of estuary modelling and management tools being developed under ERP. The simplest and least expensive approach would use a proprietary scripting language (such as Adobe Flash) or a high-level programming language (such as Java) to develop a custom processing engine. More complex and expensive implementations might use a heavyweight simulation package such as PowerSim or a webMathematica server. However, in all these cases the development effort required to produce a polished product would be considerable, and therefore this option did not initially seem feasible.

7.2.3 Approach 3: Standalone Estuary Simulator

An EstSim tool of this kind could comprise:

- A pre-compiled simulator developed using either a specialist system simulation package (e.g. Stella) or a compiled GUI-tool developed using a numerical computation package (e.g. MATLAB).

- The inclusion of pre-defined system diagrams and a set of pre-defined scenarios that would also allows the user to specify custom system diagrams or scenarios through external (open-format) run control or steering files.

- A more sophisticated implementation could include simple graphical tools or dialogue boxes for customising system diagrams and scenarios, although this would involve considerable software development effort that is beyond the scope.

- A supporting web site is developed from which the tool could be downloaded as freeware, together with model files for all UK generic estuary types. Parallel distribution on CD would be possible.

This might produce a very usable product, with a simple GUI-based tool developed in MATLAB probably offering greater ease of use than a pre-packaged Stella-type model (which would require users to learn how to use what is still quite a complex piece of application software). In the case of a tool built using MATLAB (or similar), it is possible to maintain some of the research-level functionality for R&D into generic properties of system behaviour; although this could be de-activated in a version distributed amongst a broader user community.

7.2.4 Approach 4: A Semi-Standalone Estuary Simulator

A variation on the above architecture might involve:

- A set of pre-defined model files (system diagrams, datasets and run control files) for application with a freeware or low-cost run time version of a proprietary system simulator (e.g. Simile, Stella).

- A supporting web site from which the model files are downloaded as freeware, with links to freeware versions of required simulation package. Parallel distribution on CD might be possible although there are licensing issues associated with the re-distribution of third party products, even where these are available at no cost from the vendor.

This is the least satisfactory of the above options, in that it ties the simulator to a specific proprietary package on which the majority of users would require training.

7.2.5 Selection of a Preferred Option for Implementation

The initial review recommended that a combination of approaches 1 and 3 is the most fruitful and achievable within EstSim. However, the review also concluded that in the longer term, and given sufficient resources, approach 2 is more beneficial. It was noted that in the future, this approach could be used to bring together different strands of qualitative modelling embracing geomorphology, hydrology, ecosystem dynamics, and socio-economics. Such a simulator could also form an important component of the Estuary Management System (EMS) that is being specified under DEFRA Project FD2119.

After reviewing the various options, timescales and assessing the end users of the system, an interface based on approach 2 has been developed and this development is documented in the following section.

7.3 Development of the EstSim Interface

7.3.1 Overview

The preferred option enables access to and exploration of the model by anyone with access to the World Wide Web. It is therefore open to all types of end users including estuary managers, government institutions, research establishments, educational facilities and indeed, the general public. The interface was developed using Macromedia Flash, for which there is a free, downloadable player available to anyone on the web. There is therefore no cost associated with using or viewing the prototype simulator via the EstSim interface.

Using Flash to provide the interface for the EstSim prototype simulator also presents a means of incorporating other data on the web site. The design of the interface therefore includes:

- An introduction to the EstSim project;
- A description of how estuaries can be classified;
- A description of geomorphic types;
- Access to the estuaries database;
- A description of the EstSim Simulator approach; and
- Access to and control of the EstSim Simulator in terms of:
    a. Running generic estuary models;
    b. Creating and running customised estuary simulations;
    c. Running simulations from two study areas.

This approach therefore also overall allows for dissemination and knowledge transfer to estuary managers regarding the system approach in line with the overall objective of the project.

7.3.2 Interface Development

Technically, the interface has been developed using a combination of Flash, Javascript, Active Server Pages and a MySQL server database. The communication between each element is shown in Figure 30.

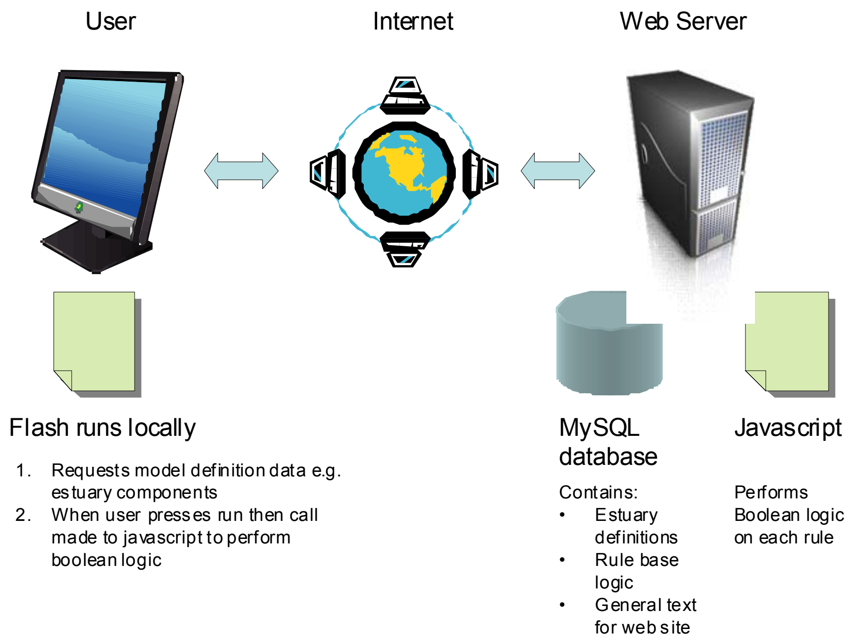


Figure 30. Communication setup

Figure 31. The main screen of the interface

Figure 31 shows the start up screen of the interface to the EstSim Simulator tool, and is accessed via:

http://www.discoverysoftware.co.uk/EstSim/EstSim.html.

The interface has a number of menu buttons (on the left) and circular buttons (in the centre) that allow access to different parts of the system. For instance, by clicking on the Introduction button the interface will show text which provides an introduction to the project (Figure 32).

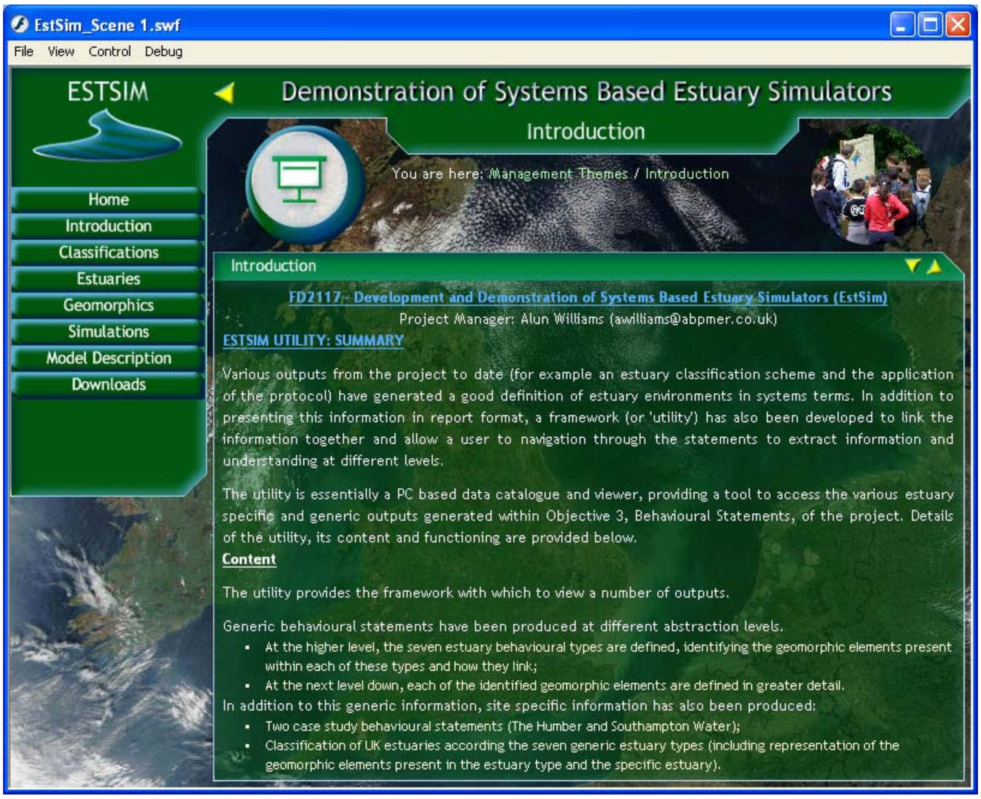


Figure 32. **An introduction to the EstSim project**

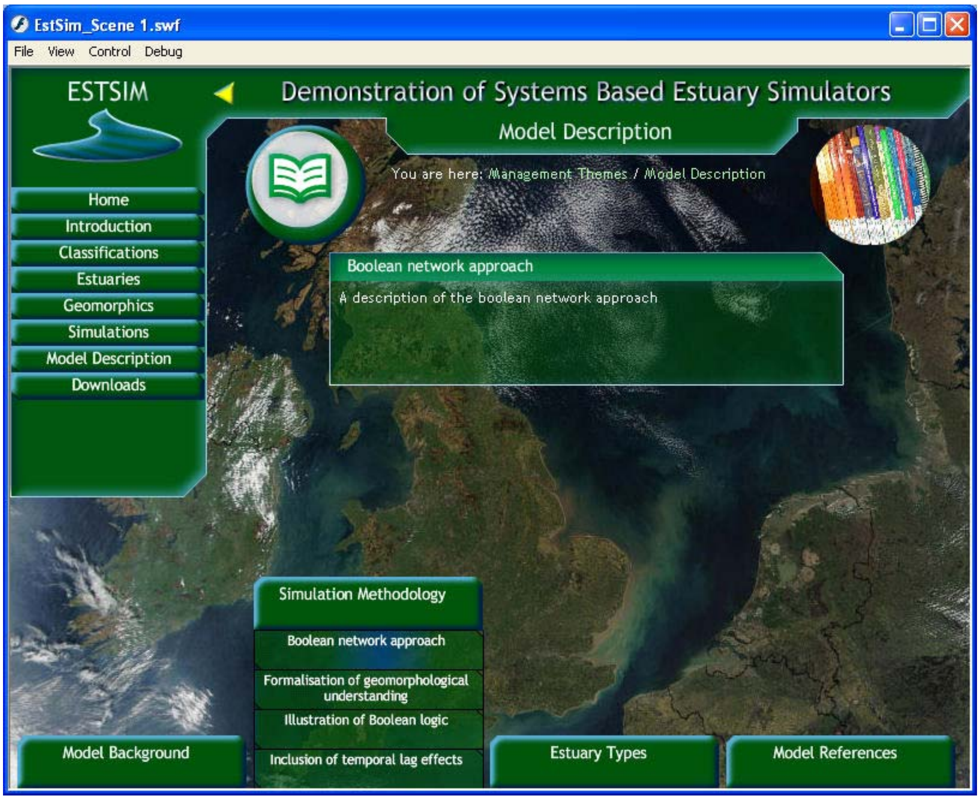


Figure 33. Further information is available via tabs and vertical menus

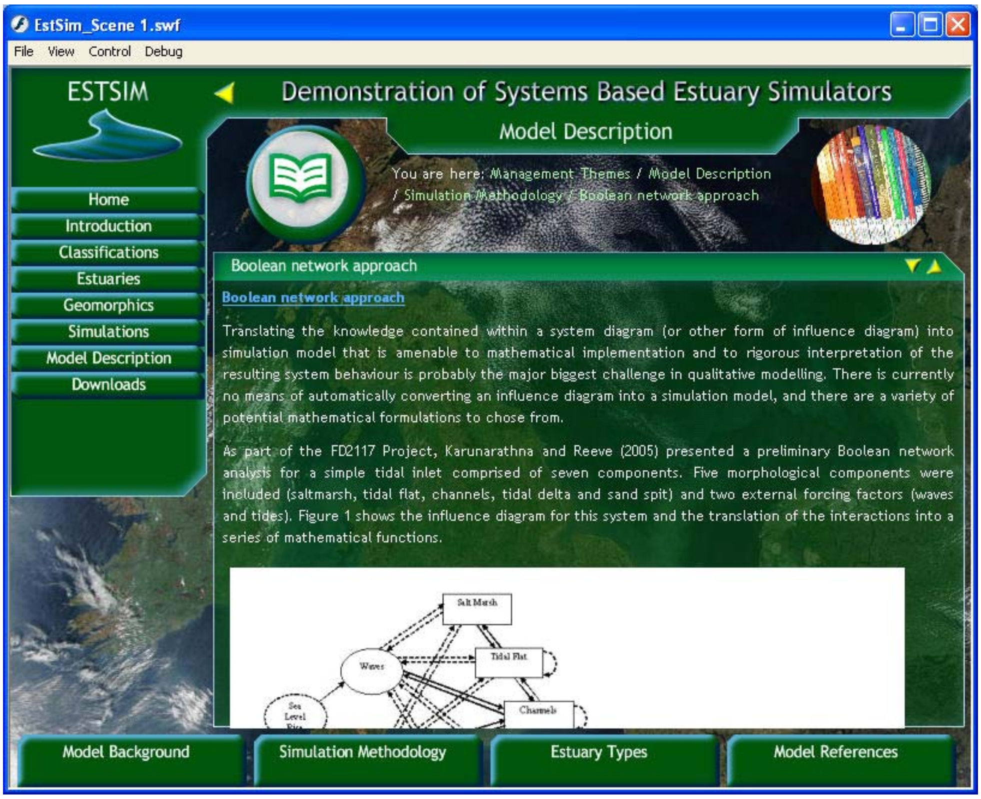


Figure 34. After clicking on a topic further information is displayed

Other buttons including the Classifications, Geomorphics, and Model Description buttons provide more detailed descriptions that can be further investigated using a series of tabs and vertical menus (see Figure 33). Clicking on a topic in these menus provides more detailed information (Figure 34).

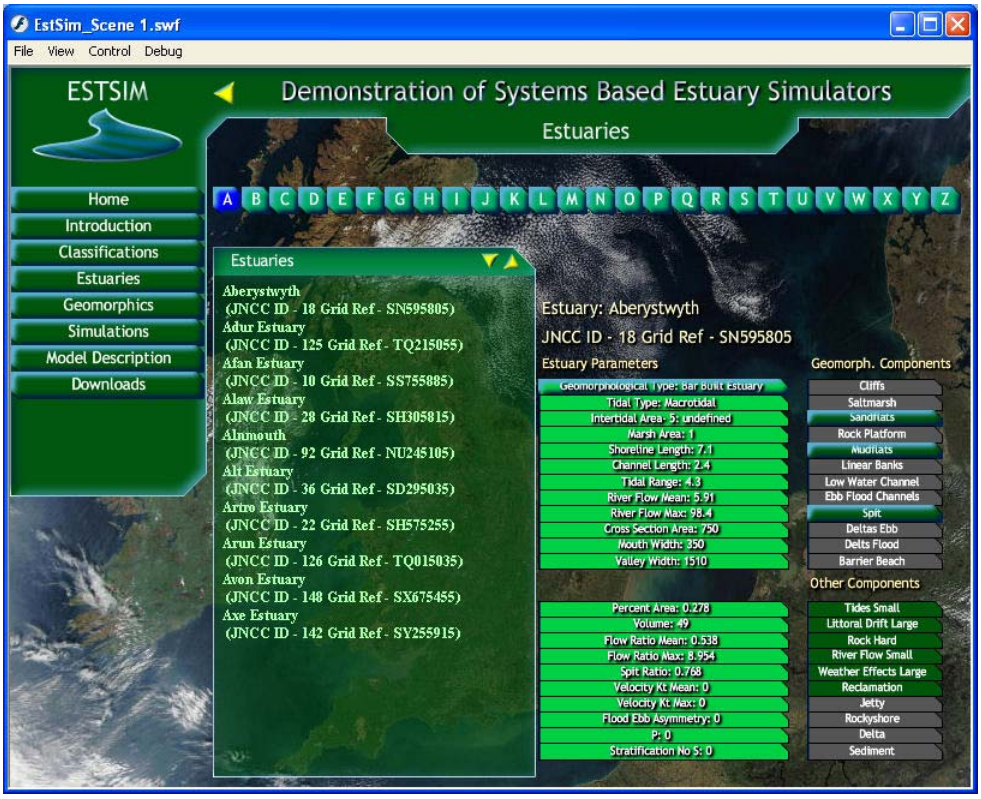


Figure 35. Estuary information from the UK Estuaries Database

The Estuaries buttons link to information in the UK Estuaries database, in which estuaries are listed alphabetically; different estuaries can be selected by clicking on the appropriate letter, and then the estuary of choice. Figure 35 shows details for Aberystwyth estuary. Menu items with a 3D appearance can be clicked on to find out more information about certain geomorphic types/elements or to proceed to a model for that estuary type.

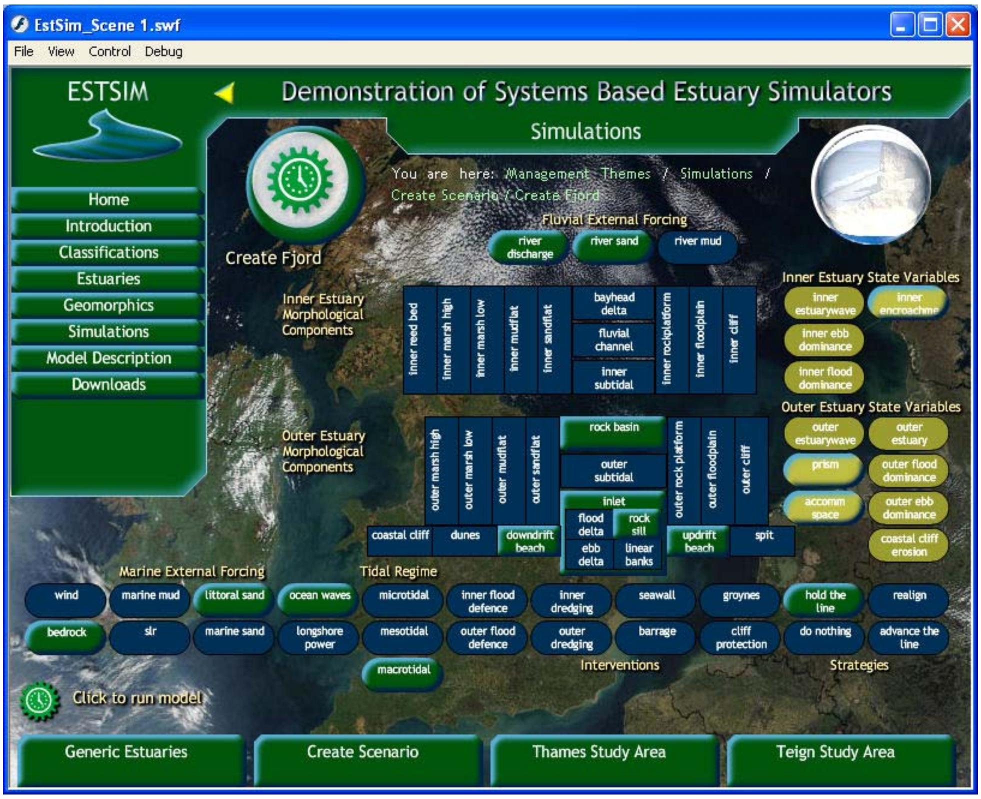


Figure 36. Creating a new scenario based on a generic fjord

Clicking on Simulations will take the user to the Prototype Simulator. The four tabs provide access to generic estuaries, creating a scenario of the user's choice or to scenarios relating to the two pilot test areas, the Thames and Teign. Figure 36 shows the interface for creating a new scenario based on a generic fjord.

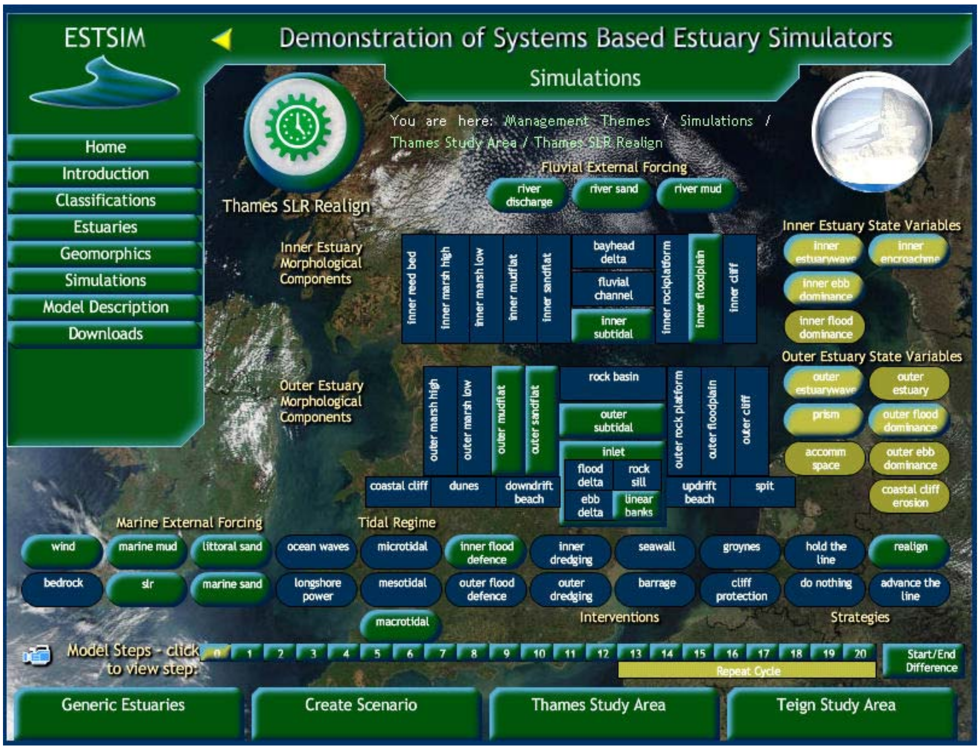


Figure 37. Illustrating the step bar, which gives access to the model results

The interface shows different elements of the estuary grouped by fluvial, inner and outer estuary, and coastal/marine systems. There are also options to specify interventions and strategies. The green 3D buttons show those elements that are present in a generic fjord, and the user can turn these off or on by clicking on them. Once the user has defined their estuary they can run the model by clicking on the clock icon (lower left). Once the model has run, the results are displayed within the same interface. A model step bar appears below the estuary elements showing each step in the model. Figure 37 shows 21 steps where steps 13-20 are repeated.

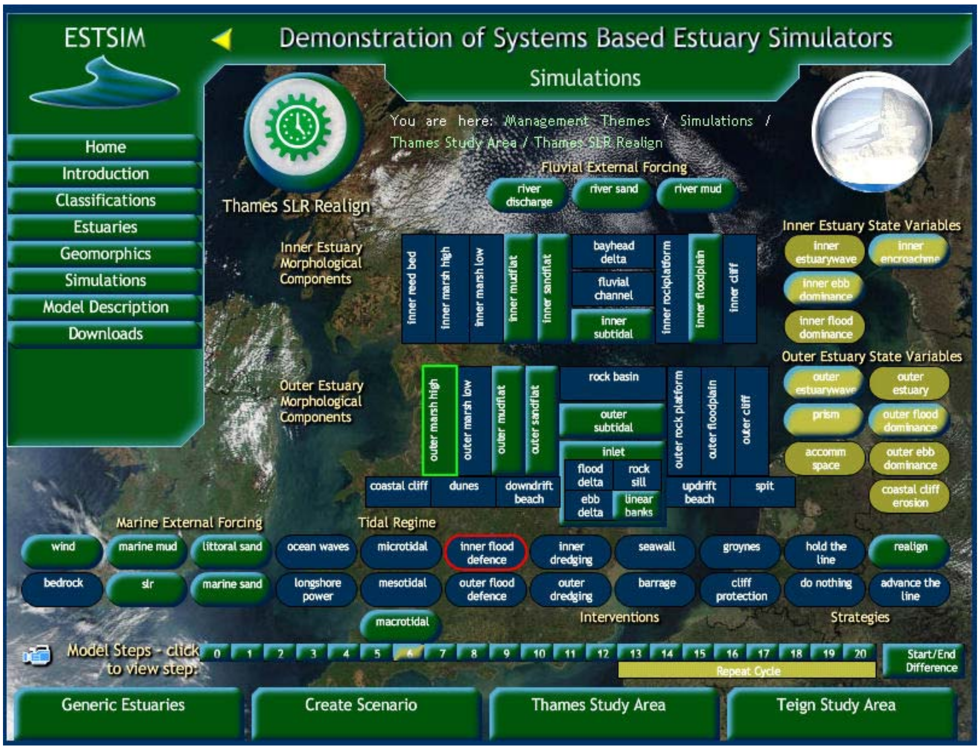


Figure 38. Illustrating the results at one step in the model

Any step can be displayed by clicking on the appropriate number in the model step bar, at any time during the simulation. Figure 38 shows the results for one particular step in the model results. Those elements that are highlighted in 3D are currently switched on; those that have a green border (i.e. outer marsh high) were previously off but are now on, whilst those with red borders (i.e. inner flood defence) were previously on but are now off.

The user may also click on the Start/End Difference button to summarise what estuary/coast elements have been switched on or off during the entire run. Finally, the user may animate the whole model run by clicking on the Camera icon (lower left).

7.4 Development of the 'Research Code web page'

In addition to the EstSim interface outlined above, the project has also developed a research code web site. The intention is to make the MATLAB code that has been developed to implement the Prototype Simulator, available to the research community for future evaluation and development, where researchers are able to download the Prototype Simulator code and make their own changes in MATLAB.

The Prototype Simulator code has been implemented in MATLAB and presently supports:

- Representation of estuary system influence diagrams for the generic estuary types presented in Section 3, using standardised sets of variables and Boolean functions.
- Initial condition-based simulation of system evolutionary trajectories.
- State variable space simulation, based on either analysis of all possible states (small N systems) or statistical sampling of these states (large N systems), that can be used to identify and classify equilibrium states, and derive various measures of system complexity.

As an alternative to modifying the code, an interactive interface to the Simulator code has been developed using MATLAB's built-in GUI tools. This provides file selection dialog boxes, access to various run control parameters, the ability to switch between scenario and state-space analysis, and the display of model results. Figure 39 illustrates a layout for a version of the GUI and its relation to underlying model code, the Boolean function library and a set of estuary definition files.

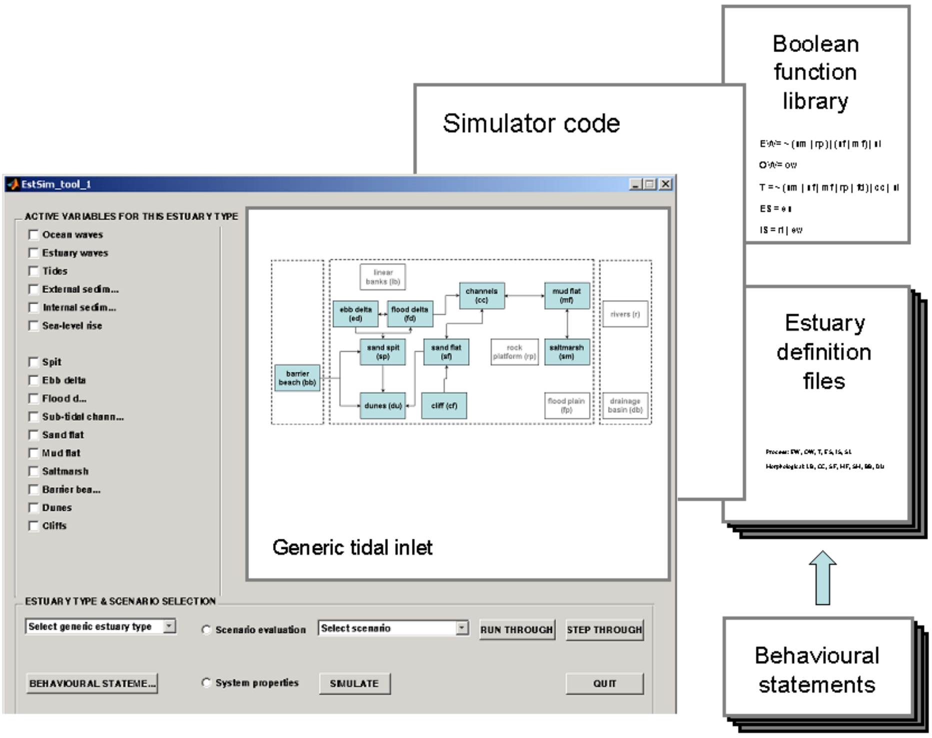


Figure 39. Illustration of early prototype GUI for standalone EstSim tool developed in MATLAB

The GUI-based tool has been compiled into an easy to use application that can be freely distributed to a wider range of users who do not have access to MATLAB software. This, together with the full MATLAB source code, has been made available via the Internet (www.geog.ucl.ac.uk/ceru/EstSim).

As a simple standalone tool, the MATLAB-based simulator is intended to supplement the web-based interface previously presented in the previous section.

8. Conclusions and Recommendations

The following section draws together the outputs and findings of EstSim to provide a series of conclusions regarding the application of the systems based approach to estuaries and the Prototype Simulator. A series of recommendations for further research are then provided.

8.1 Prototype Simulator: 'Model Summary'

From the development and testing of the Prototype Simulator described in this report, the following 'model description' has been developed which summarises the key aspects in terms of theoretical background, development, application, capabilities and testing.

8.1.1 Purpose

The purpose of developing the Prototype Simulator was to take a systems-based description of the geomorphological elements present within an estuary, and through a mathematical formalisation of the influences between the morphological and process components, investigate its response to natural and anthropogenic changes. At the present level of development the Prototype Simulator is not appropriate in isolation to evaluate estuary management options. However, it can be used to explore geomorphological behaviour within estuaries and provide a guide to other modelling studies, or as an educational tool.

8.1.2 Background

The EstSim Behavioural Statements report (ABPmer, 2005) reviewed the systems approach and provided background understanding for developing system diagrams for estuaries, as well as a diagram for each of seven generic UK estuary types. In each case, the system diagram maps a set of influences between the morphological and process components within the estuary, and the adjoining coastal system, including positive and negative feedback between components. The systems approach was formalised with a series of Boolean variables and functions; i.e. essentially a rule-based approach. The behaviour of each system component (variable) in response to combined inputs from other components is defined using the Boolean functions. The continuous non-linear behaviour of the system is approximated by a discontinuous Boolean variable; functions are available for the coast-estuary sub-system, the outer estuary sub-system and the inner estuary sub-system. This keeps the complexity of the proof of concept model to a manageable level, although there is nothing inherent in the approach that would prevent further complexity being added in future developments. The Boolean functions are operated simultaneously at discrete time steps and determine whether components, defined as Boolean variables, exist in on or off states (e.g. presence or absence). The discrete time step and synchronous updating of all state variables at each step can lead to spurious cycles, and a decay term was included in the simulator to damp out these cycles, as they can lead to unrealistic intermediate configurations. The decay term also represents the temporal lag effect that conditions the response of morphological components to changing processes in geomorphological systems.

8.1.3 Input

Input to the Simulator is via the selection of an estuary type from one of the pre-defined seven generic estuary types. This defines the estuary in terms of its component geomorphological elements. The presence or absence of components in the estuary definition can be modified including the external forcing, outer estuary morphology and inner estuary morphology to (1) set up a user-defined estuary with specific (non-standard) features or (2) impose a change to system state, e.g. to represent anthropogenic input. The setting up of a user-defined estuary currently requires expertise in estuary geomorphology to ensure a realistic interpretation of the given estuary system.

8.1.4 Output

The outputs of the Prototype Simulator is a table showing the final state of the estuary in terms of presence or absence of each of the external forcing, system state, outer estuary morphology and inner estuary morphology variables. The final state can be approached in a monotonic or cyclic fashion, and should be interpreted as a tendency rather than an absolute answer. The output requires some expertise in estuary geomorphology to interpret it and, as with any modelling, the results need to be taken in context.

8.1.5 Temporal Scales

The Prototype Simulator can be applicable across the medium to long term, which is implicit in the top-down approach. The approach predicts steps in the evolutionary path but the steps do not have an associated real timescale within the estuarine system.

8.1.6 Validation

The EstSim method has been applied to the Ribble Estuary and Southampton Water (French & Burningham, 2007) and to the Thames and Teign (Rossington *et al.*, 2007). In all cases, the simulator can obtain a largely correct depiction of gross estuary properties with the generic estuary types and rule base. This conclusion is made in terms of the qualitative model output when compared with observed estuarine features and responses; in reality these are value judgements rather than quantifiable results. French & Burningham (2007) conclude that there are subtle estuary-specific aspects of inherited morphology, sediment transport, hydrodynamics (e.g. the double high water in the Solent), and intervention history that would require customisation of the model functions. The ability to customise was investigated to a limited extent by Rossington *et al.* (2007) who concluded that EstSim was able to reproduce the observed features of the Thames and Teign. Further validation studies are recommended to obtain more confidence in the results, i.e. by verifying the rule-base and examining the response to particular effects in specific documented cases.

8.1.7 Range of Applicability

In its generic form, EstSim can be applied to any one of the seven UK estuary types, as well as user-defined estuaries, based on factors for external forcing, system state variables, outer estuary morphology and inner estuary morphology. The model requires expert knowledge of estuary morphology to set up the model for specific estuaries and in order to interpret results. In addition, minor modifications may be required to capture particular estuary specific aspects of processes and morphology, which additionally requires a good understanding of processes and morphology. The present implementation of the model does not allow for the magnitude of an effect to be determined, or for the scale of the presence of a morphological variable, e.g. saltmarsh; it cannot distinguish between a few square metres of marsh or a hectare of marsh. The approach makes use of system-based abstractions (idealised simplifications) of the estuary as a whole and its component geomorphological features. The model can be used to determine the directions of change but, in its present form, is not able to determine sensitivities of the estuary system to change due to its discrete (all or nothing) approach.

Some of the limitations noted mean the prototype simulator is not a suitable tool, in isolation, to address estuary management options and remains at its present level of development primarily a research tool. However, the approach provides a useful means of formalising some of the more qualitative geomorphological knowledge and capturing characteristic behaviour. It is recommended that the detailed consideration of the capabilities and limitations of the approach presented in Section 6 of this report be observed prior to any application of the approach.

8.1.8 Accessibility

The MATLAB research level code is available on-line
(http://www.geog.ucl.ac.uk/ceru/EstSim)

and the Java version available through the web-based Interface
(http://www.discoverysoftware.co.uk/EstSim/EstSim.html).

The model itself once set up runs very quickly (order of seconds).

In addition, summary details of the EstSim project can be found on the Estuary Guide website (http://www.estuary-guide.net/) in the context of other methods and models available to assess morphological change in estuaries developed within the Estuaries Research Programme and other R&D.

8.2 Conclusions

EstSim has been successful in providing exploratory level research into the systems-based approach for the simulation of estuary change. The research has been formalised and the resulting prototype simulator is beginning to reveal potential in this field, although it must be emphasised that at this stage this is still primarily an R&D tool. In addition, FD2117 has provided a valuable qualitative framework for the application of the systems based approach to estuaries.

The study has provided formal definition of UK estuaries, in systems terms, and included in this is a database of UK estuary behavioural types. Behavioural descriptions have been produced at the generic level providing a reference source and also providing a framework for specific estuary behavioural statements.

The definition of UK estuaries has been mathematically formalised to develop a behavioural or qualitative model in the form of the Prototype Simulator. This predictive systems-based tool is capable of capturing characteristic morphological behaviour and provides a framework for formalising qualitative geomorphological knowledge.

The study has developed a web-based interface that provides a visualisation tool for the Simulator and additionally hosts a number of other key outputs from the project. The interface therefore provides a means to disseminate the research and promote knowledge and understanding of the systems-based approach.

8.3 Recommendations

The research undertaken within EstSim has revealed the considerable potential of the systems-based approach and its application to develop qualitative or behavioural models to simulate estuary response to change. A series of recommendations stemming from this work are made below. These recommendations address how the concepts developed within the project may be taken forward at a number of different levels, from the building upon the qualitative framework for estuary behavioural statements, to complementary approaches to mathematical formalisation through to specific further research to enhance the Boolean network approach developed here.

8.3.1 The Systems Based Approach

- EstSim has provided the formal definition of estuary systems in a manner consistent with that developed for the open coast within the Futurecoast study (Defra, 2002). This definition provides the framework for the development of specific estuary behavioural statements, should this be progressed in the future. Such a development would allow for a consistent baseline of morphological knowledge and data for estuaries in England and Wales. This could build on some of the concepts applied in FD2117 and also on the development of datasets within estuaries in various phases of ERP. There would potentially be important benefits across various aspects of the Agency's work, for example: WFD would be a particular beneficiary, in terms of providing the underpinning morphological knowledge to inform work on ecological status.

8.3.2 Complementary Approaches to Mathematical Formalisation

A number of alternative approaches exist to capture defined relationships within a mathematical framework in order to develop a behavioural model. Within EstSim, a review has been carried out of the following three alternative approaches:

- Boolean network approach;
- Network Dynamics (or loop analysis); and
- ASMITA (Aggregated Scale Morphological Interaction between Tidal basin and Adjacent coast) (Stive *et al*., 1998).

The review of these approaches is presented in Appendix C. The review concluded that in reality estuary systems are too complex to be fully described by any of the considered approaches alone and the approaches should be considered complementary. It is therefore highlighted that there may be future options to combine the Boolean network approach with more quantitative methods such as ASMITA and loop analysis.

8.3.3 Boolean Network Approach

Future research into the Boolean network should focus on the following areas:

- The evaluation of more refined variable sets and the development of approaches (and software tools) for the development and testing of complex, yet logically, rigorous Boolean functions:

- Further experimentation with linked sub-systems as a means of minimising the complexity of individual functions, whilst increasing the ability of a Boolean model to resolve the subtleties of estuary system behaviour;

- Investigation of the operator variance associated with each stage of the modelling process (i.e. system mapping, influence diagram construction, formalisation of knowledge into model functions);

- Experimentation with variable decay terms to encompass a broader variety of non-synchronous behaviour;

- A refinement could be made to enhance the function library allowing for selective application of management policies to the different sub-systems;

- Many of the estuary variables which are set to “1” or “0” are in reality partially present (i.e. somewhere in between 0 and 1). Deciding whether the Simulator has correctly predicted this sort of estuary property has been made using expert judgment. A means of making this evaluation process more rigorous would be valuable both for the future development of the Simulator and for its subsequent use: and

- As part of any further development of the approach, there would be benefit from additional testing on both generic estuary types and specific estuaries. Translation of the results into responses for the different generic estuary types to a series of prescribed forcing / intervention and intercomparison of these responses would be beneficial.

8.3.4 Linkages: Modelling and Decision Support Framework (MDSF)

- The EA / Defra have developed MDSF (Modelling and Decision Support Framework) to assist with the development of a number of plans and strategies (e.g. CFMPs and SMPs). MDSF automates and standardises parts of the process of developing and preparing such plans. MDSF does not perform modelling, but incorporates the results from external models for the purpose of interpretation. It is acknowledged here that any further development of approaches to predict changes in estuarine morphology, such as EstSim, need to consider the potential for integration with frameworks such as MDSF. The Prototype Simulator developed in FD2117 is not suitable for integration, at its present level of development, with a higher level decision support system. However, it is recognised that this is an issue for consideration in any development of management tools that may occur within later phases of ERP.

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APPENDIX A. BEHAVIOURAL DESCRIPTION OF THE GEOMORPHIC ELEMENTS

A.1 Behavioural Description for Cliffs

A1.1 Definition of Geomorphological Element

Cliffs are defined as vertical or steeply sloped faces, forming a distinct break in slope between the land and the shore. Sea cliffs can be found along the open coast, sometimes close to an estuary mouth, and glacially formed cliffs can form the boundaries of some types of estuary valley. Coastal slopes (or bluff) are similar, but of a generally lower gradient. Both types of feature can be active (i.e. exposed to marine action) or relict (i.e. formed during previous stages of (higher) relative sea level history and now left stranded).

It is important to note that sea cliffs and slopes are not only affected by marine action (e.g., waves, tides and currents acting at their toe), but also by sub-aerial (weathering) and sub-surface (groundwater) processes which act upon the slope above the limit of wave action. Indirectly, sea spray may affect the sub-aerial processes; indicating the complexities associated with gaining an understanding of the processes to which a sea cliff or coastal slope may be exposed.

A1.2 Function

In terms of their primary function within an estuary, cliffs act as a boundary to the overall system. Within certain types of estuary valleys, the cliff or coastal slope may limit the extent of marine inundation (and by implication, may impede transgressive ‘rollover’ of the estuarine intertidal during a rise in sea level).

In addition to this, cliffs can also supply sediment to an estuary system, although this is very much dependant on the nature of the cliff and the degree of exposure. This function dictates that cliffs are, by their very nature, an erosional landform.

A1.3 Formation and Evolution

Cliff or slope recession is initiated when the stresses acting on the feature exceed the shear strength of the material. This situation may arise due to a combination of a number of factors. In basic terms, these comprise external factors which may exist or occur which increase the shear stresses applied or internal factors which may exist or arise which result in a decrease in the shear strength of the material.

Evolution is also highly dependent on the rate of supply of material to the cliff or slope toe from the face relative to the rate of removal of this debris by wave or tidally-induced currents at the cliff base. The variations in resultant form of cliffs can be illustrated by considering two extreme scenarios. Firstly, in a system where the rate of supply of debris is considerably greater than the rate of its removal from the cliff base, debris material will accumulate over a period of time. This results in the creation of a talus slope with a profile angle consistent with the angle of repose of the debris material. This form is produced most frequently in sea cliff systems that experience a rotational mass movement and the overall sea cliff slope angle decreases as a result.

In the opposite extreme case, where the rate of material input from sea cliff erosion is considerably less than the rate of removal of debris from the cliff toe, the sea cliff slope will retreat whilst generally maintaining a constant slope profile angle. The actual slope angle and rate of retreat will depend upon the lithology of the material of which the cliff is comprised. An example of the typical recession rates in rock materials of different lithology is presented in Table A1.

Table A1. Typical Recession Rates of Cliffs Composed of Different Materials (After Sunamura, 1983)

Cliff Composition	Typical Recession Rate (m per year)
Granite	< 0.001
Limestone	0.001 to 0.01
Shales	0.01
Chalk	0.1 to 1
Tertiary sedimentary (sandstone, mudstone)	0.1 to 1
Quaternary sedimentary	1 to 10
Recent volcanic	10 to 100

The strength of the rock plays an important role in the pattern and rates of cliff or slope erosion throughout the UK. For example, in broad terms, the sea cliffs formed of relatively hard rock comprise a steep face and are presently retreating very slowly where marine erosion and cliff recession are of limited frequency and often small-scale. Such cliffs may be fronted by a boulder apron, narrow beach, rock platform or plunge directly into deep water. In contrast, intense marine erosion and cliff recession rates occur on the unprotected cliffs or coastal slopes formed of soft sedimentary rocks and glacial (drift) deposits along the south and east coasts of England.

A1.4 General Form

It has been suggested (MAFF, 1996) that for a particular geological setting and set of environmental conditions there will be a characteristic set of recession processes (cliff behaviour) giving rise to characteristic cliff forms, as defined below and illustrated in Figure A1 below:

A1.4.1 Simple Cliff Face Systems

These systems are generally characterised by a steep cliff face, narrow foreshore zone and rapid removal of toe debris. Erosion typically occurs as rockfalls, topples or slides from which material is deposited directly on the foreshore.

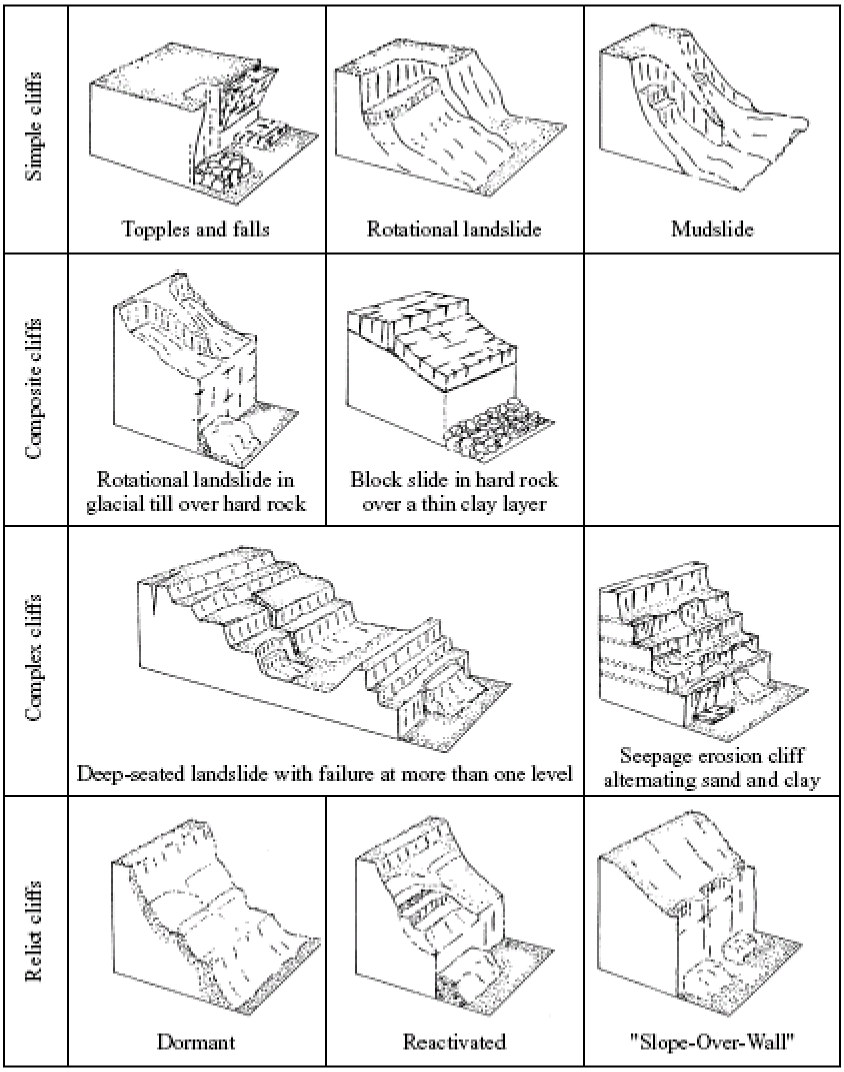

Figure A1. Characteristic cliff behaviour unit types (MAFF, 1996)

A1.4.2 Simple Landslide Systems

These systems are first time failures in previously un-sheared ground, or repeated failures in recently sheared ground. Toe erosion of cliff debris leads to oversteepening of the cliff face and a deep-seated rotational slide develops.

A1.4.3 Composite Systems

These systems typically comprise inter-bedded hard and soft rocks. This can generally be as either soft rock caps resting on hard rock or as hard rock caps resting on softer rock. The latter case presents greater sensitivity to recession.

A1.4.4 Complex Systems

These systems comprise a series of sub-systems, such as scarp and bench features, within the cliff. Each sub-system has its own input, storage and output of material, whereby the output from one sub-system forms a cascading input to the next. There can be some considerable time lag before material reaches the cliff toe.

A1.4.5 Relic Systems

These systems comprise sequences of pre-existing landslides, which are presently subject to relatively little recession, but could be susceptible to re-activation due to debris removal, foreshore lowering or increasing pore water pressure.

A1.4.6 Sub-Features - Caves, Arches and Stacks

Differential erosion between relatively resistant and relatively erodable cliff materials can result in the creation of caves, arches, stacks and other related sub-features. Such features often are the result of accelerated erosion along structural weaknesses, particularly bedding, joint and fault planes, and in the fractured and crushed rock produced by faulting. These features form in rocks, which, despite containing weaknesses, have sufficient inherent strength to stand as near vertical faces, or as the roofs of caves (Trenhaile, 1997).

A1.5 General Behaviour

In general terms, sea cliff behaviour displays a number of important components. Firstly, unstable conditions will be created within the cliff, possibly due to any one, or any combination, of the following: foreshore lowering and undercutting of the slope base by marine action, possibly leading to over-steepening of parts of the cliff face; sub-aerial weathering; increase in groundwater pressure). Following “triggering events” such as storms and/or intensive rainfall, material becomes detached from the cliff and is transported, via a number of potential mechanisms, to the foreshore near the cliff base. This debris is deposited and accumulates, providing a degree of protection to the cliff base against direct wave action until, ultimately, it is removed by marine processes and re-distributed elsewhere within the coastal system.

Unlike many other coastal landforms (e.g. beaches, tidal flats), sea cliffs cannot experience regression (a seaward advance of the landform whilst maintaining a constant profile through the deposition of sediments) in response to changing environmental conditions.

Sea cliff recession will depend upon a number of factors, which may:

- Promote mass movement of cliff material; and
- Control the rate of removal of debris from the cliff base.

A1.6 Forcing Factors

The principal forcing factors are marine erosion, weathering and groundwater conditions.

The amount of marine erosion is dependent upon the balance between the shear strength of the material in the cliff or slope and its exposure to waves and tidal currents, which generate shear stresses. The magnitude of these stresses is dependent on the exposure of the site, which is governed by the offshore conditions, its water depth and nearshore topography, and the degree of protection offered by the fronting inter-tidal area (e.g. inter-tidal beach or flat, shore platform).

Weathering can take two main forms, namely corrosion (the chemical alteration (or decomposition) of the rock by salt water) and corrosion (the mechanical weathering (or disintegration) of the rock by abrasion). Mechanical weathering may more rapidly break down large pieces of rock, which then become subjected to increased rates of chemical weathering. Mechanical weathering may be caused by a number of factors (e.g. mechanical loading/unloading; thermal loading/unloading (e.g. cycles of freeze and thaw); wetting and drying cycles; pressure effects from salt crystal growth; and root wedging. Chemical weathering too may be caused by a number of factors (e.g. solution; oxidation; reduction; hydration; hydrolysis; leaching; cation-exchange), which serve to alter rock crystals, sediment grains or the cements, which bind grains together (Blyth & de Freitas, 1984). In combination, these may:

- Create fissures and enlarge joints, thereby reducing the strength of the cliff-forming materials;
- Create pathways for the ingress of water into soft rocks, thereby aiding in the process of decomposition;
- Cause small movements which tend to reduce shear strength;
- Provide sufficient stresses to trigger failure.

Changes in groundwater conditions within certain types of cliff or slope can be a major triggering factor of landsliding. The voids (or pores) between particles of sediment are filled with fluid (water or air). The pressure of the fluid within the pores can increase due to periods of long and intense rainfall, snowmelt, groundwater seepage, undrained loading, blockage of subsurface water flow, poor surface water disposal and leakages from pipes. This can lead to the promotion of instability within the cliff, although a time lag between the perceived cause and the actual event is common.

In addition, biological factors may also reduce the strength of rocks. Examples include: boring and grazing of coastal rocks by marine organisms, and the growth of plant roots into joints and bedding planes. Biological weathering is rarely a triggering factor in cliff recession, but assists in preparing a cliff for failure by slightly reducing its material strength. It should be noted, however, that biological factors may also enhance stability of soft cliffs, through the binding of material within plant roots. Indeed, stabilisation programmes involving cliff vegetation through the use of engineered swards have been used in southern England (Tyhurst, 1996).

A1.7 Evolutionary Constraints

At the most fundamental level, cliff or slope recession is constrained by:

- The strength of the material in the cliff or slope;
- The stresses applied to the cliff or slope; and
- The rate of removal of debris from, or foreshore lowering at, the cliff or slope toe.

A1.8 Behavioural Timescales

A1.8.1 Short-Term (Responses Within a Year)

When considered over the short-term, cliff behaviour appears episodic, complex and uncertain. Behaviour is often characterised over this timescale by no change along many cliff sections with relatively localised failures in one or two particular locations in response to lowering foreshore levels and/or increasing pore water pressure.

A1.8.2 Medium-Term (Responses Over Decadal to Century Scale Changes)

Over the medium term, more uniform patterns of recession emerge, as the entire cliff appears to move landwards.

A1.8.3 Long-Term (Responses Over Decadal to Holocene Timescales)

Over the longer-term (e.g. centuries), cliff behaviour may be controlled by larger-scale plan form evolution such as the creation of embayments within headlands.

A1.9 Interactions with Other Geomorphological Elements

A1.9.1 General Interactions (Elements Within Estuary System)

A proportion of the material released from cliff or slope erosion may be relatively coarse, non-cohesive sand or gravel of a sufficient size and composition to contribute to the debris stock of sediment at the cliff or slope toe. Ultimate re-distribution of this debris may result in material contribution to beach building or feeding of offshore bars, barrier beaches or spits elsewhere in the coastal system. Also, a proportion of the material released from cliff erosion may be fine, cohesive silts and clays of a size and composition which results in their immediate suspension in the water column and transport offshore or along the coast to feed estuaries and their tidal flats and saltmarshes.

It is also important to recognise that cliffs and slopes are also afforded a degree of natural protection against marine action by the fronting inter-tidal zone (beach, tidal flat, rock platform and, occasionally, saltmarsh). These features dissipate, refract and reflect incoming energy (generated by waves and tides) and reduce the amount of energy that reaches the toe of the cliff or slope. A classic study by Savigear (1953) attributed a spatial transition from marine to subaerial cliff profiles within Carmarthen Bay to a progressive reduction in wave energy resulting from the extension of the Laugharne Spit and the growth of saltmarsh. Alternatively, the presence of coarse sediment within the breaker zone may reinforce wave erosion as a positive feedback mechanism.

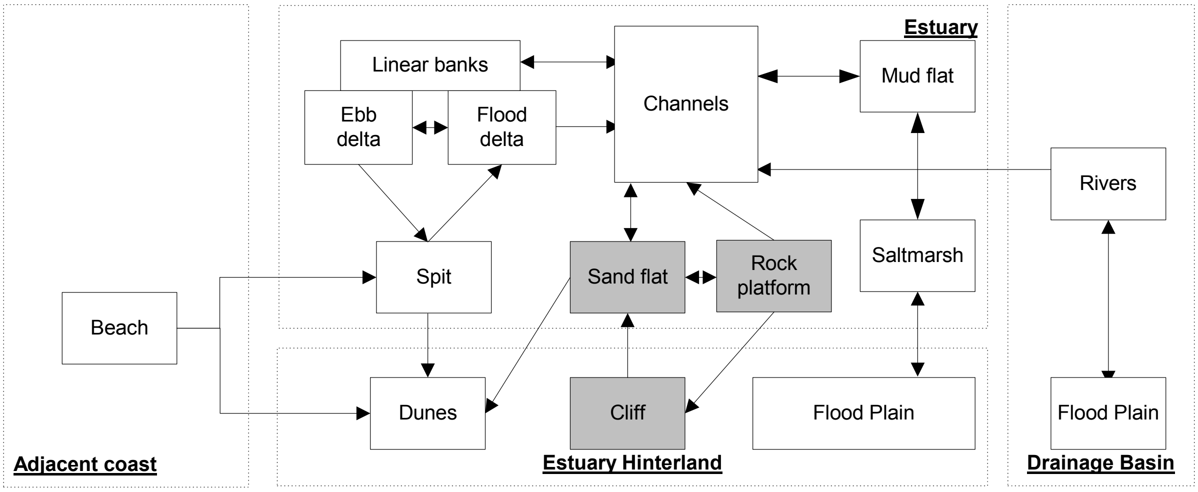

Figure A2. Interaction with other elements - Cliff

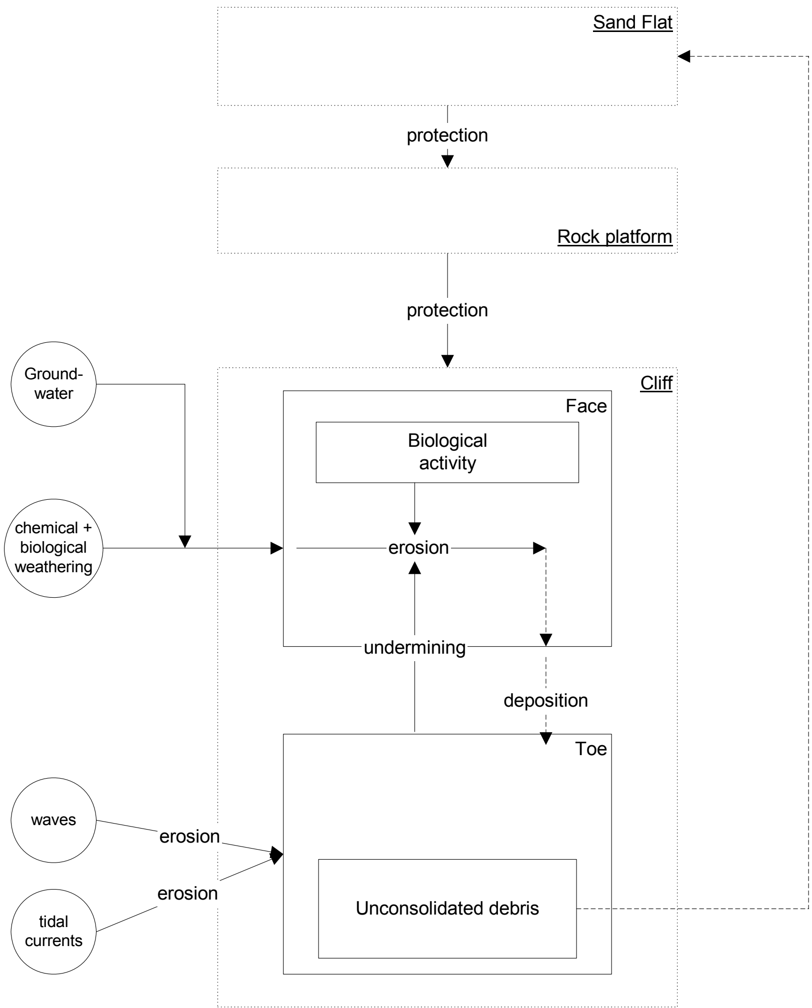

Figure A3. Short to medium term system diagram - Cliff

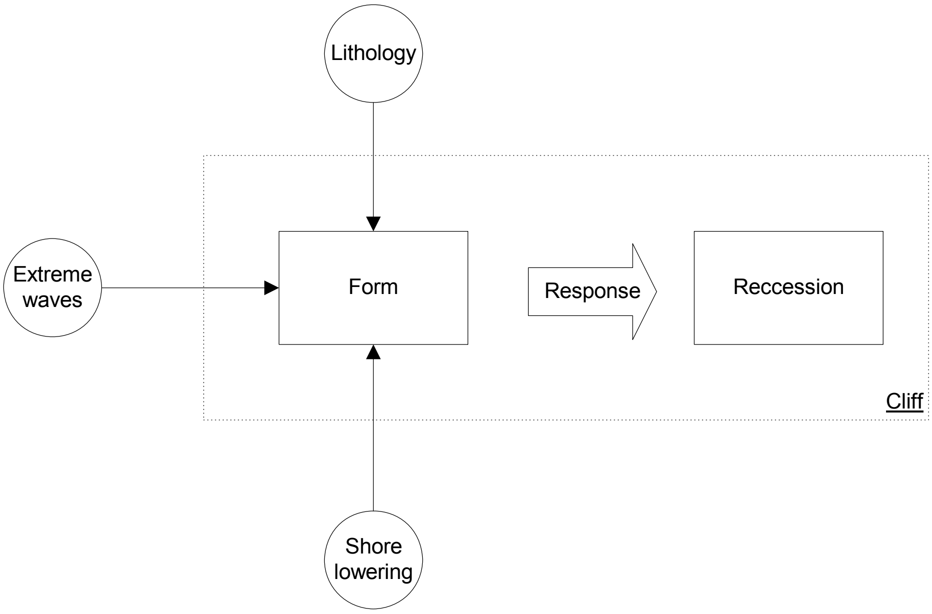

Figure A4. Medium to long-term system diagram - Cliff

A2. Behavioural Description for Barrier Beaches

A2.1 Definition of Geomorphological Element

Barrier beaches are narrow and elongated accumulations of sand and/or shingle fronting low-lying hinterland. Barrier features can become breached during severe storm events, leading to the creation of a tidal inlet if the breach is not sealed by either natural processes or by management intervention. A recent UK example is the breaching of the Porlock gravel barrier in Somerset in October 1996, which has led to the creation of a new tidal inlet.

A2.2 Function

The function of barrier beaches is to provide a ‘barrier’ against tidal flooding to the hinterland. This is achieved by means of tidal and wave energy dissipation and physical blocking of rising tidal levels.

A2.3 Formation and Evolution

Typically barrier beaches can be formed either by the breaching of a spit or by the emergence and subsequent enhancement and landward transgression of an initial bar, built by constructive wave action. In the latter case, the barrier formation started as relative sea levels rose during the Holocene and swept up sediments lying on the present-day seabed, transporting them landwards where they accumulated sufficient sediment volumes to form bars that then further developed into barriers. As relative sea levels continued to rise, so the barriers transgressed landwards until their interception with rising topography, such as sea cliffs, to form inter-tidal beaches. In areas where the topography is low-lying, the barriers remain in a transgressive mode in response to continued relative sea level rise. Due to the relative exhaustion of seabed sediment stocks, most barriers are contemporarily fed with sediments by littoral processes.

Where barriers have become permanently breached, so a tidal inlet will form, with an associated inlet channel and ebb and flood tide deltas present. In these cases, the low-lying hinterland will revert to areas of sand flat, mud flat or salt marsh.

A2.4 General Form

Barriers can be comprised of sand and/or gravel and posses three components: a seaward face; a crest; and a landward face. In addition, dunes may be perched on the barrier crest. Gravel barriers will generally exhibit a steeper seaward profile gradient than their sand counterparts, whilst the crest and landward face of either sediment class may be vegetated.

Sub components may include wash over fans and wash over flats, both of which are accumulations of sediment on the landward face of the barrier created by water flows pushing material over the crest.

A2.5 General Behaviour

Under the presence of a sufficient supply of sediments, barrier behaviour will mostly be transgressive, with landward migration in response to rising relative sea levels. This will occur through repeated processes of crest build up followed by episodic washover, with the over-flowing water pushing sediments from the crest to the landward face (Carter, 1988).

Where sediment supply becomes critically low, for example due to the provision of coastal defence works along adjacent updrift coastal frontages or exhaustion of seabed sediment stocks, the form of the barrier is likely to change from a drift-alignment to a more segmented, swash alignment.

Breaching may result from crest cutback due to erosion of the seaward face and crest, the lowering of crest levels during periods of overwashing, or a combination of both processes. Single or multiple breaches may develop. In the absence of sufficient longshore sediment supply, the breach can remain intact and a new tidal inlet can form (Orford *et al.*, 1996). If longshore sediment supply is large (when compared against the flushing power of the new inlet), then the breach is likely to be ephemeral and naturally become sealed.

Overstepping occurs when the barrier is unable to maintain its entire form in response to increases in relative sea level rise. In such cases, the barrier will usually become overwashed initially, with a base of material remaining on the seabed and the remainder of the material being dispersed by wave and tidal processes.

A2.6 Forcing Factors

Barriers are subject to wave-driven longshore and cross-shore sediment transport processes, and, to a lesser extent, tidal processes. Where barriers are intact features protecting a low-lying hinterland, they can also be subject to hydraulic forces caused by seaward flow through the barrier of an excess water head caused by overtopping events or after periods of high intensity rainfall. In addition, the reverse process can also occur whereby seawater may cross a barrier from the seaward to the landward side, through seepage (Carter, 1988). This process is dependant on the nature of the deposits, with a significant role on gravel barriers due to their higher permeability and an insignificant role on sand barriers. The process of seepage can, in certain situations, reduce barrier stability and hence increase the potential for barrier breaching. Where breaches occur and a new inlet is formed, barriers become subject to marine processes on both their seaward and landward sides.

A2.7 Evolutionary Constraints

The key constraints to barrier evolution are sediment supply and wave exposure, backshore characteristics and the rate of relative sea level rise. Sediment supply is the key factor which dictates the health of the barrier and hence its susceptibility to breaching during periods of extreme wave activity. Where sediment supply is sufficient, it is likely that the barrier will be less susceptible to permanent breaching and tidal inlet creation and the barrier will remain more dynamically responsive to short-term and long-term pressures. However, where contemporary sediment supply is constrained, the barrier may be both more susceptible to breaching (due to reduced volumes of sediment within the barrier structure and a change in its planform morphology from drift- to swash-alignment) and less likely to naturally seal any breach that does occur.

The transgressive response of barriers to rising relative sea levels will become constrained by rising topography as the barrier moves back to intercept such landforms. The topography of the hinterland is also important in the context of shallow depressions or channels, into which barrier sediments can transgress, effectively reducing the crest height of the barrier. The geological nature of the hinterland is also important as this too may influence the ability of the barrier to transgress. Additionally, the rate of relative sea level rise may determine whether the barrier is able to transgress or whether instead it will become outpaced by relative sea level rise and ultimately will be overstepped and break down.

A2.8 Behavioural Timescales

A2.8.1 Short-Term (Responses Within a Year)

Over the short term, barriers will exhibit dynamic responses to individual ‘frequent’ storm events and seasonal wave climates, with processes of cross-shore and longshore sediment movement occurring and changes in profile gradient and crest height observed.

A2.8.2 Medium-Term (Responses Over Decadal to Century Scale Changes)

Where wave activity is such that overwashing occurs, barrier sediment can be moved from the seaward face, to and then over the crest, to become deposited on the landward face, causing washover fans and flats to encroach on the hinterland. Overwashing can result in two potential responses: (1) beach roll-back and crest lowering or (2) crest roll-back and reforming at higher elevation (Bradbury, 2000). Over this medium term barrier behaviour will therefore be dominated by changes in vertical and horizontal position. The ability of a barrier to respond to changing forcing and migrate accordingly will depend on rate of relative sea level change, sediment supply and the degree of wave exposure. In the case of a transgressive barrier response, the barrier could migrate across the hinterland, at a rate controlled by rate of relative sea level rise, exposure to storm conditions, sediment composition and supply and hinterland topography and lithology.

A2.8.3 Long-Term (Responses Over Century to Holocene Timescales)

Over the longer timescale, barrier behaviour could cover a significant range of occurrences, from landward migration in response to modest relative sea level rise, through breakdown processes (e.g. segmentation, washover, overstepping or breaching and new inlet formation) under conditions of reducing sediment supply and/or increasing wave exposure.

A2.9 Interactions with Other Geomorphological Elements

A2.9.1 General Interactions (Elements External to the Estuary System)

Barriers are fed with sediment from adjacent beaches by processes of littoral drift and from any available offshore sources. The latter process can occur as slow, progressive feed during periods of constructive wave action, or as a large pulse of sediment during storm conditions, which mobilise material from storage in offshore banks or deltas. However, such periods of storm activity can also cause barrier crest cut-back and temporary movement of sediment from the barrier to the lower foreshore. Periods of storm action can also result in offshore transport of sediments from a barrier

A2.9.2 General Interactions (Elements Within the Estuary System)

When a barrier becomes breached, it will enable tidal waters to flood the hinterland and a new tidal inlet, with associated channels and ebb and flood deltas, to form.

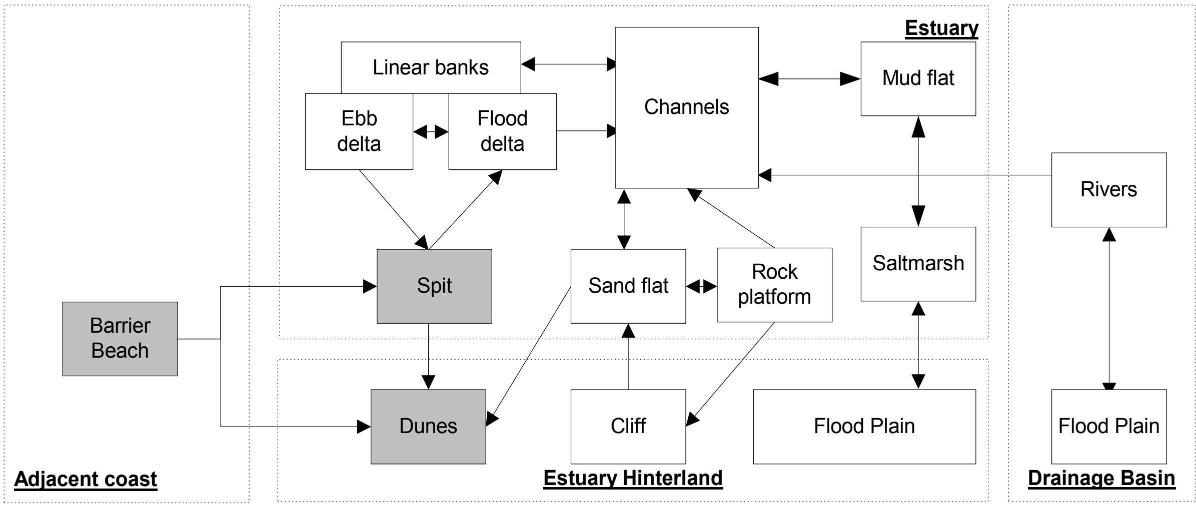

Figure A5. Interaction with other elements - Barrier beach

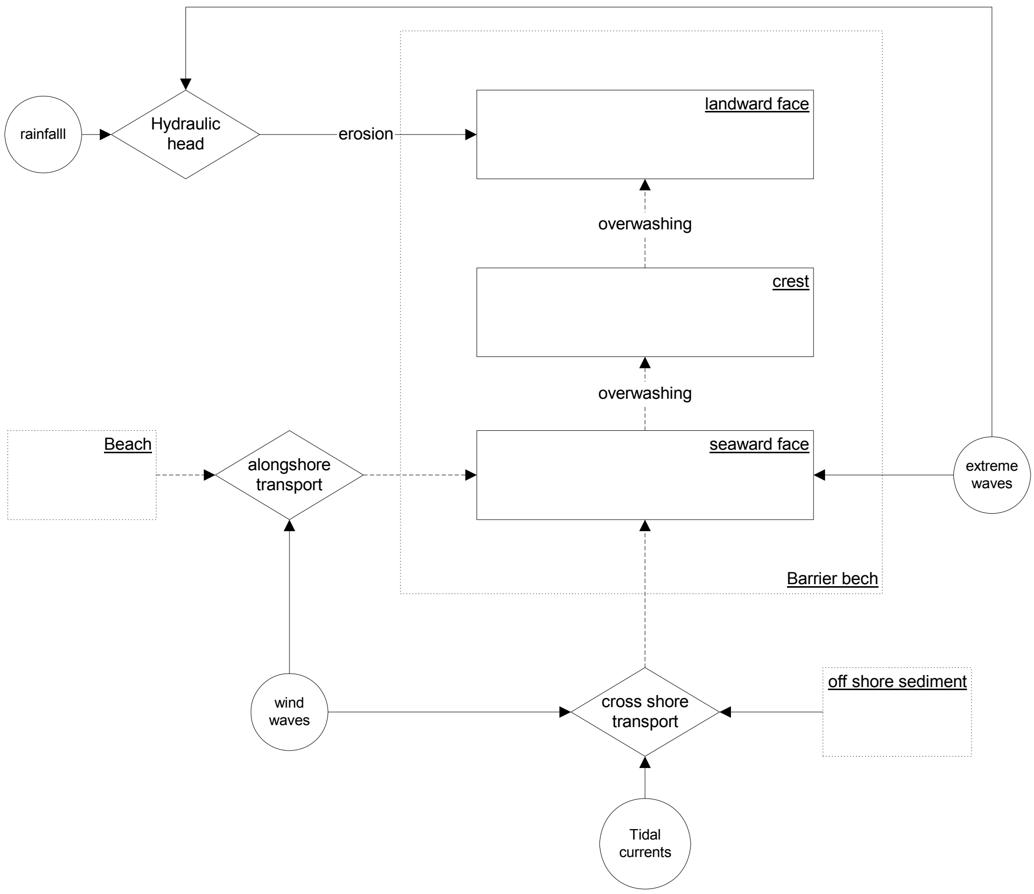

Figure A6. Short to medium term system diagram - Barrier beach

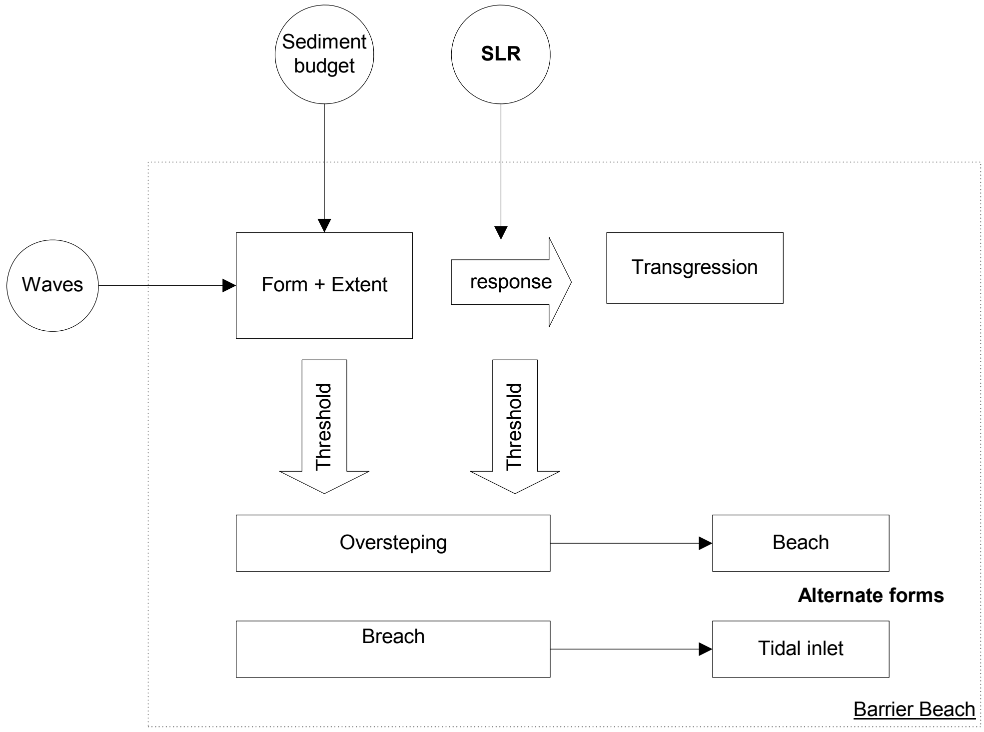

Figure A7. Medium to long-term system diagram - Barrier Beach

A3. Behavioural Description for Spits

A3.1 Definition of Geomorphological Element

Spits are narrow and elongated accumulations of sand and/or gravel that project out from the coastline across part of the mouth of an estuary and, as such, are influenced by marine processes on both their seaward and landward sides. They are formed as a product of the interaction between longshore drift, moving non-cohesive sediment along the coastlines adjacent to the estuary mouth, and the tidal processes operating through the mouth. In areas where local coastal drift reversals, or ‘counter drift’, exists updrift of the estuary, spits can form at both sides of an estuary mouth, growing towards each other. These are referred to as double spits and classic examples can be found along many of the harbours in The Solent. Many spits are characterised by a curved termination at the distal end, caused by the wave action acting at this location.

A3.2 Function

Spits can be seen to serve several functions within in the context of an estuary system. Spits represent a sedimentary interaction between the adjacent open coast and an estuary and as such their existence provides a constraint on the estuary mouth, acting as a barrier to tidal inundation, constraining the estuary channel and mouth and providing shelter to the generally intertidal areas in their lea.

A3.3 Formation and Evolution

For spits to develop, there is a requirement for the along-shore coastal transportation of sand or gravel and the presence of an abrupt change in the main coastline configuration, such as caused by the presence of an estuary. As the shore-parallel littoral processes become influenced by the ingress and egress of water from the estuary, so the longshore transport rate is reduced and much sand or gravel becomes deposited at the estuary mouth. As this deposition continues, the spit will grow in length, prograding across the estuary mouth. This will continue until some critical balance is achieved between the longshore supply and deposition of sediment and the passage of tidal waters through the estuary mouth. In estuaries with relatively low volumes of tidal discharge and/or extremely high volumes of longshore drift, continued spit growth can divert the mouth of an estuary significant distances along the coast (e.g. River Adur in West Sussex) or, ultimately, lead to mouth sealing (e.g. Combe Haven, East Sussex). However, in many cases of extensive spit growth, episodes of breaching are often characteristic, thereby creating a new mouth position, followed by further periods of elongation. For example, in the hundred years leading up to the mid 1930s, Mudeford spit at the mouth of Christchurch Harbour experienced five cycles of significant progradation and breaching (Kidson, 1963). Much debate exists in the literature concerning whether double spits at estuary mouths are the result of breaching processes (e.g. Robinson, 1955) or counter-drift (Kidson, 1963). Whilst breaching of a spit can provide a ‘plug’ of material that can be transported to the opposite side of the estuary mouth, from where an opposing spit can develop, counter-drift usually remains responsible for re-sorting this material and in most cases where double spits exist, it is most likely that some form of counter-drift is responsible for spit formation and development.

A3.4 General Form

Spits can be comprised of sand and/or gravel and possess three components: a seaward face; a crest; and a landward face. In common with barrier beaches, dunes may be perched on the crest of a spit. Gravel-dominated spits will generally exhibit a steeper seaward profile gradient than their sand-dominated counterparts, whilst the crest and landward face of either sediment clast may be vegetated. Sand dominated spits tend to be flatter features. Typically, spits front low-lying sand or mudflats and saltmarshes, which are protected by the spit against wave activity.

A3.5 General Behaviour

As spits are formed at locations where wave-driven littoral drift and tidal processes combine, they are usually relatively dynamic features that can be subject to changes in profile gradient, crest height, planform position and even their presence.

Considering the longshore behaviour, a spit is dependent on the balance of interactions between the littoral sediment supply and subsequent deposition, and the tidal processes operating through the estuary mouth. This can either curtail spit development to a limited length (where the tidal processes are more significant than littoral processes) or can lead to spit elongation across the estuary mouth, diversion of the mouth and even eventual mouth blockage (where the littoral processes are more significant than tidal processes). In areas where spit elongation is observed, it is often possible to identify a series of recurves within the feature, each of which marks the former end of the spit.

In a cross-shore sense, a spit generally behaves in a similar fashion to a barrier, in that tidal and wave activity tends to push material up-profile during ‘normal conditions’. During slightly more extreme conditions, material may be moved so far up the profile that it becomes deposited on the spit crest, but during extreme conditions, the crest material is pushed back down the landward face, thereby causing a landward migration of the plan form position.

Episodes of temporary or permanent spit breaching can also occur, caused by either wave activity lowering the crest so that flooding occurs through the breach, or by tidal processes operating from the landward side of the spit causing destabilisation.

Over longer timescales, spits can exhibit major changes in form. Their response to rising relative sea levels will depend on the rate of relative sea level rise and the stability and inertia of the spit itself. Under modest rates of relative sea level rise, a spit is likely to experience landward transgression, whereas during periods of rapid relative sea level rise, the feature may be unable to transgress at a sufficient pace and instead break down to form a lower chenier on a sand or mud flat.

A3.6 Forcing Factors

Spits generally are more common in areas of micro-meso tidal range, such as parts of eastern and southern England and west Wales (Pethick, 1984). They exist due to a combination of both wave-driven along-shore transport processes and tidal processes through the estuary mouth.

A3.7 Evolutionary Constraints

Sediment supply to the spit is often important to its continued presence. This is because spits are initially formed as ‘drift-aligned’ features (i.e. the shoreline is oriented obliquely to the dominant wave crests so that some alongshore transport of sediment is observed along the shore). Although spits are often considered to be sinks of sediment, some material is continually removed from the spit and transported offshore, into the estuary or further along the coast, bypassing the estuary mouth within ebb tidal shoals where present. In the absence of continued supply, the spit will tend to become progressively denuded of sediment and its appearance will become progressively more segmented and ‘swash aligned’, caused by internal re-working of available sediments.

A constraint on the degree of spit growth, in the case of continued sediment supply, is the flushing capacity of the estuary. This flushing capacity is a balance between the rate of sediment supply along the spit, predominately controlled by wave action, and the action of tidal flows and fluvial discharge through the mouth. The action of waves driving transport along the spit will act to elongate the spit whereas the flows through the mouth will act to maintain a cross-sectional area and hence prevent spit growth in certain situations. For example, in estuaries with a very large tidal prism, it is improbable that a spit could grow sufficiently to seal or significantly divert the mouth. However, in estuaries with a small tidal prism, spit growth can commonly divert the estuary mouth, unless training works or artificial sediment recycling/bypassing activities are in place to limit this.

A3.8 Behavioural Timescales

A3.8.1 Short-Term (Responses Within a Year)

Over the short-term, spits will exhibit dynamic responses to individual ‘frequent’ storm events and seasonal wave climates, with processes of cross-shore and longshore sediment movement occurring and changes in profile gradient and crest height observed.

A3.8.2 Medium-Term (Responses Over Decadal to Century Scale Changes)

Over the medium term spit behaviour will vary according to a number of factors, for example sediment supply. Spit behaviour may involve erosion or accretion, resulting in vertical or horizontal changes in the form of the feature, and changes in the position of the feature. For example, under a scenario of relative sea level rise, a spit may migrate landward through the process of sediment being moved from the seaward to the landward side.

In addition, spits are known in a number of cases to exhibit cyclical behaviour over these medium term timescales. This can involve a period of spit growth and elongation followed by a breach. If the breach is maintained, the sediments in the isolated section may become dispersed and the spit may begin a further stage of elongation and growth.

A3.8.3 Long-Term (Responses Over Century to Holocene Timescales)

Over the longer term, spit behaviour could cover a range of occurrences, from significant progradation, through landward migration in response to modest relative sea level rise, to breaching or breakdown of the feature during more extreme (i.e. less frequent) storm events or rapid rates of relative sea level rise.

A3.9 Interactions with other Geomorphological Elements

A3.9.1 General Interactions (Elements External to the Estuary System)

Spits have important interactions with the adjacent shore beaches. It is from these areas that sediment is supplied to the spit.

A3.9.2 Deltas

In some particular types of estuary, namely spit-enclosed drowned river valleys and tidal inlets, both spits and flood and ebb tidal deltas can be present. In these cases, important sediment transport pathways exist that incorporate both the spit and the deltas. A proportion of the sediments will become stored within the spit or delta features, whilst other sediments will pass through the complex pathways, episodically moving off the spit to the flood tide delta, then to the ebb tide delta and then back to temporary storage in the spit or ultimately progressing to the downdrift side of the estuary mouth and thereby bypassing the estuary.

A3.9.3 Sandflats, Mudflats and Saltmarsh

Some material exchange can also occur between the spit and the adjacent sand flats within the estuary. Spits provide a degree of protection to backing sand flats, mud flats and salt marshes from direct wave attack. As the position, or presence, of the spit changes (e.g. due to landward migration, temporary or permanent breaching, breakdown of the feature), so the exposure to wave penetration of parts of the outer estuary changes. This could, for example, have the effect of causing or accelerating erosion of inter-tidal areas, or reducing the rate of accretion.

A3.9.4 Channel

Spit behaviour will have a direct impact on an estuary or inlet mouth. The spit will exert an influence on channel dimensions at the mouth and channel dimensions will respond to any cyclic behaviour involving spit elongation and breaching. In the event of a spit breach that is maintained through tidal and wave action, the siltation is likely to be experienced in the estuary or inlet mouth (Pontee *et al.*, 2002).

A3.9.5 Dunes

Spits can become vegetated on their crests and landward slopes and in the case of particularly large sand spits, dunes can develop due to aeolian transport of sand and subsequent colonisation by vegetation.

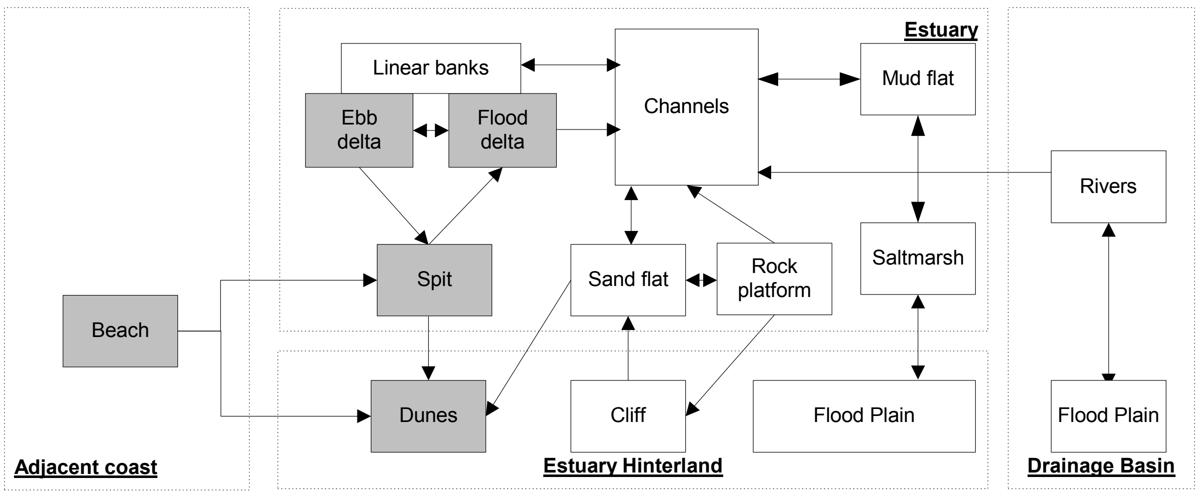

Figure A8. Interaction with other elements - Spits

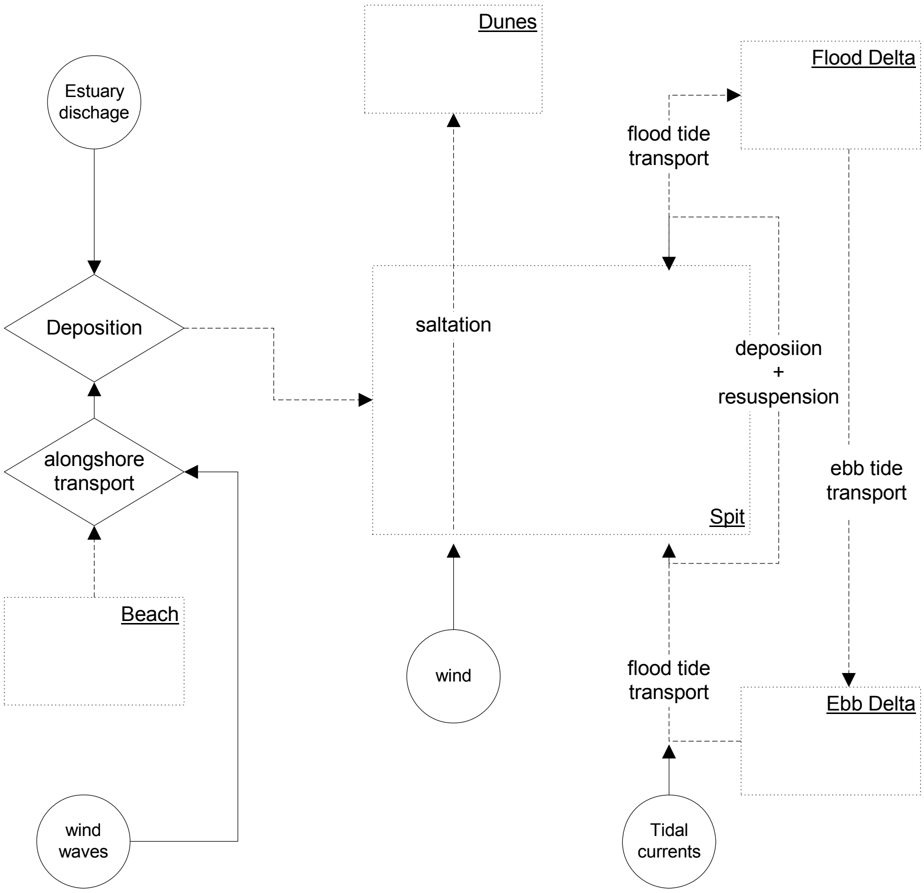

Figure A9. Short to medium term system diagram - Spits

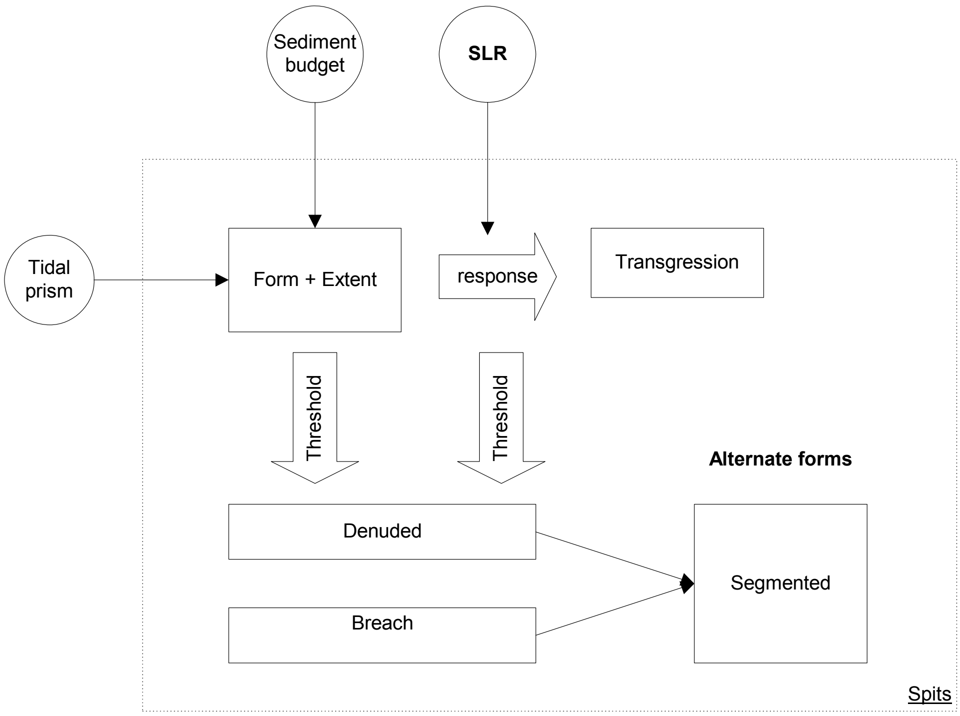

Figure A10. Medium to long-term system diagram - Spits

A4. Behavioural Description for Dunes

A4.1 Definition of Geomorphological Element

Coastal dunes are accumulations of sand that has been blown by the wind from the foreshore to the backshore. Such features are characterised by the presence of vegetative cover.

A4.2 Function

The function of a dune system is both to provide protection to the adjacent landward hinterland and to provide a store of sediments available to the fronting foreshore. In terms of the wider coastal or estuarine system, the function is therefore fulfilled primarily during extreme events. Under such conditions, dunes provide an energy dissipation role, acting as a buffer to extreme waves and protecting the adjacent hinterland. In addition, during these extreme events, dunes provide a supply of sediment to replenish the fronting foreshore, allowing the foreshore to adapt its form.

A4.3 Formation and Evolution

The wind-blown (aeolian) processes that result in dune formation are initiated when the wind stresses acting on sand particles of the foreshore exceed the shear strength of the material (which is related to sediment grain size). This process is known as saltation and particles move in this manner until their progress becomes interrupted by some obstruction, such as debris at the mark of the highest tide. Here, accumulation starts and as the mound of sand increases to form embryonic dunes, so vegetation can start to colonise. As embryonic dunes continue to accumulate sediment, they rise in height, increase in width and connect with neighbouring embryonic dunes to form more continuous ridges (often up to 2m in height) parallel to the shoreline. These ridges, due to their increased elevation, become vegetated by major dune species (e.g. marram grass). These species increase the surface roughness of the foredune and assist in the trapping of sediment, resulting in rapid deposition within the vegetated zone. This leads to rapid increases in dune height, which, in the UK, can be up to approximately 10m.

As the foredune height increases towards a self-limiting level, it will become subjected to an increasingly stronger wind velocity regime at its crest, which, eventually, will result in saltation processes moving sand landwards. On the lee side of the dune crest, the velocity regime decreases substantially, resulting in deposition and the initiation of the development of a new dune ridge. Due to the process of erosion from the crest and lee-side deposition, the entire dune ridge appears to “rollover” and move landwards (Pethick, 1984; Carter, 1988). Assuming an accretional environment prevails, as the ‘roll-over’ process occurs, new dunes are created seaward of the migrating ridges. This results in the creation of a series of fully developed ridges, separated by troughs or valleys.

A4.4 General Form

A coastal dune field will often comprise a series of sand ridges running parallel to the shoreline, with each ridge being separated from another by marked troughs or valleys (Pethick, 1984). Other fields may have a more complex form, comprising ridges running perpendicular, or at oblique angles, to the shoreline. Typical ridge heights in the UK range from 1 or 2m to 20 or 30m and their morphology generally comprises relatively steep windward slopes and gentler lee slopes (Pethick, 1984). Each dune ridge represents a different stage in a dune field's development (Goldsmith, 1978). The crest of each ridge may be flat or undulating, but occasional areas of unvegetated low depressions (known as blow-outs) may occur.

As dune ridges migrate landwards through a succession, they eventually become lower in height and less parallel to the shoreline. This is due both to the progressive reduction in saltation that occurs with progressive movement landward through the dune field, and to the reduction or disappearance of marram grass within older dunes. As a result, the ridges become fragmented, increasingly susceptible to blow-outs and, ultimately, the creation of u-shaped parabolic dunes. Parabolic dunes typically have vegetated arms orientated roughly parallel to the predominant wind direction and unvegetated centres which are subjected to downwind movement.

A4.5 General Behaviour

Dune behaviour is generally linked to its stage of succession, with pioneer stages (embryonic dunes and foredunes) being typified by sand deposition to enable dune formation and growth. Intermediate stages involve the migration of dune ridges and formation of new ridges to establish dune fields, whilst the mature stages are characterised by the lowering of dune ridges, loss of vegetation cover and, due to increasing susceptibility to blow-outs, the formation of parabolic dunes. Generally, dune fields are perceived to be sediment stores, but episodically dunes can supply sediment to the fronting inter-tidal beach when wave activity is extreme.

A4.6 Forcing Factors

Unlike all other coastal landforms, dunes are formed by wind-induced sediment movement rather than water-induced movement (Pethick, 1984). This involves, during periods with strong onshore wind velocities, aeolian processes transporting sand-sized sediment landward. Hence wind speed and direction is an important forcing condition in dune formation and evolution.

During periods of relatively high wave action, some of the sediment stored within the dune system can be eroded and moved seaward to feed the beach profile. This is often perceived to be a major concern to coastal management since the volumes of material involved can be relatively large, but this is a temporary state and following periods of calmer wave action, sand will once again usually move from the beach to be stored within the dunes (Carter, 1988). In addition, sediment stored within a dune system can be lost inshore.

A4.7 Evolutionary Constraints

The evolution of dunes could be constrained by either a reduction in sediment supply or the lack of accommodation space to enable dune succession.

A4.8 Behavioural Timescales

A4.8.1 Short-Term (Responses Within a Year)

In the short-term, dune behaviour can be extremely dynamic, with significant sediment accumulation or significant local sediment loss, due to blow-outs or erosion of the seaward margins, both possible outcomes.

A4.8.2 Medium-Term (Responses Over Decadal to Century Scale Changes)

Dune behaviour over medium timescales will consist of changes in the position and nature of a dune system. Depending on the degree of landward space and the sediment supply, a dune system may 'roll-over' landward in response to an increase in relative sea level. Conversely, under a scenario of falling relative sea level a dune system may prograde seaward, under a scenario of sufficient sediment supply.

A4.8.3 Long-Term (Responses Over Century to Holocene Timescales)

Over longer-time periods entire dune fields can develop, containing a series of ridges created during different stages of its evolution. Over similar timescales, entire dune fields may also be lost due to erosion or inundation or alternatively a dune system may stabilize or become a relict feature. The change in relative sea level is the critical controlling factor in the behaviour of dune systems over this timescale. In addition, the supply of sediment will determine the nature of the features response the prevailing relative changes in relative sea level.

A4.9 Interactions With Other Geomorphological Elements

A4.9.1. General Interactions (Elements Within Estuary System)

The key interaction is between the dune and the fronting inter-tidal foreshore. Sand is supplied to the dune from the foreshore by aeolian processes, but can also be temporarily supplied from the dune to the fronting foreshore during extreme events. Dunes can also develop on the crest of major spit or barrier features; with Spurn Head being a classic example. In such situations, it is possible that a marsh system may develop in the lee of the dunes, to which the dune system provides protection.

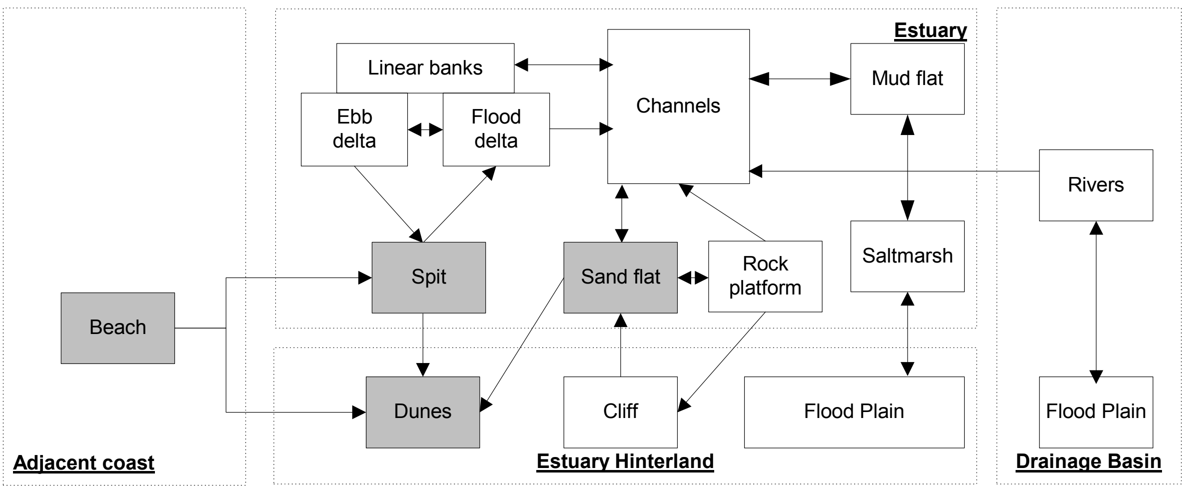

Figure A11. Interaction with other elements – Dunes

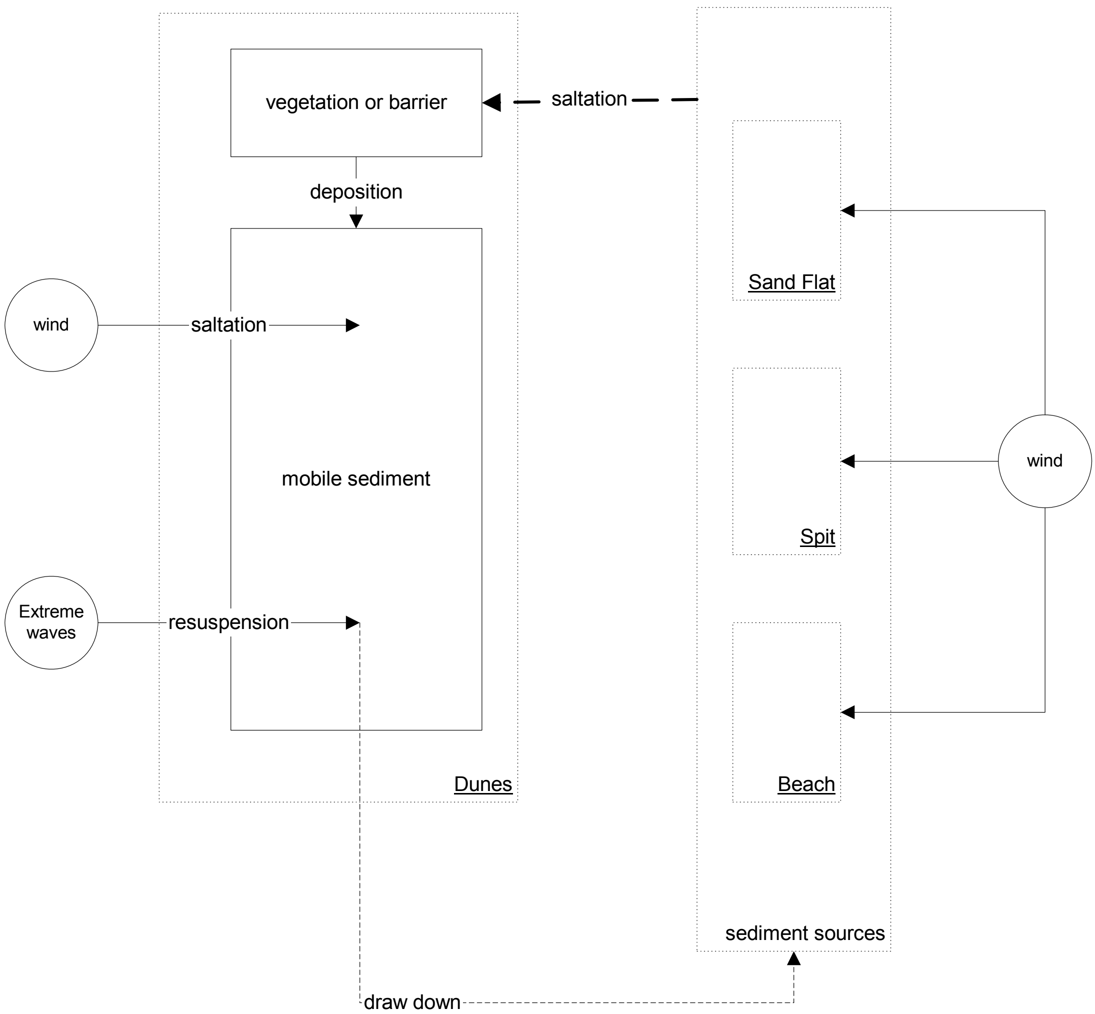

Figure A12. Short to medium term system diagram - Dunes

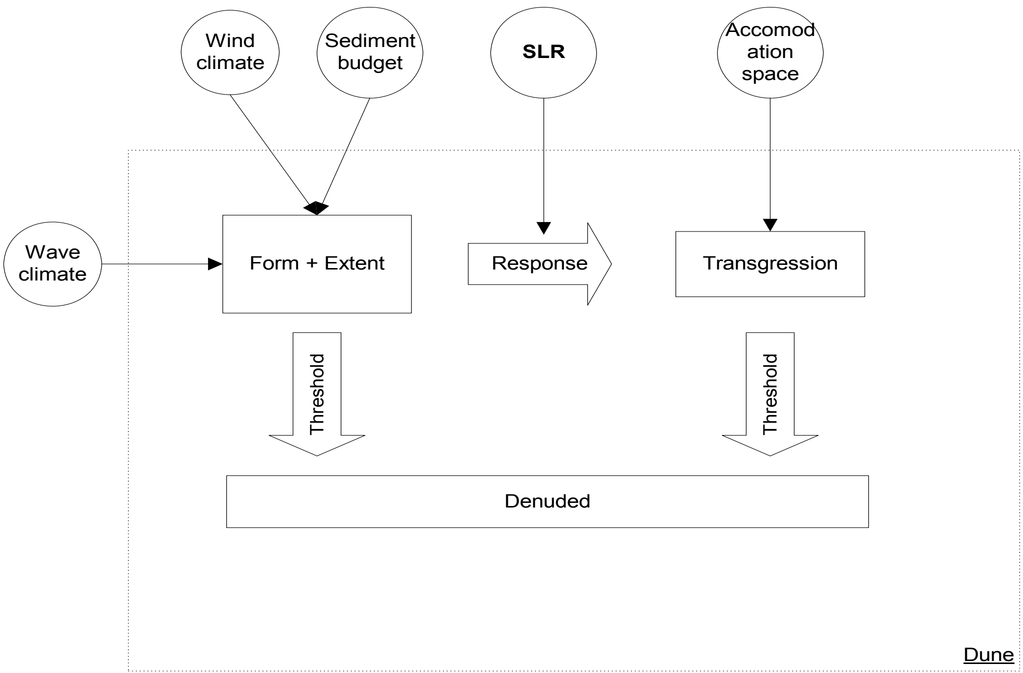

Figure A13. Medium to long-term system diagram - Dunes

A5. Behavioural Description for Deltas

A5.1 Definition of Geomorphological Element

Deltas can be defined as accumulations of river- or marine-borne sediment found in the vicinity of the estuary mouth. Their existence is dependant upon a sufficient supply of material and favourable wave and tidal conditions. Deltas can exist as flood or ebb features. For the purpose of this study the occurrence of linear sand banks within an estuary mouth is considered as a modified delta with littoral supplied sediment to the mouth of an estuary incorporated into elongated sand accumulations aligned with the current flow.

A5.2 Function

Within the estuarine system, deltas act to dissipate wave energy at the estuary mouth thus providing protection. In addition, they also act as a sediment sink. Under certain conditions the delta will also act as a sediment source i.e. when the wave characteristics provide sufficient energy to suspend bed material. A delta represents a sedimentary interaction between the estuary and the coastline to either side of the estuary mouth.

A5.3 Formation and Evolution

If more sediment is supplied to an estuary mouth or tidal inlet than can be redistributed by the dominant processes, then a delta will be formed. Conversely if the waves and currents can remove more sediment than is being delivered to the estuary mouth, then the delta retreats or the sediment load is incorporated directly into the beach or within an estuary and delta is not formed.

There are therefore two generalised situations in which delta formation will occur:

- If the fluvial sediment supply exceeds the flushing capacity of processes at the estuary mouth;
- When wave driven longshore transport supplying sediments to an estuary mouth from an adjacent coastline is interrupted by the interaction of wave and tidal processes at the mouth.

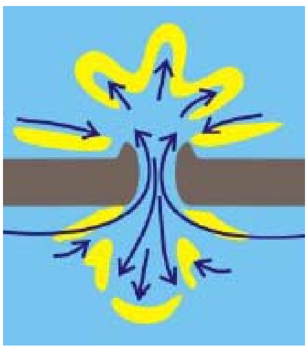

Figure A14. Schematic illustration of Delta formation processes at a Tidal inlet/estuary mouth

A5.4 General Form

Deltas can be classified according to the relative importance of fluvial, tide and wave processes in their formation. The relative importance of these processes will play a role in dictating the form of the Delta. Van Rijn (1998) classified three distinct types of deltas, as follows:

- River-dominated deltas form where rivers supply a sufficiently large sediment load to overwhelm the rate of marine-induced re-working and removal. They are often comprised of numerous branching river distributary channels and the presence of lobes. These deltas tend to be long narrow features;

- Wave-dominated deltas form where river- or coastal-borne sediment is sorted and transported from the estuary mouth in both longshore directions by waves. Such sediment is often transported to features such as beaches, barriers and spits. Typically such deltas are wide features with multiple outlets; and

- Tidally dominated deltas form in meso-tidal estuaries where the tidal conditions are sufficient to transport sediment to the estuary mouth. Such deltas tend to comprise ebb delta located seaward of the estuary mouth or tidal inlet and flood delta located inside the estuary mouth or tidal inlet.

A modified delta may form in macro tidal estuaries as linear sand banks with sand accumulations aligned parallel to the flow.

A5.5 General Behaviour

Delta behaviour is complex and results from a combination of the relative dominance of the driving processes (fluvial, wave and tidal processes) and the supply of sediment. Whilst tidal processes play the predominant role in the formation of the tidal delta, wave-generated processes are also important, tending to supply the coarser material to the flood tidal delta. Often finer materials are progressively removed from the flood tidal delta resulting in an eventual differential between the adjacent updrift and downdrift beaches. However, fine sediments may also be transported from the flood delta to the ebb delta and subsequently feed the downdrift coastline.

A5.6 Forcing Factors

At the mouth of an estuary three processes will contribute to delta formation and the distribution of sediments (Defra, 2002):

- Inertia-dominated material: The inertia created by high velocity outflow results in the material spreading and diffusing as a turbulent jet. The expansion of this jet reduces its velocity resulting in a reduction of its sediment carrying capacity. The sediments are deposited in a radial pattern, with the coarsest material deposited near to the point where the jet expansion begins and the finer material further afield. With the continual discharge of sediment, the delta will accrete vertically and eventually have a frictional effect on the material;

- Friction-dominated material: The continual deposition of sediment from the turbulent jet will eventually cause the restriction of the jet. This in turn will result in the formation of bars and channels;

- Buoyancy-dominated material: The mix of fresh and saline water often results in stratification, which in turn initially results in the material being isolated from bottom friction effects. Consequently, the sediment will be distributed over a wide area until the upward entrainment of seawater across the density interface results in its deceleration and settlement.

Within tidally dominated estuaries, tidal interaction has three important effects:

- At estuary mouths, mixing obliterates the effect of vertical density stratification thus eliminating the effects of buoyancy;
- Tide-dominated sediment transport is bi-directional; and
- The zone of fluvial-marine interactions extends across a wider area.

A5.7 Evolutionary Constraints

The evolution of a delta may be constrained by a number of factors, such as:

- Sediment supply (including the source and nature of sediments and the rate of supply);
- River, wave and tidal processes, and their interaction at an estuary mouth;
- Coastal alignment and nearshore bathymetry (including the configuration of the adjacent coastline, the position and nature of the estuary mouth, the behaviour of adjacent spits etc).

A5.8 Behavioural Timescales

A5.8.1 Short-Term (Responses Within a Year)

In the short-term, delta behaviour will be dominated by changes in size and form and migration of the feature. This behaviour will be in response to variations in forcing processes of river flows, waves and tides resulting in variations in exposure and sediment supply.

A5.8.2 Medium-Term (Responses Over Decadal to Century Scale Changes)

Over the medium term, even if the tidal inlet as a whole is in dynamic equilibrium with the forcing factors, appreciable local changes in morphology can be observed. These may lead to the spatial relocation of the complete inlet system, or just components within it. Examples of such local changes are the shoal-channel cycles, which for the Wadden Sea inlets have cycle periods of many decades (de Swart, 2002).

A5.8.3 Long-Term (Responses Over Century to Holocene Timescales)

Over longer-time periods, delta behaviour will be linked to the behaviour of the estuary mouth in response to changes in relative sea level and variations in sediment supply.

While the gross morphological changes of outer deltas may be determined by global processes forcing these changes such as relative sea level rise or a gradual decrease of the basin area, it is expected that the local, (quasi-) rhythmic changes of outer deltas are determined by processes intrinsic to the outer delta. This so-called free behaviour is hypothesised to be driven by subtle, second-order effects embedded in the first-order signal of intra-tidal and intra-event fluxes of water and sediment interacting with the bottom evolution (de Swart, 2002).

A5.9 Interactions With Other Geomorphological Elements

The interactions of deltas with other geomorphological elements have been investigated to varying degrees. Typically the ebb tidal delta has been the focus of much of this work, especially along US coast and within the Wadden Sea (van der Vegt *et al*., 2004). In most recent years this work has taken the focus of modelling the interactions, behaviour and evolution of such features over varying timescales. An example is that of the ASMITA model which has recently been developed from a one element to a three element numerical scheme (Stive, 2003).

Deltas are ultimately dependent upon the presence of a river or estuary and the supply of sediment from:

- Rivers (via channel system); and/or
- Longshore transport from shoreline sources (spits); and/or
- Onshore transport from the eroding seabed.

A5.9.1 General Interactions (Elements External to the Estuary System)

Essentially, deltas play an important role in the exchange of material between the coastal zone and estuary (or backwater basin) (*cf.* van Leeuwen *et al*., 2003). There is therefore an important sedimentary interaction between a delta and adjacent coastlines.

These features often provide considerable natural protection to the coastline adjacent to estuary mouths (Dyer & Huntley, 1999). Reductions in the delta volume, sediment supply or reclamation within the estuary, will lead to reduced natural protection to adjacent shorelines and, hence, increase their susceptibility to erosion.

The response of a tidal delta (in terms of volumetric reduction) to such anthropogenic changes can be very significant, but is not instantaneous. Instead, due to the inherent time lags within the coastal system, it can take decades or centuries of slow progressive ebb-delta modification to fully respond to such interventions.

Deltas/linear banks act as large sediment stores. Whilst this material tends to remain within the bank temporarily, it may, due to changes in forcing factors, be released to re-enter the sediment transport pathway. This could be either in the longshore, onshore or offshore directions. It is likely that this behaviour will be over a short- to medium-term period, rather than the long-term, whilst the bank responds to changing conditions to re-attain equilibrium.

Perhaps the more significant interaction that the banks have with other elements within the local system is with the immediate shoreline. Here banks refract incoming waves influencing wave energy at the shoreline. In turn this will control shoreline evolution and, subsequently, backshore features in response to wave processes.

A5.9.2 Spits/Barrier Beaches

The above 'general interactions' discussion focuses on the link between deltas and the adjacent coastline. This interaction equally applies to spits and barrier beaches. A strong linkage exists between spit/barrier beach behaviour and delta behaviour, with cycles of spit/barrier growth and breaching affecting the location and nature of the estuary mouth or tidal inlet and hence the behaviour of any delta associated with the mouth.

Deltas and spits/barriers therefore often provide the sediment linkage between an estuary and adjacent coastlines.

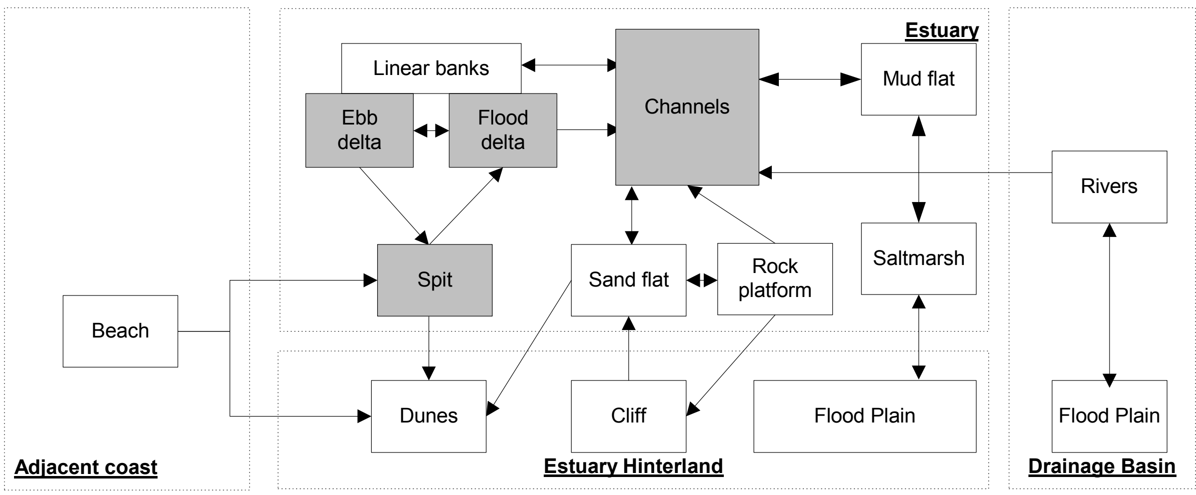

Figure A15. Interaction with other elements – Delta

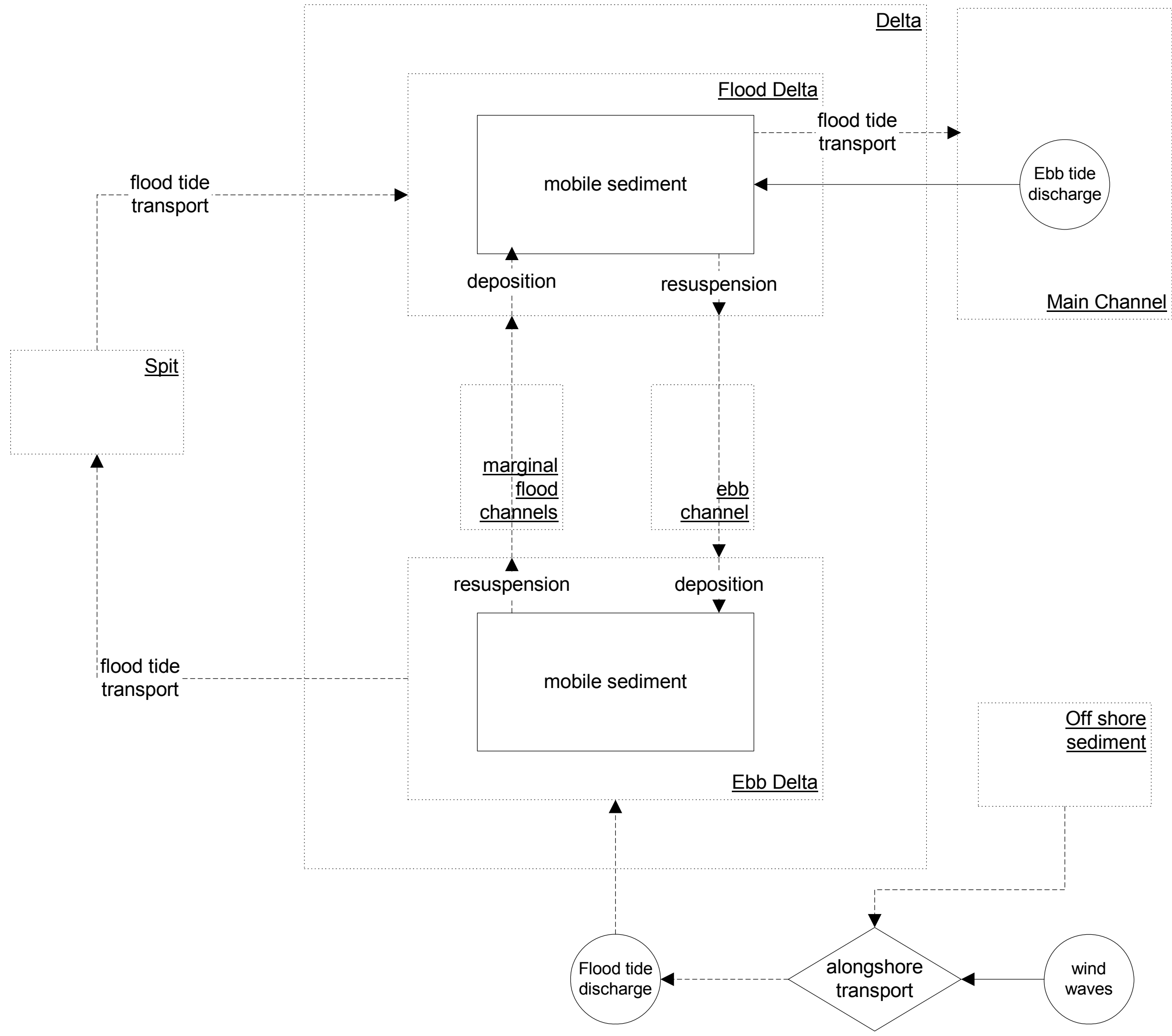

Figure A16. Short to medium term system diagram - Delta

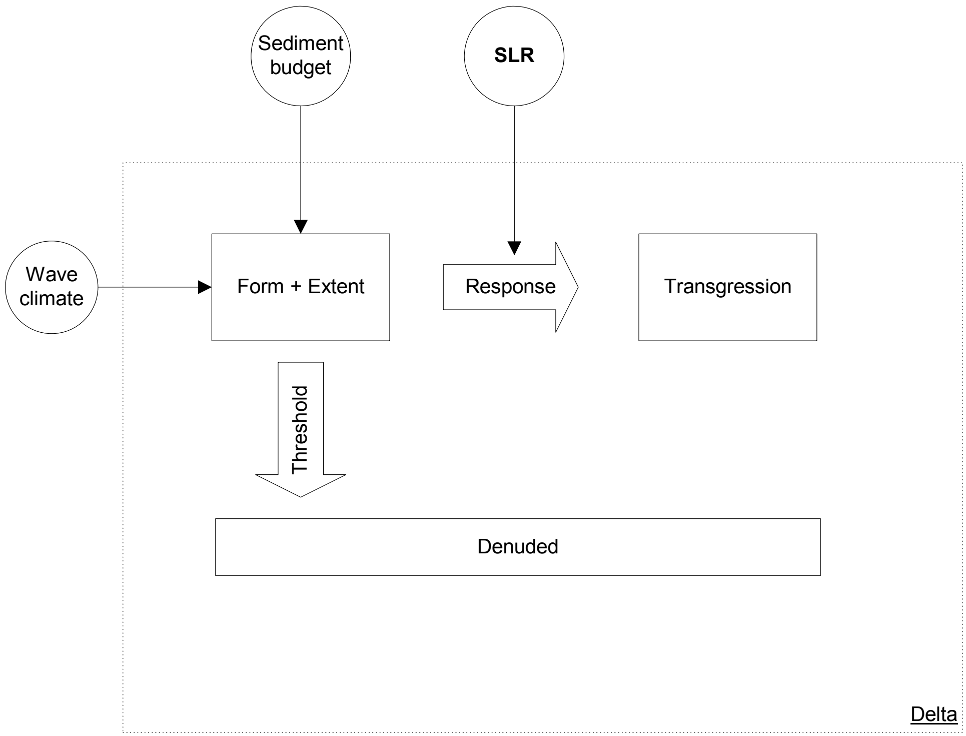

Figure A17. Medium to long-term system diagram – Delta

A6. Behavioural Description for Rock Platforms

A6.1 Definition of Geomorphological Element

Rock platforms are defined as relatively flat erosional rock bench bedforms extending across, and sometimes seaward of, the inter-tidal zone (Carter, 1988). It is important to note that they are affected not only by marine processes (such as mechanical wave erosion or abrasion by mobile non-cohesive sediments) but also by sub-aerial, chemical and biological processes that can serve to weaken the rock structure.

A6.2 Function

The function of a rock platform is to reduce wave and tidal energy before it reaches the upper inter-tidal zone. Additionally, as rock platforms erode (lower), so they: (i) control the rate of recession of backing cliffs; and (ii) release sediment, some of which can contribute to the littoral sediment budget (coarser material) and/or some of which can be transported in suspension offshore or into estuaries (finer material).

A6.3 Formation and Evolution

Rock platforms are often backed by sea cliffs and the lithology and geotechnical properties of the two are often closely related. Similarly to cliff evolution always being recessional (albeit at varying rates dependent on the rock geology), so shore platforms will not experience regression (seaward or vertical advance of the landform) since they represent a finite feature that can only become progressively more denuded. Consequently any erosion (lowering) that they experience is irreversible.

Shore platform lowering is initiated when the stresses acting on the feature exceed the shear strength of the material. This situation may arise due to a combination of a number of factors. In basic terms, these comprise external factors that may exist or occur which increase the shear stresses applied or internal factors that may exist or arise which result in a decrease in the shear strength of the material.

An example of the typical foreshore lowering rates of rock platforms comprised of rocks of different lithology is presented in Table A2.

Table A2. Typical Lowering Rates of Platforms Composed of Different Materials (Sunamura, 1983)

Cliff Composition	Typical Recession Rate (mm per year)
Granite	< 0.1
Limestone	0.1 to 1
Shales	1 to 10
Firm sandstone, mudstone	1 to 100

In depositional environments, beach sediments may sit on top of a shore platform and protect it (to some degree) against erosion, although such deposits are very mobile and, consequently, usually would only remain in-situ temporarily. Indeed, as they move across the platform, they can contribute to lowering processes through abrasion. In erosional environments, shore platforms would usually be bare of superficial sediment cover and subjected to slow rate, progressive lowering due to erosional forces.

Pethick (1984) identified that the presence or absence of a (semi-) protective sediment covering on the platform was not a simple relationship, but involved a feedback mechanism whereby a lowering of the shore platform would raise the effective depth of water. Hence, the platform would be subjected to reduced bed shear stress due to waves, with resulting values possibly being lower than the critical shear stress for erosion, at which point superficial sediments may once again begin to cover the shore platform.

A6.4 General Form

Bird (1968) identified three generic types of shore platform:

- Horizontal surface lying at high tide level;
- Horizontal surface lying at low tide level; and
- Sloping surface between high and low tide levels.

Despite the above classifications, Trenhaile (1978) identified that the mean elevation of shore platforms from around the world clustered around the mid tide level.

Shore platforms around the UK generally are gently sloping or quasi-horizontal in profile and variable in width, up to a maximum limit of 1km (Pethick, 1984).

A6.5 General Behaviour

In general terms, shore platform evolution displays a number of important components. Certain processes will lead to the detachment of clasts of material from the platform, which will then be transported by nearshore currents, often in a landward direction. These materials will then be deposited, often on the foreshore, where they constitute valuable sediment input to the beach material stock. Ultimately, these processes lead to a noticeable lowering of the elevation of the platform over time.

As previously stated, shore platform behaviour can only involve erosion, leading to lowering. The rate of lowering will depend upon a number of factors, which may: promote the erosion of clasts of material from the platform; and control the rate and direction of transport of the released material.

In broad terms, these factors can be influenced by the hardness, structure (e.g. faulting) and solubility of the rock, biological processes and the exposure of the platform to wave attack.

A6.6 Forcing Factors

The primary external cause of shore platform lowering is wave action, which may have the following impacts:

- Quarrying of rock by mechanical hammering, shock or air compression;
- Generating the oscillatory movement of abrasive particles across the shore platform, resulting in its denudation;
- Determining the subsequent transport of released material (i.e. moving sediments that potentially could provide a (semi-) protective covering away from the platform, re-exposing it to direct wave attack).

In addition to this, internal factors may result in a decrease in the shear strength of the material of which a shore platform is comprised, making the rock surfaces more susceptible to erosion by wave action. Mechanical, sub-aerial, chemical or biological weathering could cause such effects. For example, the alternating wetting and drying of the platform due to tidal movements results in water-layer weathering. This may involve physical rock breakdown caused by salt crystallisation or swelling of rock grains.

The fate (rate and direction of transport) of sediment released from platform lowering is dependent upon its composition, the direction and magnitude of the forces to which it is subjected.

A6.7 Evolutionary Constraints

Unlike many coastal landforms, shore platforms will only experience lowering over time since they constitute a finite feature, which is progressively subjected to erosion, leading to lowering.

At the most fundamental level, shore platform behaviour is dependent on:

- The strength of the material in the platform;
- The stresses applied to the platform; and
- The direction of transport of released material.

A6.8 Behavioural Timescales

A6.8.1 Short-Term (Responses Within a Year)

In the short-term, platforms will be subjected to erosion at locations where the rock has been weakened during periods of higher than usual wave and/or tidal energy exposure. This will release clasts of sediment from the platform that will subsequently be transported by the forcing conditions.

A6.8.2 Medium-Term (Responses Over Decadal to Century Scale Changes)

In the medium-term, behaviour is manifested though a general lowering of the entire platform.

A6.8.3 Long-Term (Responses Over Century to Holocene Timescales)

Over longer timescales, platform behaviour will be dominated by changes in relative sea level, affecting the elevation of a platform relative to water levels and hence exposure to erosive processes.

A6.9 Interactions with other Geomorphological Elements

A6.9.1 Cliffs

Hutchinson (1986) suggested that the rate of platform lowering controls sea cliff recession in the following way:

Rate of sea cliff recession = Rate of platform lowering/shore platform gradient

The implications of this relationship are that, irrespective of platform gradient, a lowering platform has direct implications for the degree of cliff recession. Both of these aspects in turn have implications on the volume (and type) of material that is released through erosion and becomes available to contribute to the littoral sediment budget (coarse sediments) and provide input to estuaries (fine sediment).

The rate of platform lowering can be reduced when a (usually temporary) veneer of sediment covers the platform (although this can actually also lead to increased erosion due to abrasion when the veneer is very thin and mobile).

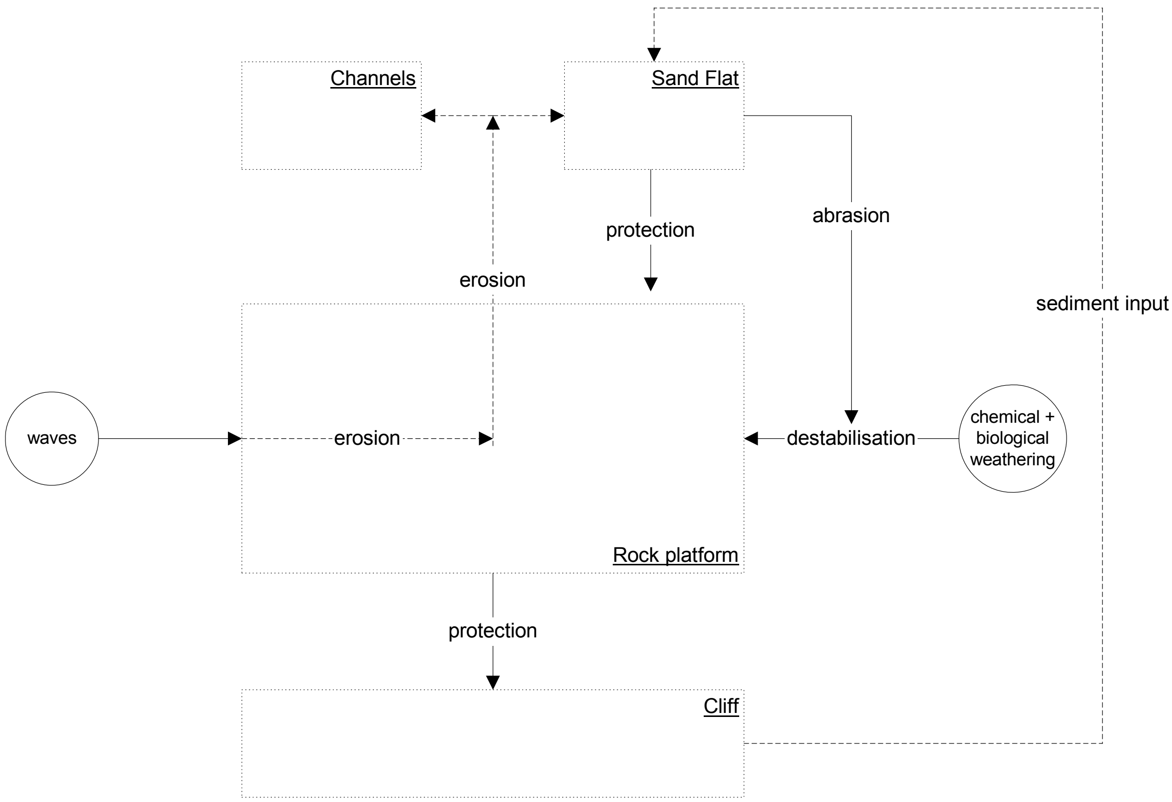

Figure A18. Interaction with other elements - Rock platform

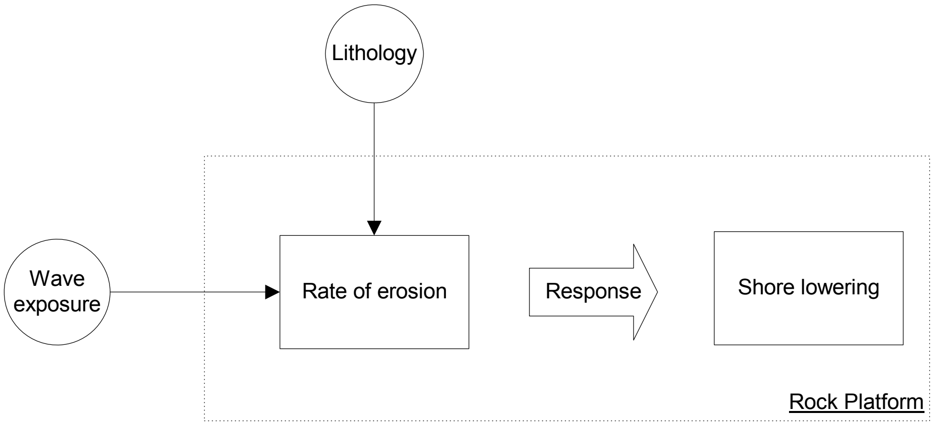

Figure A19. Short to medium term system diagram - Rock platform

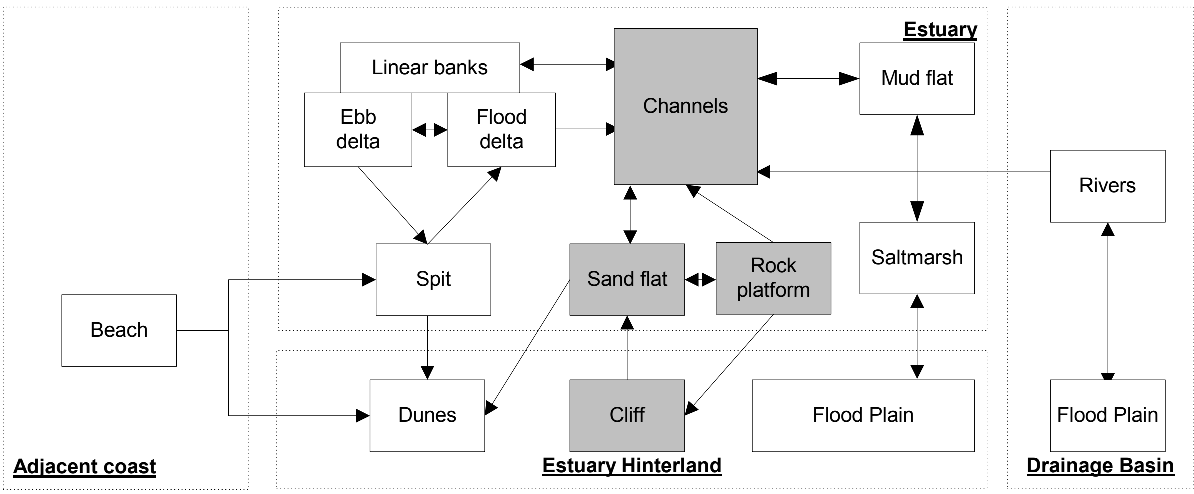

Figure A20. Medium to long-term system diagram - Rock platform

A7. Behavioural Description for Channels

A7.1 Definition of Geomorphological Element

Channels can be defined as sub-tidal morphological elements within the estuary bed, which are deeper than the surrounding deltas, banks or tidal flat features. The existence of these features is dependant upon favourable sediment and tidal conditions and can be present as a flood, ebb or main feature.

A7.2 Function

The main function of channel is the discharge of fluvial flows through the estuary to the marine environment. Channels also allow for the tidal exchange of saline waters. As such the channel therefore allows the transmission of energy and sediment throughout the estuary and in doing so provides the link between many of the geomorphic elements within the system.

A7.3 Formation and Evolution

The nature of the main channel will be dependant upon antecedent conditions and the degree of Holocene infilling with wave climate and tidal processes providing contemporary physical controls. The evolution of a main estuary channel is intrinsically coupled with evolution of the whole estuary form. A morphological concept that attempts to describe this evolution is based on the application of regime theory.

Regime theory describes an approach to channel theory that assumes some form of equilibrium relationship between certain morphological parameters, such as width, or depth and hydraulic parameters such as hydraulic slope, discharge, or flow velocity. A summary of the range of relationships available has been drawn together by Spearman and these are briefly summarised in (Spearman, 1995) and ABPmer Estuaries Morphological Guide (ABPmer, 2004). In its simplest form the relationship dictates that cross sectional area of a channel will adjust to changes in flows and *Vice versa* in order to attain equilibrium.

An alternative model of estuary and channel evolution is associated with tidal asymmetry (Pethick, 1994). In this model, tidal propagation within a wide deep channel results in a flood dominance and potential net import of sediment and accumulation on intertidal areas. As this change progresses, the morphological form evolves towards a central ‘slot’ channel with reduction in flood dominance and ebb dominance prevailing resulting in a potential export of sediment. Thus a morphological equilibrium is attained between the two channel types (See Figure A21, below)

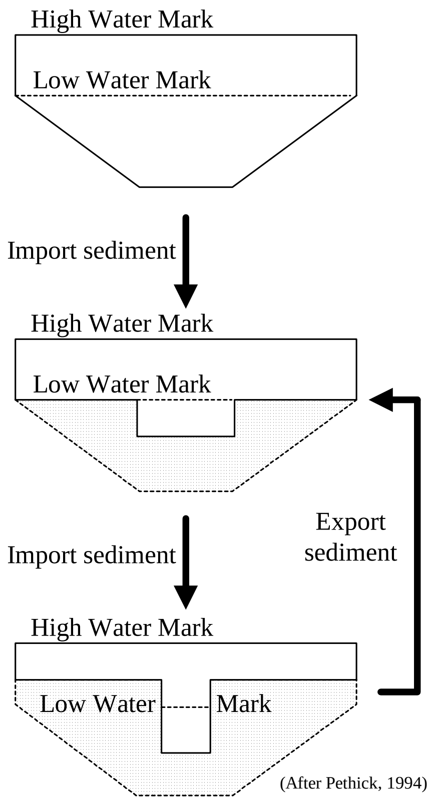

Figure A21. Stages of estuary development (Pethick, 1994)

A7.4 General Form

The general form of channels is highly variable and site specific. The principle forms of channel can be identified according to their function. Feeder channels exist linking the catchment basin to the main channel and the main channel provides the principle conduit for energy and sediment exchanges in the estuary. In certain cases, flood and ebb flow separation can occur, with peak velocities occurring in different channel at different stages of the tide. In large estuaries, the Coriolis force (due to the earth's rotation) can be an important factor in flow separation and the development of flood and ebb channels. In plan form, channels can vary form predominately straight, to meandering and braided. This form is related to channel length, gradient and energy distribution.

A7.5 General Behaviour

Channels have a range of behavioural responses to different forcing (van Rijn, 1998):

- **Meandering**. This behavioural response involves changes in the channel curvature due to erosion and accretion patterns along the channel edge. Depths will be greater and of a steeper gradient on the outside of the curve and shallower and of a gentler gradient on the inside. Meandering is an important characteristic found in the inner, or landward, sections of a number of estuaries. Meander formation in estuarine channels is complex, relative to fluvial channels, due to the presence of bi-directional flows and the mixing of saline and freshwater. Meander wavelengths in estuaries are related to tidal discharge and freshwater flows, with estuarine wavelengths greater than river wavelengths. Meandering in estuaries can be associated with mid channel shoals, either with switching occurring involving the migration of the channel from one to the other side of the shoal or flow separation either side of the shoal;

- **Lateral shift/channel switching**. A consequence of sediment erosion along the channel edges. This occurs in the direction of the net cross-channel sediment flux. Sediment eroded from the bars and shoals is transported into the channel and result in a reduction of the cross-sectional channel area. As a result of the systems need to return to equilibrium, currents will act to erode the channel sides resulting in a net shift of the channel. Channel instability of this nature is a process related to meandering and can be an important process in certain estuaries. This process can result in progressive lateral shifting of the channel, as defined by the movement of the thalweg, or sudden channel switching. The precise causes of catastrophic channel switching are likely to be estuary specific. However, at a generic level a number of triggers can be identified, such as high freshwater flows (above a critical threshold level and coincident with a certain tidal state) and antecedent conditions. Channel switching has been noted as an important process in a number of UK estuaries, notably including the Humber (Pontee *et al.*, 2004);

- **Widening and narrowing**. Changes in the channel form due to variations in the tidal volume passing through the channel;

- **Rotation**. A larger scale lateral shift can occur at the channel mouth. This can be a consequence of changing wave action or other forcing which acts to cause deposition on the updrift side and eroded on the downdrift side of the estuary. This change will be accompanied by channels on the ebb delta;

- **Length change**. This is a consequence of the currents cutting into a bar or shoal. This process results in an increase in channel length. Length changes may also occur due to channel infilling. This may result in a channel becoming incised or alternatively may cause an increase in channel sinuosity thereby increasing the channel length.

A7.6 Forcing Factors

Physical processes within a channel are essentially dependant upon the gross properties of the estuary within which the channel is a component, including:

- Tidal Range;
- Wave climate;
- River discharge;
- Channel scale (width and depth and cross sectional area); and
- Sediment availability and composition.

The interaction of these influences with the morphological form determine the specific internal characteristics and behaviour, including:

- Energy dissipation and speed of tidal propagation;
- Tidal asymmetry and ability for net import and export of sediment; and
- Degree of mixing (longitudinally and laterally) between saline and freshwater (and effect on sediment transport through residual currents, position of turbidity maximum and flocculation).

A7.7 General Behaviour

The behaviour of a channel will in part be a function of its location within the estuarine system. Upstream channels associated with the transitionary zone between fluvial and fully estuarine conditions will have a form dependant to a greater degree from fluvial discharges, where as the form of a main channel of an estuary co-adjusts with physical processes.

A7.8 Behavioural Timescales

A7.8.1 Short-Term (Responses Within a Year)

Over the short term channel behaviour will be influenced by episodic events, such as fluvial flood events. These events can act as triggers to channel switching.

A7.8.2 Medium-Term (Responses Over Decadal to Century Scale Changes)

Over the medium term, channels will also undergo a morphological adjustment to sea level rise. This response occurs over a long temporal period, but is ultimately dependant upon the rate of sediment supply and relative sea level change. Two examples have been taken from van Rijn (1998):

(1) Relatively rapid sea level rise

- Sediment supply is insufficient therefore the channels are unable to respond;
- The tidal channel volume will increase, in turn leading to an increased tidal prism;
- Whilst the channels will undergo some siltation, this will be more than balanced by increased channel dimension in order to accommodate for the increased tidal prism; and
- Channels within the outer delta will increase.

(2) Relatively slow sea level rise

- Sediment supply is sufficient to allow the channels to respond;
- Tidal channel volume, and thus tidal prism, remain constant; and
- Equilibrium is maintained, as the sediment supply and demand balance remains constant. However, if supply were to outmatch demand, deposition will occur. This may ultimately lead to a decrease in the tidal prism and estuary closure.

A7.8.3 Long-Term (Responses Over Century to Holocene Timescales)

Over the longer term, the development of the channel will be linked to the evolution of the overall estuary form. The channel is likely to widen or narrow and lengthen or shorten as the estuary translates in position in response to relative changes in relative sea level.

A7.9 Interactions With Other Geomorphological Elements

A7.9.1 General Interactions (Elements Within the Estuarine System)

Whilst the responses of the channels have been described above in the context of sea level rise, the changes that occur will be intrinsically linked to other features within the estuarine system. Indeed any changes to the form and behaviour of channels will be observed in corresponding changes to, primarily, the intertidal area (saltmarsh and mudflat), deltas and banks and spits.

This process occurs as the migration of channels allows the release of sediment surrounding geomorphic elements e.g. sand and mudflats, saltmarshes, dunes, spits, etc. This sediment is then available to be reworked by the prevailing processes and deposited elsewhere to contribute to these existing geomorphic elements or form new versions of the pre-existing elements.

In addition to this direct impact on features from channel migration, the movement of the channel may also impact on adjacent features through changes to the degree of exposure to wave and tidal action.

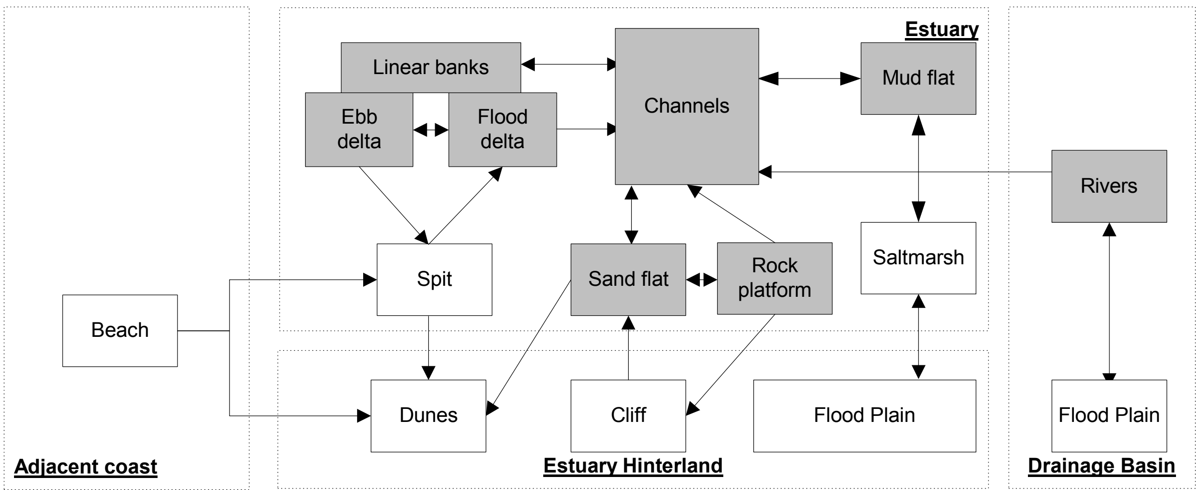

Figure A22. Interaction with other elements – Channels

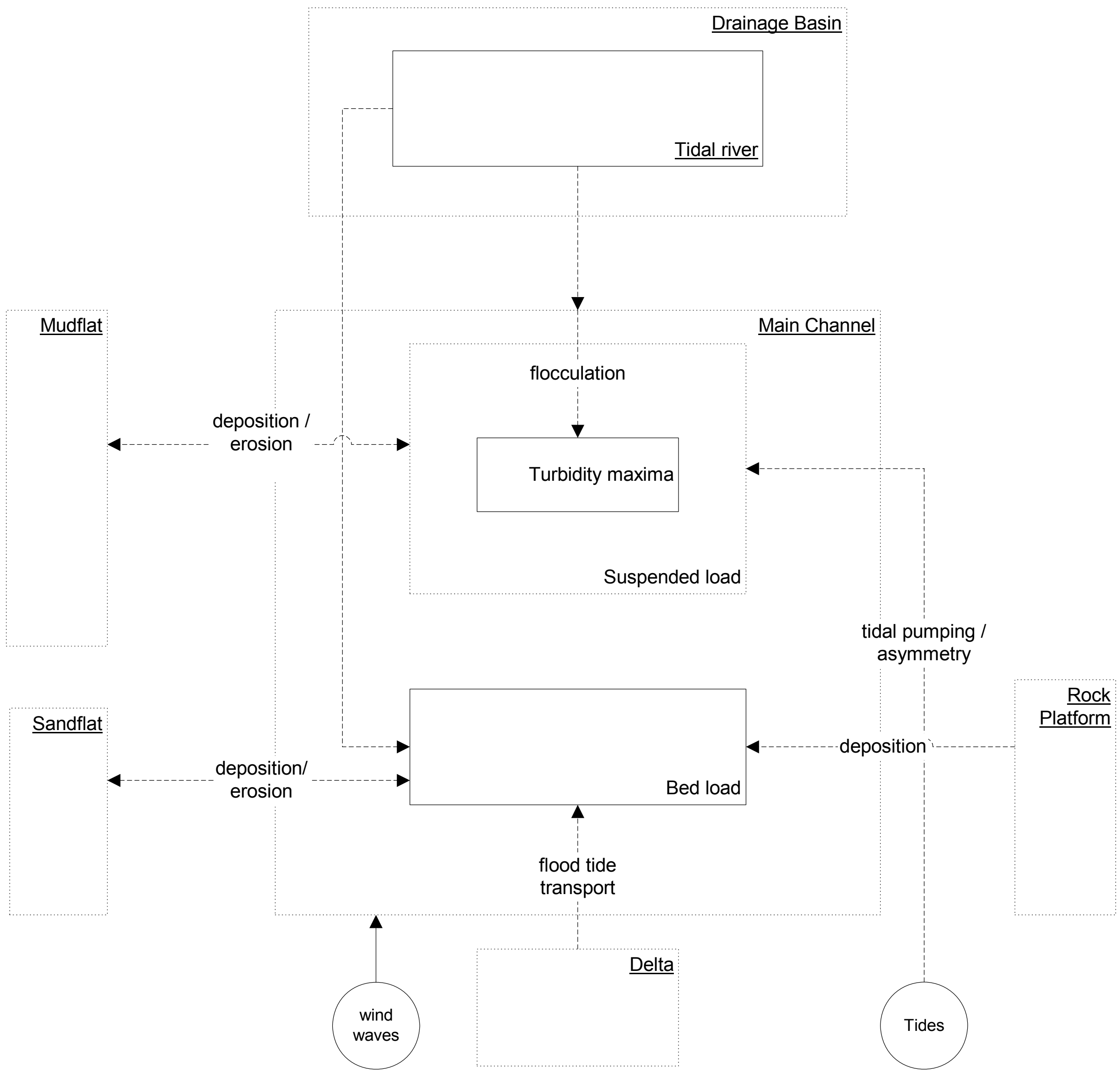

Figure A23. Short to medium term system diagram - Channels

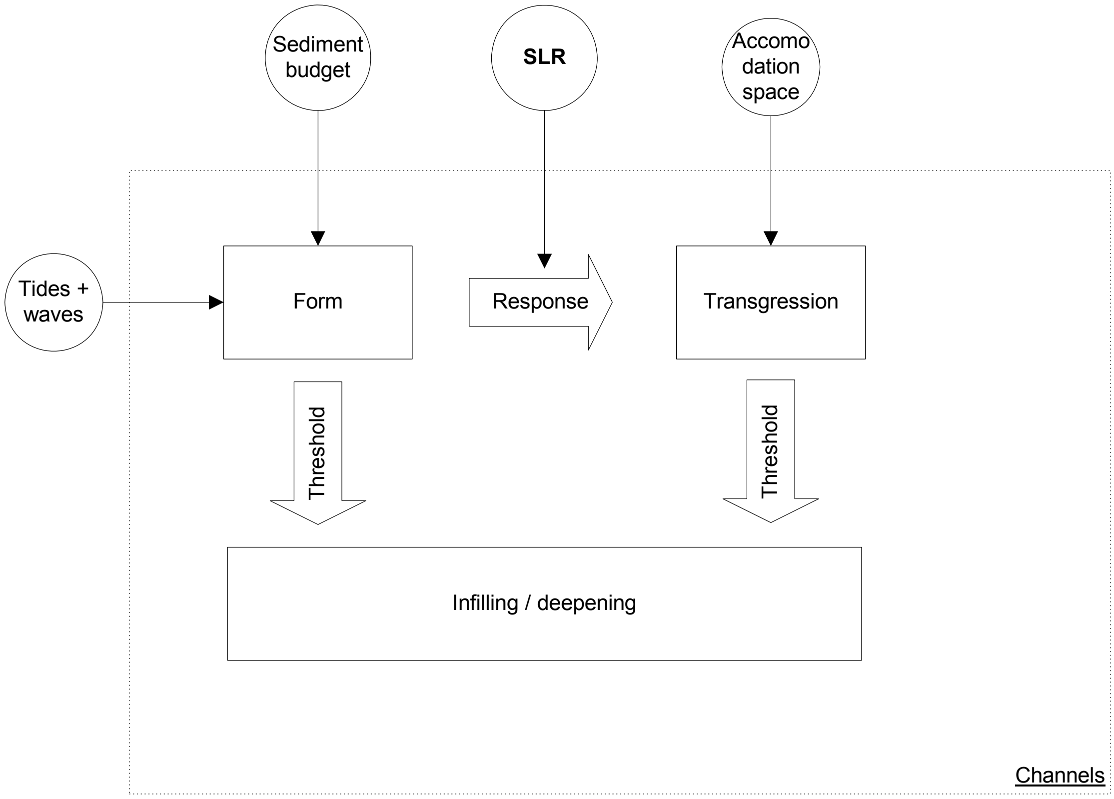

Figure A24. Medium to long-term systems diagrams - Channels

A8. Behavioural Description for Mud Flats

A8.1 Definition of Geomorphological Element

Intertidal mudflats can be defined as accumulations of cohesive sediments found along the margins of estuaries where there is a sufficient supply of fine grained sediment and prevailing conditions that permit their deposition in intertidal areas. Mudflats occur in estuaries from around the mean low water mark to around the mean high water mark. Therefore mudflats are often bounded to their seaward side by the subtidal channel of an estuary and to the landward side they translate into areas of saltmarsh. In areas where saltmarsh is absent on the landward side of the mudflat the flat may be bounded by some form of sea defence or the rising topography of the hinterland.

A8.2 Function

Within an overall estuarine system, a mudflat performs a number of functions. In terms of energy, the main function is the dissipation of wave and tidal energy. In terms of sediments, the mudflat can act as a source or a sink for fine grained sediments depending on variations in the factors controlling mudflat development.

A8.3 Formation and Evolution

It has been suggested that there are two end conditions, or profiles states, in terms of mudflat cross-shore profile shape (Kirby, 1992, see Figure H1). These two profile states can be related to the general behaviour of the profile and the prevailing forcing processes.

- Convex Profile: This profile shape involves the steepest (i.e. highest gradient) section being located close to the low water mark (i.e. the lower mudflat). The minimum slope will be towards the upper end of the profile (i.e. the upper mudflat). This profile is associated with depositional processes, whereby there is a net increase in sediment on the mudflat over time (Dyer, 1998).

- Concave Profile: This profile involves the maximum slope occurring at the upper mudflat with the minimum slope close to low water. This profile shape is associated with erosion and a net deficit in terms of sediment input. This type of profile is often characterised by a small cliff at the saltmarsh - mudflat boundary. This feature is present due to the fact that a steep slope occurs at the top of the profile concentrating wave attack at high water over a narrow area of mudflat (Dyer, 1998).

Characterising a mudflat according to profile shape provides a good initial basis with which to understand the behavioural trends of this geomorphological element. As profile shape can be related to behavioural trends such as erosion or deposition, these trends can in turn be related to the processes that are dominant in causing, or controlling, the trends. The convex, depositional profile is generally associated with mudflats dominated by tidal flows whereas a concave, erosionary profile is generally associated with mudflats dominated by wave action.

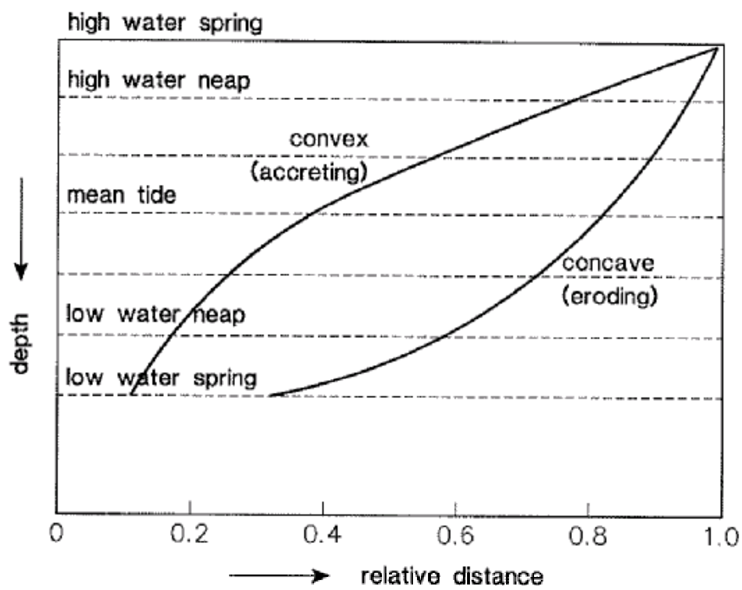

Figure A25. Characteristic concave and convex mudflat profiles (van Rijn, 1998)

Relating profile shape to behaviour is, however, a general rule and cannot be universally applied. The contradiction of this general rule is likely to reflect the influence of another factor on behaviour or the occurrence of a constraint to morphological development that prevents the natural behavioural tendency. One influence on profile shape that has been suggested is shore plan shape, with lobate shorelines demonstrating slightly more concave profiles and embayed shorelines a less concave profile.

In reality mudflats are likely to be between these two end states of concave and convex and it is possible that elements of both will be present within the same profile. As such, the profile at any point in time will reflect the dominance of the various driving forces and constraints at that time.

A8.4 General Form

Mudflats can be subdivided by their cross-sectional profile. This profile can be conveniently divided into three sections, as follows (Dyer, 1998):

- The lower mudflat: from mean low water springs to mean low water neaps;
- The middle mudflat: from mean low water neaps to mean high water neaps; and
- The upper mudflat: from mean high water neaps to lower margins of saltmarsh or mean high water springs.

On this profile a distinctive break in gradient often exists within the middle mudflat, distinguishing the lower from the upper mudflat.

A number of morphological features are often present on the mudflat profile. Channels cutting through the mudflat have a variety of forms and vary in depth and nature according to their location on the mudflat profile and the width of the flat. The occurrence of cliff features within the mudflat are generally an indication of erosional processes (Dyer, 1998), although it should be noted that these features can also be formed in accretional environments. Most commonly these features either occur at the upper limit of the mudflat (i.e. at the boundary with saltmarsh) or around mid-tide level, where the break in slope between the upper and lower mudflat occurs.

A8.5 General Behaviour

The behaviour of the mudflat will be dictated to a large extent by the balance between erosion and deposition processes.

A8.5.1 Deposition

Cohesive sediments are fine grained and as such will be transported as suspended load as opposed to bedload. Deposition of suspended sediments will occur when the settling velocity of the sediments is greater than the shear velocity of the flow. In accordance with this the rate of deposition will therefore, be controlled by the velocity of flows, suspended sediment concentrations and the grain size of material in suspension.

The grain size of a suspended sediment particle will determine its settling velocity. This will, in the case of cohesive sediment, be relatively low and based on this velocity alone a particle would not have sufficient time, even during slack water periods, in which to settle through the water column and deposit on the mudflat. However, the process of flocculation makes the deposition of the fine grained, cohesive sediments on a mudflat possible.

A8.5.2 Erosion

Erosion of mudflats mainly consists of the re-suspension of cohesive sediments. The rate of erosion is controlled by the balance between wave and current induced shear stress and mud shear strength and the duration of exposure of sediments to wave attack and flows.

The shear stress imposed, by waves on the mudflat is determined by the wave height and the water depth (as a function of tidal range as discussed above).

The shear strength of the mudflat (i.e. the erodibility) will be determined by a number of factors. The most influential of these is de-watering of the deposited sediments. This occurs during exposure to the atmosphere due to the fall of the tide. The decrease of surface moisture content that occurs during the de-watering process results in cohesion. This cohesion has the effect of raising the threshold for sediment erosion. Biological processes can also impart additional strength on the sediments (e.g. algae acting to bind sediment together).

A8.5.3 Wave Current Interactions

The above sections have discussed the relative important of waves in exerting a control on the erosion of mudflat sediment and tidal current in the deposition of sediment on the mudflat. These roles can be explored further to provide an insight into how their interaction exerts a control on mudflat behaviour and hence form. Waves are rapidly attenuated across a mudflat and refracted to be approximately shore normal. Wave action acts to stir up the bed and re-suspend sediments. The subsequent transport of these sediments is however, then controlled by tidal flows.

A8.5.4 Biota

It is also important to recognise the role of biota in exerting an influence on the processes of erosion and deposition on an intertidal mudflat. This is the subject of ongoing research attempting to further understanding and quantify the influence of biota. Within the EstProc (EstProc, 2004) project investigations have focused on quantifying the impact of biota on estuary hydrodynamics and sediment dynamics.

In broad terms the influence of biota can be grouped into stabilising processes or destabilising processes. These processes will obviously exert an influence on erodibility, either contributing to accretion or erosion across a mudflat.

A8.6 Forcing Factors

The processes of transport erosion and deposition of suspended sediments are driven by the forcing from waves and tidal currents.

Wave processes across mudflats will largely dictate erosion, or re-suspension, of sediments across the mudflat profile. Sediment cohesion following deposition and exposure of material will raise the erosion threshold such that re-suspension by tidal currents on following tides is less likely. As a result of this, waves control mudflat erosion and ultimately provide a check on mudflat morphology.

The duration of wave attack is a crucial factor determining the degree of erosion. The period over which any particular location on a mudflat profile is exposed to wave attack is a function of tidal range. Typically, tidal range therefore exerts a fundamental influence, or constraint, on the extent of intertidal mudflat in an estuary. Intuitively, considering this principle, the greater the tidal range, the shorter the duration of wave attack at high water and therefore the greater the extent of fine-grained mudflats. Mudflats are likely to be much more extensive in macro- relative to meso-tidal estuaries.

Due to the relatively low settling velocities of cohesive sediment, settling through the water column and deposition on the mudflat surface is unlikely to occur under wave action. Tidal flows across mudflats largely dictate deposition of sediments on the mudflat. As tidal level rises, velocities increase until around the mid-tide level, when half the flats are covered and velocities are at their maximum. As the tide reaches the upper mudflats at high water, velocities fall approaching slack water (Pethick, 1984). Deposition rates would therefore be expected to be greatest on the upper mudflat. This depositional process associated with varying tidal velocities results in a grading of sediment composition, with sediments on a mudflat fining landwards (Pethick, 1984). In general, deposited sediments can vary from sandy silts below mid-tide to silty clays in the high tide zone.

The role of waves and currents in forcing, and hence controlling form, can also be considered with reference to tidal flat hypsometry (i.e. the distribution of surface area with respect to elevation). Hypsometric trends on tidal flats can be related to the relative dominance of waves or tidal currents. Under wave domination, a concave hypsometry results while a higher relative importance of tides leads to convex hypsometry and long-term accretion. Plan shape has also been shown to exert a significant influence on tidal flat hypsometry, with this influence of equal importance to the dominance of either waves or tides.

A8.7 Evolutionary Constraints

A number of constraints to mudflat development can be identified:

- Suspended Sediment Supply: The process of mudflat formation and subsequent evolution is dependant on a supply of cohesive sediment. This supply is required to allow the mudflat to adjust to the applied driving forces.

The development of a mudflat under a scenario of adequate suspended sediment supply and a deficit in supply would be significantly different.

- Migration Space: The dynamic nature of mudflats mean they require space in which to migrate in response to changing conditions. A lack of migration space will constrain the position of the mudflat profile and result in different behavioural trends. There are many forms of constraint that fall under the overarching migration space heading. These can be either natural (such as a geological hard point or rapidly rising hinterland topography) or man-made (such as sea defences).
- Tidal Range*:* Tidal range can be considered a constraint to evolution in the sense that it will control the extent, and to some degree the composition, of mudflats that can develop in an estuary.

A8.8 Behavioural Timescales

A8.8.1 Short-Term (Responses Within a Year)

Over tidal cycles, a process of sediment re-cycling occurs on mudflats. This process involves the transport of material between the upper and lower mudflat on successive tides. This recycling and movement of sediment within the mudflat profile is the mechanism through which the profile is able to respond the variations in forcing over these short time scales.

A8.8.2 Medium-Term (Responses Over Decadal to Century Scale Changes)

Mudflat behaviour over this timescale is driven by the occurrence of low frequency, high magnitude wave events and intervening calmer periods. A mudflat may exhibit accretional or erosional behaviour depending on the prevailing forcing. This behaviour will be reflected in the mudflat profile. In addition to these changes in form, changes may also occur in the vertical and horizontal position of mudflats over this timescale.

Additionally, over this timescale, mudflat behaviour may be influenced by migration of any adjacent channels, affecting the degree of mudflat exposure. Biotic factors can also play a role in influencing mudflat behaviour. For example, the presence of eelgrass can afford a mudflat surface a degree of protection from prevailing surface. Any change in the presence or extent of eelgrass may therefore affect behaviour.

A8.8.3 Long-Term (Responses Over Century to Holocene Timescales)

Mudflat behaviour over this longer timescale is driven by relative sea level rise. The behavioural response to this forcing is variable and dependant on a number of factors. As a result a number of different scenarios can be considered each with different potential behavioural responses.

Under a scenario of adequate supply of suspended sediment and sufficient migration space for the mudflat to migrate into (i.e. no geological or man made constraints) the response of the mudflat would be to accrete vertically and migrate landward to maintain the same position in the tidal frame.

Under a scenario of restricted suspended sediment supply, the mudflat is unlikely to be able to accrete to keep pace with relative sea level rise. This accretion is required if the mudflat is to maintain its position within the tidal frame. The lack of sediment to achieve this may result in the eventual drowning of the mudflat profile.

Under a scenario of restricted migration space, e.g. through rising topography or a fixed line of sea defence, the mudflat would attempt to migrate landwards. However, with a static landward margin the mudflat would become progressively squeezed between the migrating mudflat edge and the static landward boundary. This is the process of coastal squeeze.

A8.9 Interactions With Other Geomorphological Elements

A8.9.1 Saltmarsh

Mudflats and saltmarsh are interdependent geomorphological elements. Given the dependence of the two units it is vital to consider the two in conjunction with each other and to do this each of the links must be clearly defined, as follows:

Mudflat development essentially creates a low energy environment at an elevation relative to the tidal frame that is conducive to saltmarsh development. As mudflats develop, under adequate sediment supply, their ability to dissipate wave energy will increase and as a result the upper mudflat will progressively become a low energy environment. This environment encourages sediment deposition and as a result elevations increase. Hence the mudflat is progressively able to provide a surface at the correct elevation for saltmarsh colonisation.

Under relatively benign forcing conditions, there is likely to be a transfer of sediment from the mudflat surface to the saltmarsh to be deposited on the saltmarsh surface. Exchanges from saltmarsh to mudflat mainly occur during high magnitude low frequency events. Under these conditions, the saltmarsh acts as a temporary sediment supply to the mudflat. This supply is caused by the increased wave energy eroding the saltmarsh and transporting the material onto the neighbouring mudflat. In geomorphological terms, this supply of material allows the mudflat to adjust its profile to the applied forcing through widening and flattening.

In addition, under these storm conditions the saltmarsh provides migration space into which the mudflat can migrate to allow the morphological response of profile widening.

A8.9.2 Channel

The channel is the mechanism through which the main forcing factors (tidal flows and waves) are applied to the mudflat surface. The location and nature of the channel will determine the degree of exposure of the mudflat to these processes.

A channel acts as a conduit for sediment transport to the mudflat. Variations in the supply from this source would significantly affect the behaviour of the mudflat. In addition the deposition of sediments within the subtidal channel may affect the availability of sediment for deposition on the mudflat.

A8.9.3 Protective Features

For prevailing conditions to allow the formation and maintenance of mudflats, a degree of protection is required. In the middle and upper sections of an estuary, the form of the estuary itself is likely to provide this. However, in the outer sections of an estuary this protection may be afforded by another geomorphological element, such as a spit, a sandflat or an ebb tidal delta.

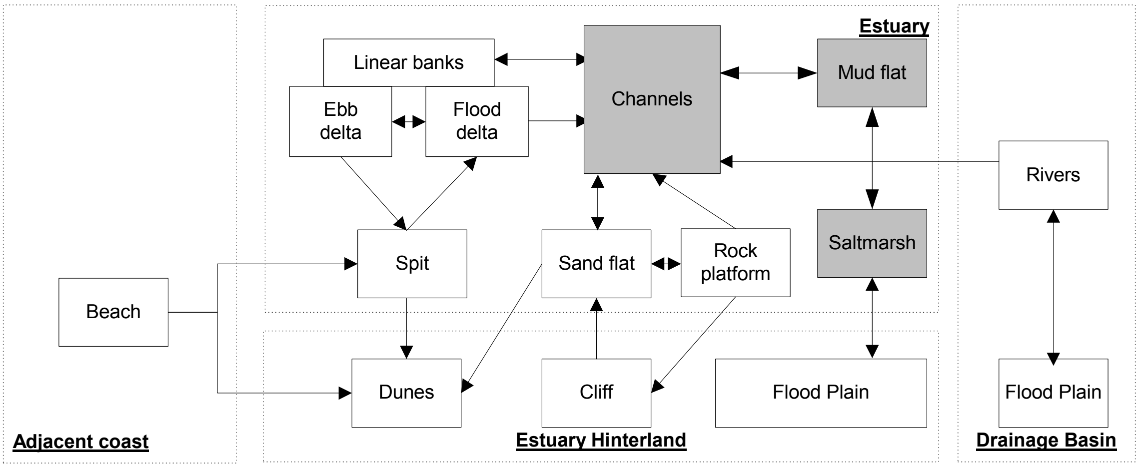

Figure A26. Interaction with other elements - Mudflats

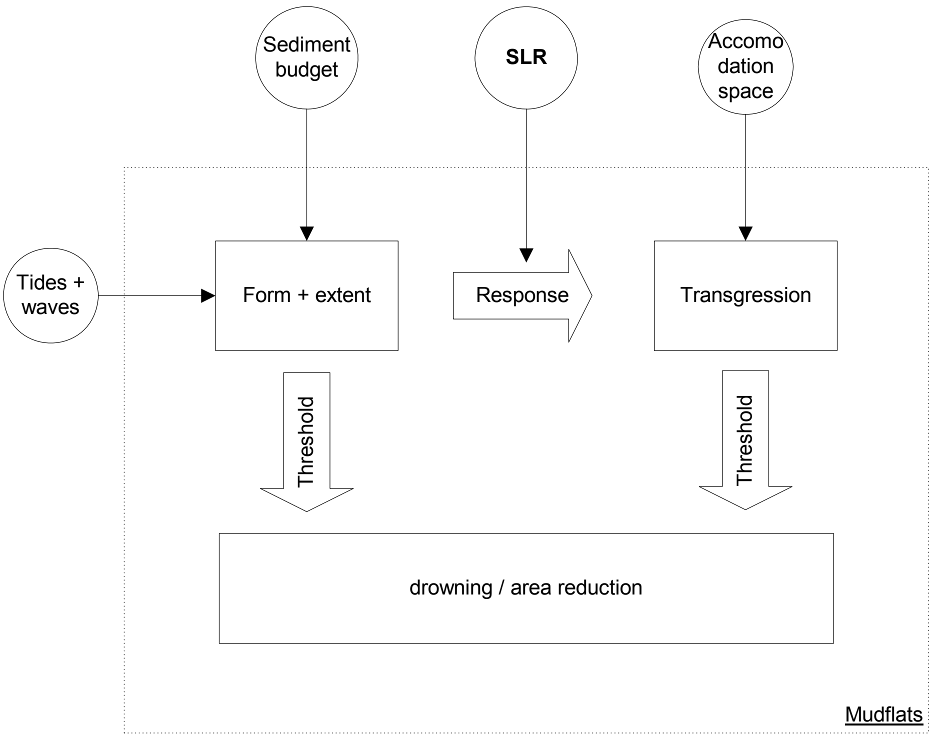

Figure A27. Short to medium term system diagram - Mudflats

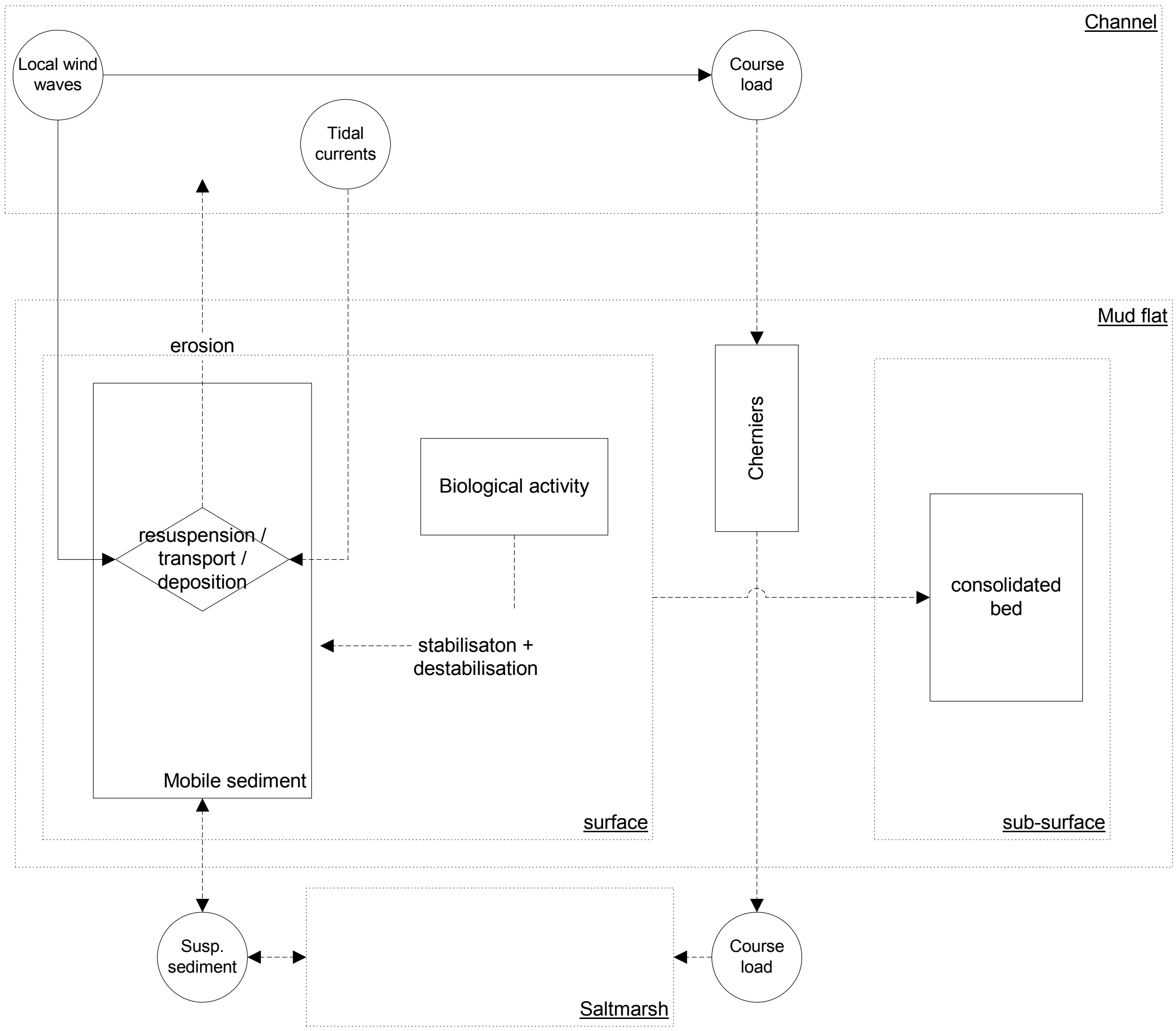

Figure A28. Medium to long-term system Diagram - Mudflat

A9. Behavioural Description for Sandflats

A9.1 Definition of Geomorphological Element

Distinction has been made here, for the purpose of defining morphological behaviour, between mudflats and sandflats. It is recognised that these landforms are part of an intertidal continuum and in many cases will occupy a similar position within an estuary in terms of the tidal frame. However, as noted, the primary concern here is behaviour and the two forms will exhibit subtle behavioural differences. These differences are the product of the differing nature of cohesive and non-cohesive sediments. The resultant changes to behaviour are explored in the following sections. It is recommended that this statement be read in conjunction with the mudflats statement.

Intertidal sandflats are defined here as accumulations of non-cohesive sand sized sediments deposited in the intertidal areas of an estuary.

A9.2 General Function

The function of a sandflat is the dissipation of wave and tidal energy. This is in common with that of a mudflat. However, differences in the interaction of form and processes, and hence energy dissipation, between the sandflats and mudflats is fundamental to behavioural differences. Sandflats also act as a store of sediment within the estuarine system.

A9.3 General Behaviour

The behaviour of a sandflat will be linked to the balance between the processes of erosion and deposition. However, the will be a subtle difference in the balance between the two processes on a sandflat relative to a mudflat. This is a critical distinguishing behavioural difference between a cohesive and non-cohesive intertidal area and is dictated by the different responses of the two sediment types to forcing conditions. The key behavioural difference is due to the difference in the critical erosion threshold between the two forms. Mudflat sediments will be more resistant to erosion (Pethick, 1984) with a higher erosion threshold than non-cohesive sandflat sediments. This difference will affect sediment transport on a sandflat and will alter the nature of the behavioural responses of this element over different timescales. Lee & Mehta (1997) note that mud profiles are generally flatter than their sand counterparts.

A9.4 Forcing Factors

Both tides and waves will play important roles on sandflats. In addition to the direct influence of both these processes, tides will also play a role in behaviour by controlling the location of wave processes across the profile and hence the duration of wave attack. A combination of the tidal range and the sand flat profile will control the width over which wave process will be translated.

A9.5 Behavioural Timescales

A9.5.1 Short-Term (Responses Within a Year)

Over the short term, a sandflat is able to alter its profile to adapt to variations in forcing, for example seasonal variations in wave climate.

A9.5.2 Medium-Term (Responses Over Decadal to Century Scale Changes)

Over this medium timescale, a sandflat is likely to adopt a profile form in response to trends in forcing (for example changes in storminess). In addition to these changes in form, changes may also occur in the position (both vertical and horizontal position) of sandflats within the estuary system over these timescales.

Additionally, over this timescale, sandflat behaviour may be influenced by migration of any adjacent channels, affecting the degree of sandflat exposure.

A9.5.3 Long-Term (Responses Over Century to Holocene Timescales)

Sandflat behaviour over this longer timescale is driven primarily by relative sea level variations, with the nature of the response controlled by a number of factors. As a result a number of different scenarios can be considered each with different potential behavioural responses. Sandflat behaviour over this timescale is similar to that described for mudflats:

Assuming an adequate supply of sediment and sufficient migration space for the sandflat to migrate into (i.e. no geological or man made constraints), the response of a sandflat under rising relative sea levels would be to accrete vertically and migrate landward to maintain the same position in the tidal frame.

Under a scenario of restricted sediment supply, the sandflat is unlikely to be able to accrete to keep pace with relative sea level rise. This may result in the eventual drowning of the profile. Under a scenario of restricted migration space, e.g. through steeply rising topography or a fixed line of sea defence, the sandflat would attempt to migrate landward but would become progressively squeezed between its migrating seaward edge and the static landward boundary. This is the process of coastal squeeze.

A9.6 Interactions With Other Behavioural Elements

A9.6.1 Beach/Dune

Sand flats may in certain situation be backed by beach and dune systems to the landward side. Where present, the behaviour of these elements will be closely linked. The formation of a dune system to landward of a beach and sandflat will be controlled by a number of factors. The period of drying will dictate if the required aeolian transport of sands will occur. This will in turn be controlled by the period tidal range and cross-shore profile of sandflat. In addition the sediment composition will exert an influence as will the orientation of the flat with respect to prevailing winds.

A9.6.2 Channel

The channel is the mechanism through which the main forcing factors (tidal flows and waves) are applied to the sandflat surface. The location and nature of the channel will determine the degree of exposure of the sandflat to these processes.

The channel will provide the main conduit for sediment transport supplying the sandflat with sediment (sediment may have originally been derived from offshore via longshore drift movement on a spit and through an ebb/flood delta). During erosional events, sediment may also be lost to the channel for redistribution within the system.

Lateral migration of a channel may erode a sand flat, thereby releasing sediments into the estuary system.

A9.6.3 Cliff

In a situation where a sandflat is directly backed by a cliff, cliff erosion can provide a direct feed of material during high energy conditions. A sandflat will also provide energy dissipation to a backing cliff feature providing protection.

A9.6.4 Rock Platform

In the case where a rock platform is present, overlying sandflat sediment may aid erosion of the rock platform through abrasion but can also provide protection from direct wave attack.

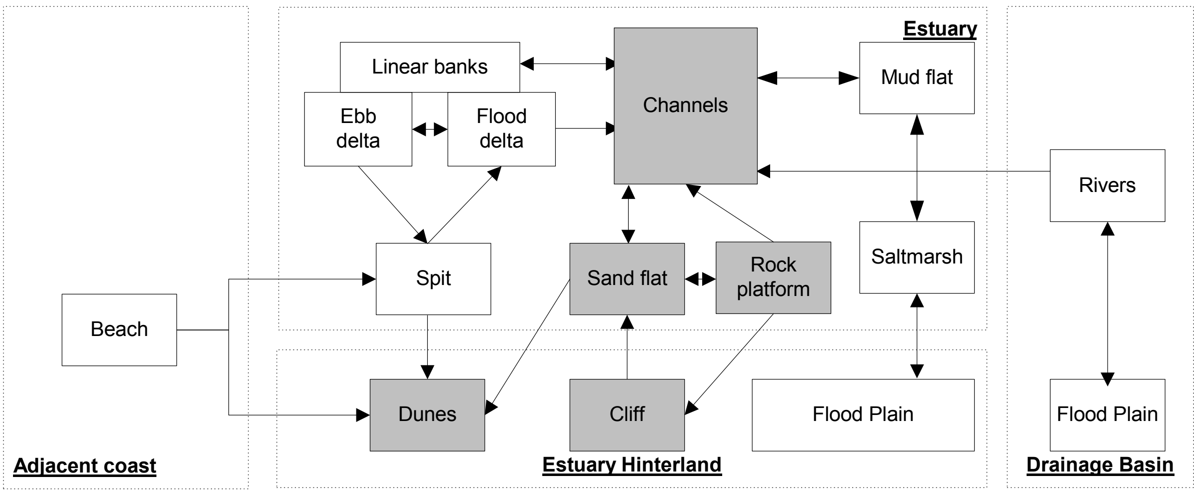

Figure A29. Interaction with other elements - Sandflats

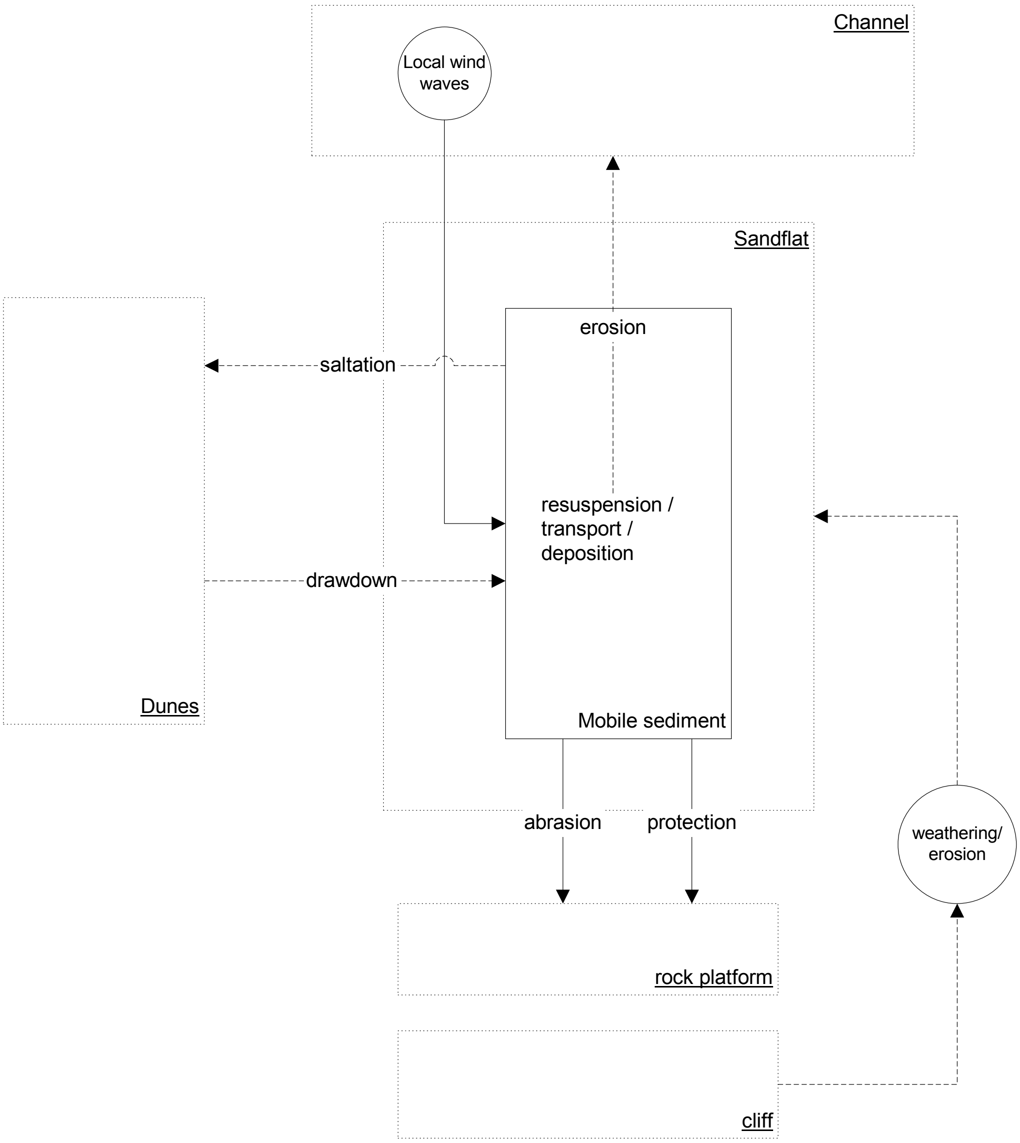

Figure A30. Short to medium term system diagram - Sandflats

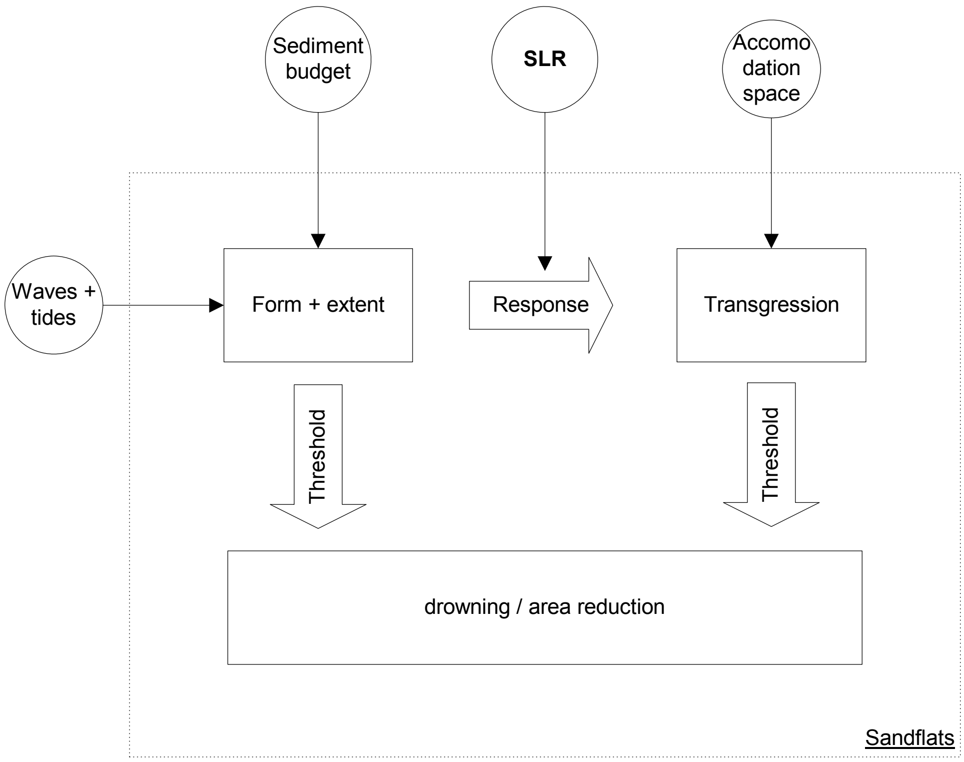

Figure A31. Medium to long-term system diagram - Sandflats

A10. Behavioural Description for Saltmarsh

A10.1 Definition of Geomorphological Element

Saltmarshes can be defined as accumulations of cohesive sediments vegetated by salt tolerant plant species found along the intertidal margins of estuaries. Saltmarshes generally occupy the upper inter tidal zone at higher elevations of mudflats, in areas inundated less frequently by the tide in the UK. Typically saltmarshes occur between mean high water neaps to high water spring tides. Above this elevation, the marsh is likely to give way to either terrestrial fresh water plant species or some form of defence or sea wall or the rising topography of the hinterland. At its lower margins saltmarsh is likely to be bounded by mudflat. In areas without mudflat, saltmarsh may adjoin the main sub tidal channel of an estuary or lie in the lee of a feature that acts to dissipate tidal and wave energy. The presence of vegetation on the saltmarsh surface results in significantly different processes, morphology and behaviour relative to neighbouring mudflats.

A10.2 Function

Within the overall estuary system areas of saltmarsh act to dissipate wave and tidal energy and hence afford protection to the adjacent hinterland, in addition a saltmarsh represents a significant sink for sediments within the estuary.

A10.3 Formation and Evolution

For saltmarsh to develop there is a requirement first for a sandflat or mudflat to form and evolve. For this to occur the prevailing conditions must be conducive to the transport and deposition of cohesive sediments. This requires a relatively sheltered low wave energy environment with adequate supply of suspended sediments. Eventually, as elevations rise at the upper mudflat, this process will lead to a decrease in the duration of tidal inundation on the upper intertidal (Pethick, 1984). A critical point will be reached where the duration of exposure of the mudflat permits colonisation by halophytic (salt tolerant) vegetation.

The higher the tidal range the larger the vertical range of any saltmarsh habitat. In terms of tidal inundations, sites with elevations that will experience less than about 450 tidal inundations would be expected to develop saltmarsh, whereas mudflat will develop at levels that experience greater that 500 inundations per year (Burd, 1995).

Initial colonisation is likely to occur on mudflat areas of higher elevation than the surrounding intertidal. These higher elevation areas could be the result of a number of factors, such as:

- Organic activity; and
- Relatively higher areas between pre existing mudflat channels.

The establishment of this initial vegetation then encourages further sediment deposition and further colonisation, forming patches of vegetation (Pethick, 1984). In addition, marshes may grow up around existing creeks within intertidal flats. Patches of developing vegetation will, over time, become joined to form a continuous area of vegetation. As this development takes place, important changes also occur to the flow regime across the newly formed marsh. Flow becomes more confined to channels or creeks. As accretion of the marsh surface occurs the number and duration of tidal inundations is further reduced. This allows different plant species to colonise these higher levels of the marsh.

Over the long term the rate of deposition decreases as the reduced tidal inundations limit the sediment supply. A marsh matures asymptotically, towards an elevation at which further deposition is sufficient to offset the effects of relative sea level rise and compaction.

A10.4 General form

When considering the form and behaviour of areas of saltmarsh it is convenient to consider the different geomorphological features that are present within this element. Four principal component features occur on areas of saltmarsh. These are:

- Saltmarsh surface;
- Creeks;
- Salt pans; and
- Cliffs.

Each of these features will be controlled by different processes and hence will perform a different function or role within an overall area of saltmarsh. However, it is the combination and interaction of each of these features that will determine the behaviour of the saltmarsh system as a whole. The processes associated with each of these features are discussed below.

A10.4.1 Saltmarsh Surface

A large proportion of saltmarsh area is marsh surface. The saltmarsh surface plays a role in the dissipation of wave and tidal energy. Studies regarding the role of the marsh surface in wave attenuation have shown that wave height reduction over saltmarsh is approximately four times higher that over sand flats. In addition, the marsh surface acts as a significant sink for sediments.

Marsh surface behaviour will vary both vertically and horizontally in the long term. Vertical variations will occur as the marsh matures in a feedback relationship between elevation, tidal inundation and sedimentation. Short term vertical variations may also occur, driven by variations in, for example, suspended sediment concentration and biological activity.

The cross-sectional shape of a saltmarsh is likely to vary over time. The variations are a reflection of spatial variations in sediment deposition across the marsh surface. A convex profile will be produced when sedimentation rates are greatest towards the centre of the marsh, falling off to landward and seaward, whereas a concave profile will be the result of deposition towards the upper or lower sections of the marsh. A number of factors will control the shape of the saltmarsh profile, not least the maturity of the marsh, i.e. the stage of development of the marsh will dictate where on the marsh surface the zone of maximum accretion occurs.

The typical mature cross sectional profile of a saltmarsh can be characterised as convex - concave (See Figure A32) (Pethick, 1984). At the seaward margin the saltmarsh exhibits a convex profile, with a flat main central section and a concave landward slope. This profile is a reflection of the number of tidal inundations and therefore the likely deposition rates i.e. a convex lower slope indicative of deposition processes at the lower marsh where inundation numbers and durations will be highest and the concave upper marsh landward slope located in an area of limited inundation and hence limited deposition (Pethick, 1984).

In horizontal terms, the marsh surface may extend or migrate landward or seaward. The seaward limit of the saltmarsh surface can be marked by the presence of a cliff feature up to 1m in height. These cliffs can be formed and develop in both an erosional and accretional environments.

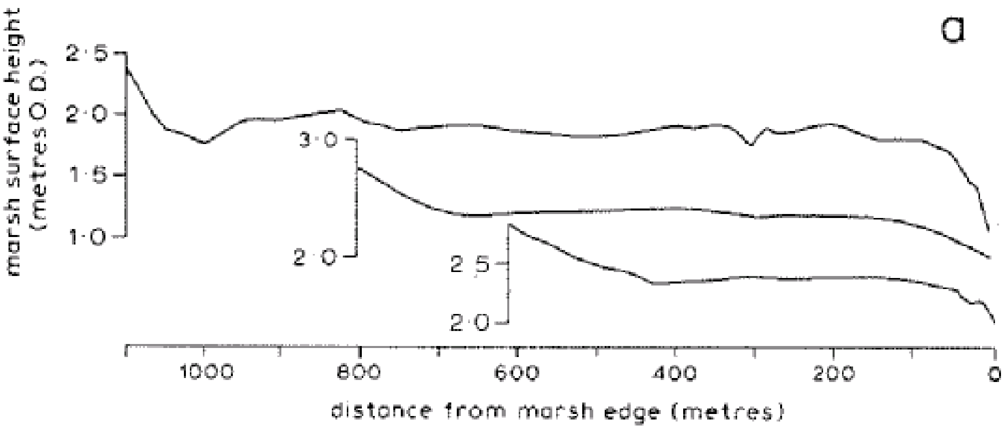

Figure A32. Profile across saltmarshes in the Tamar Estuary (Pethick, 1984)

A10.4.2 Marsh Creeks

The creek systems found within saltmarshes are a vital component of the overall system. In plan view, creek systems appear similar to fluvial drainage systems. However more detailed consideration shows distinct differences between the two. Flows within saltmarsh creeks are two way and in addition saltmarsh creeks experience bank full conditions on a regular (tidal) basis. Investigation of the surface area of marshes and the relation to creek density suggests that the main function of the creeks is not drainage of the ebb tide from the marsh. Rather the details of the creek systems appear to be dependent on the tidal prism entering the marsh on the flood tide. This suggests, therefore, that the function of saltmarsh creeks is to dissipate tidal and wave energy in a similar way to a main estuary channel. In addition, marsh creeks can also act to drain freshwater flows.

Creeks act to funnel the oncoming flood tide and distribute the tidal water into the marsh (Carter, 1988). The creeks transfer water through progressively smaller channels thereby dissipating the tidal energy through increased friction. As water levels in the creeks rise and the banks are overtopped water is allowed to spill onto the marsh surface (Carter, 1988). The increased frictional resistance on the surface then causes deposition of sediments in suspension. From this perspective the creeks perform an irrigation function transporting water and, hence suspended sediments, to the marsh surface.

In addition to transporting suspended sediments associated with tidal flux, flow in the creeks also acts to recycle sediments within the marsh system (Carter, 1988). This occurs as creek banks are undercut causing bank slumping. The sediment produced by this process may be transported seaward or alternatively (i) re-deposited in creeks or (ii) deposited on the saltmarsh surface. Within the creeks, deposition is most likely to occur in the vicinity of creek meanders. On the saltmarsh surface, areas of greatest deposition occur adjacent to the creeks as material is deposited immediately after spilling onto the marsh during bank full stages of the tide. This results in the formation of levees (Carter, 1988). Levee deposition of this sort will in term effect the nature of the local colonising species.

A10.4.3 Salt Pans

A further common saltmarsh feature is saltpans. These consist of shallow pools filled with water on the marsh surface. Although these features are an element of the overall saltmarsh form they are essentially relict features, as defined above, and are therefore not included as a component within the systems diagram.

A10.4.4 Cliffs

A cliff feature regularly occupies the transition zone between mudflat and saltmarsh zones and indicates the boundary between mobile mudflat sediments and the more stable saltmarsh sub-surface, which is influenced by the vegetation root structure. It is believed that these features can occur in both erosional and accretional environments (Gao & Collins, 1997) and under wave action (local wind waves or ship wash) these zones can be come highly dynamic.

A10.5 General Behaviour

Much of the behaviour of a saltmarsh is dependant on the balance between the processes controlling erosion and deposition.

A10.5.1 Deposition

As an area of mudflat becomes colonised by saltmarsh species, the nature of the deposition processes are dramatically altered. Saltmarsh vegetation presents an increased frictional roughness to the intertidal surface. This results in two specific impacts on the flow regime above the saltmarsh surface. Firstly, a zone of zero velocity occurs close to the bed. Secondly to compensate for this dramatic decrease in the lower layers of flow, the upper layers of the flow increase in velocity. The net result of this is actually a lower sedimentation rate on a saltmarsh relative to a mudflat. However, reduced near bed velocities protect the recently deposited sediment from re-suspension and as a result saltmarsh tends to accrete far more rapidly than mudflat.

In addition to this basic process, the presence of vegetation on the saltmarsh surface exerts several other important influences on deposition, for example:

- Plant stems set up flow eddies trapping sediments and resulting in areas of high deposition;
- Increases in flocculation locally can be caused by plant species that provide salt from their stems increase salinity levels. This increased flocculation could, in theory, lead to increased deposition; and
- Saltmarsh plants may be underlain by algal mats producing a sticky surface that traps sediments more effectively.

Deposition of sediments on a saltmarsh can occur on differing parts of the marsh, including:

- Saltmarsh Surface Accretion: The main mechanism of marsh growth and expansion is deposition on the marsh surface. This can cause the vertical and/or horizontal development of the marsh; and
- Creek Deposition: Sediment may also be deposited within tidal creeks either from the re-working of pre-existing saltmarsh sediment or the introduction of new sediments.

A10.5.2 Erosion

Due to the frictional influence of saltmarsh vegetation on flows, erosion of a saltmarsh through the re-suspension of fine-grained sediments is less frequent than erosion on neighbouring areas of mudflat. Erosion of saltmarsh sediments will occur when the shear stress imposed by physical processes exceeds the shear strength of the saltmarsh surface.

As with deposition, saltmarsh erosion can occur in relation to any of the geomorphological features identified, as follows:

- Erosion of the marsh edge (cliff);
- Enlargement of the pans or creeks. This process can occur via either bank collapse or headward erosion/retreat and may result in the occurrence of areas of bare un-vegetated mudflat within the marsh; and
- Marsh surface erosion. The deterioration of marsh vegetation can lead to generalised scour and surface lowering.

The process of erosion and deposition and hence the behaviour of a saltmarsh should also be viewed in the context of biological interactions.

A10.5.3 Biota

It is also important to recognise the role of biota in exerting an influence on the processes of erosion and deposition on an intertidal mudflat. This is the subject of ongoing research attempting to further our understanding and quantify the influence of biota (EstProc, 2004). In broad terms the influence of biota is exerted through a number of processes that can be grouped into stabilising processes or destabilising processes. These processes will obviously exert an influence on erodibility, either contributing to accretion or erosion across a mudflat.

A10.6 Forcing Factors

The processes of erosion and deposition discussed above are driven, in the case of saltmarsh, by the two principal driving forces of waves and tidal currents.

Wave processes in marsh areas will dictate the erosion or re-suspension of sediments. However, due to the high position of areas of saltmarsh within the tidal frame, both the frequency and the duration over which the saltmarsh surface will be exposed to wave attack is limited relative to seaward areas of mudflat and can lead to changes in saltmarsh area.

Tidal processes across saltmarshes largely dictate deposition processes. Tidal processes transport suspended sediment onto the saltmarsh. Tidal flows are distributed through the marsh area via the marsh creeks and, at higher stages of the tide, over the marsh surface itself.

As noted, the tidal stage will also regulate wave attack and in this sense exerts an indirect influence on marsh erosion.

A10.7 Evolutionary Constraints

A number of constraints to saltmarsh development can be identified:

A10.7.1 Suspended Sediment Supply

Sediment supply to the saltmarsh surface is critical to the depositional processes that are central to the formation, evolution and maintenance of saltmarshes. The rate of deposition is dictated by suspended sediment concentrations in the tidal water over the marsh surface. Variations in sediment supply will significantly affect the way in which the saltmarsh behaves in response to the applied driving forces.

A10.7.2 Migration Space

A saltmarsh is a dynamic landform. In order for this landform to respond to changing forcing, there is often a requirement for migration space. This is essentially space into which the saltmarsh is able to migrate. The behaviour of the saltmarsh may be significantly different if there is a constraint imposed on the migration space. This constraint could be in the form of a natural factor (such as a geological hard point or rapidly rising hinterland topography) or man made (such as sea defences).

A10.8 Behavioural Timescales

A10.8.1 Short-Term (Responses Within a Year)

Over the tidal durations, water and sediment exchanges occur that are critical to sustain the vegetation on the saltmarsh surface. The saltmarsh surface is subject to periodic tidal inundation, the frequency and duration of which is dictated by the elevation relative to tidal levels, supplying suspended sediment. Flows and suspended sediments are affected by the frictional influence of the vegetated surface providing the potential for sediment deposition. This periodic cycling of sediment onto the saltmarsh surface over a tidal frequency provides the means for saltmarsh morphological response.

A10.8.2 Medium-Term (Responses Over Decadal to Century Scale Changes)

Over this medium timescale, the behaviour of a saltmarsh will be dictated by the saltmarsh response to low frequency high magnitude wave events and intervening tidally dominated calmer periods. During storm events, erosion of the saltmarsh is likely to occur and marsh edge erosion will act as a sediment supply to the adjacent mudflat, thus allowing the two elements to respond to the applied forces. During these periods it is also possible that the boundary between the saltmarsh and mudflat (potentially marked by a cliff feature) will migrate landward. These erosional processes are replaced with depositional processes during the tidally dominated intervening periods. In these calmer periods sediment is transported onto the marsh area via the fronting mudflat and deposited. This allows marsh recovery to occur (both vertically through deposition on the marsh surface and horizontally through recovery seaward of the marsh edge).

It is also possible for biotic factors to influence saltmarsh behaviour over these timescales. The influence of Spartina *(Spartina anglica*) in UK estuaries is an example of this. The grass spread, partially naturally and partially due to deliberate introduction, in the late 1800s and early 1900s and resulted in initially rapid sediment accretion (Toft *et al.*, 1995). The subsequent regression of Spartina then led to saltmarsh erosion.

A10.8.3 Long-Term (Responses Over Century to Holocene Timescales)

Saltmarsh behaviour over this longer timescale is driven by primarily by relative sea level change. Relative sea level rise will mean an increase in water depth and hence a change to the frequency and duration of tidal inundation on a particular area of marsh surface. This change will affect marsh accretion rates and marsh development. The actual behavioural response to this change in forcing is highly dependant on the nature of a number of factors, leading to a number of different scenarios:

A scenario can be considered whereby there is an adequate supply of suspended sediment and sufficient landward migration space for the saltmarsh to migrate into (i.e. no geological or man made constraints). Under rising relative sea levels the marsh surface will rise vertically and translate landward (or potentially advance). Under this response the marsh accretes to keep pace with relative sea level rise and maintain its relative position within the tidal frame.

Under a restricted sediment supply scenario, the marsh surface is unlikely to be able to accrete vertically to maintain its position in the tidal frame to compensate for the rise in water level. As a result water depths over the marsh will progressively increase and the marsh may eventually drown.

Under a restricted migration space scenario, an area of saltmarsh would attempt to migrate landwards. However, with a static landward margin, e.g. through rising topography or a fixed line of sea defence, the marsh would become progressively squeezed between the migrating saltmarsh edge and the static landward boundary. This is the process of coastal squeeze.

These idealised behavioural responses over the long term assume a monotonic increase in relative sea level that would lead to a progressive change in forcing with a corresponding response. However, in reality, fluctuations in the rate of change of relative sea level and the direction of change will occur with corresponding potential for recession as well as progradation.

A10.9 Interactions With Other Geomorphological Elements

A10.9.1 General Interactions (Elements Within the Estuary System)

The exchanges between saltmarsh and mudflats are explored in Appendix H. In addition, the saltmarsh interacts with an estuarine floodplain through the action of flooding and drainage during extreme water levels and rainfall events respectively.

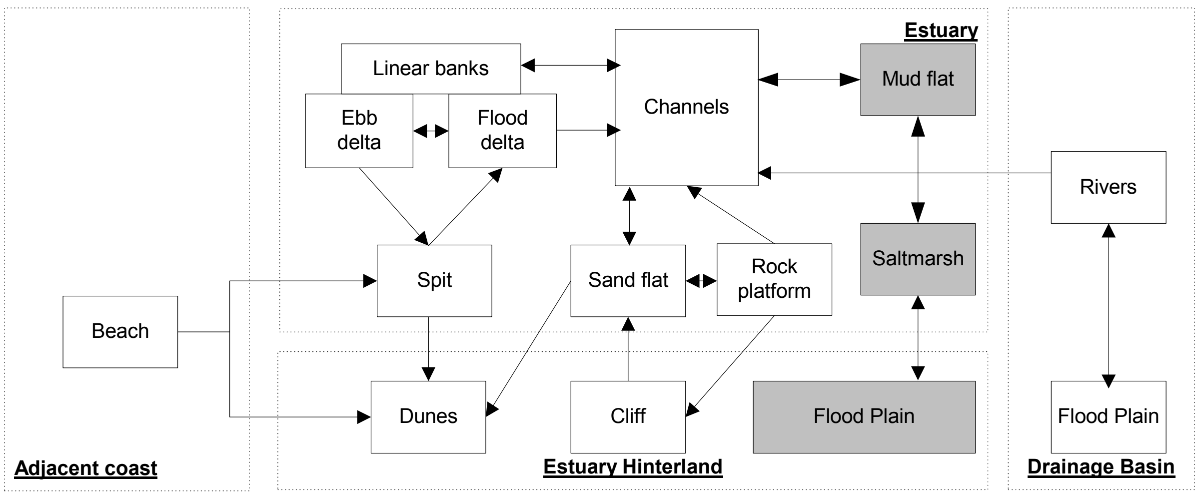

Figure A33. System diagram (saltmarsh) - Interactions with other elements

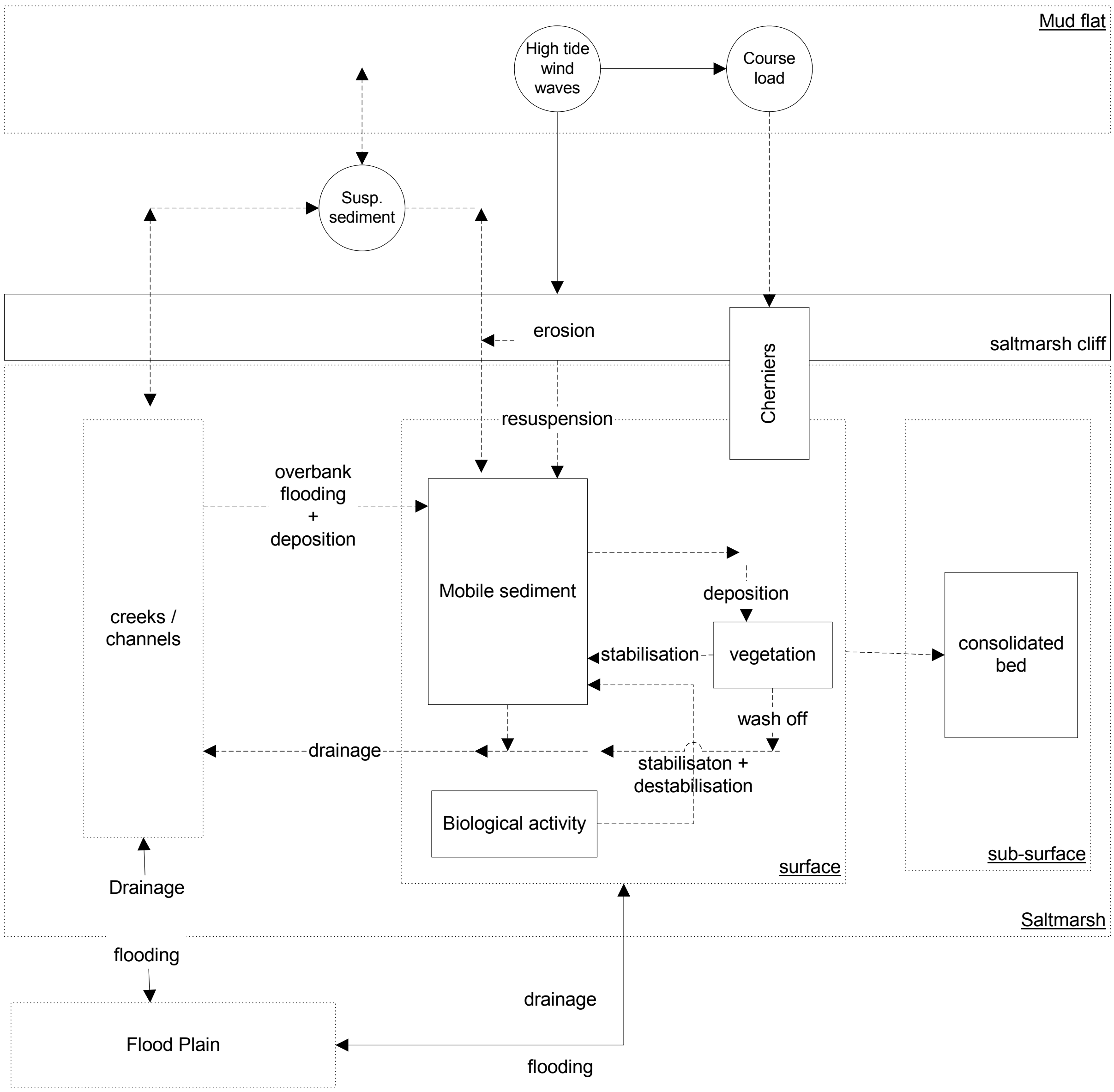

Figure A34. System diagram (saltmarsh) - Short to medium term

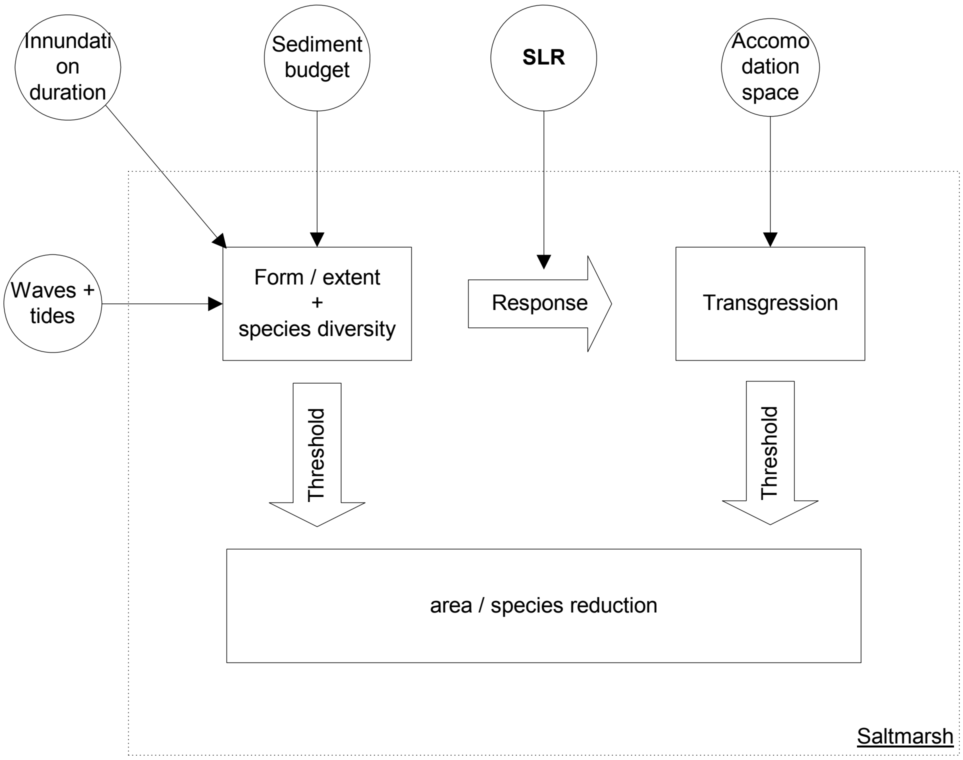

Figure A35. System diagram (saltmarsh) - Long-term

A11. Behavioural Description for Drainage Basin

A11.1 Definition of Geomorphological Element

A drainage basin is the topographic region from which a river receives its water due to drainage. It can be considered as the area covered by a single fluvial (non-tidal) system with division between other drainage basins defined by watersheds that act as topographical barriers.

A11.2 Function

The primary role of a drainage basin is to enable the storage and subsequent transportation of water and sediment derived from the local climate and the basin watershed via the river network, to the estuary and sea.

In the context of the estuarine system, the drainage basin therefore regulates the inputs of water and sediment to the system and interacts with the estuarine form and processes. In general terms, UK estuaries are less influenced by fluvial activities than their counterparts in more mountainous regions of the world.

A11.3 Formation and Evolution

The formation of a river basin is a function of its inherited topographic location. Evolution of its form and characteristics will then result from modification to the key forcing factors that input energy to the system. The climatic conditions have the most important direct influence on the drainage basin characteristics with changes to precipitation regimes and vegetation cover altering other system elements and drainage characteristics. This is discussed in more detail below.

A11.4 General Form

The inherited relief and geological composition dictates the initial form with ongoing physical processes altering this form through erosion and accretion.

The drainage basin is a morphological feature that is composed of a range of connecting and overlapping elements:

- Topographic surface/catchment;
- River network (rivers, streams and channels);
- Tidal river; and
- Flood Plain;

A11.4.1 Topographic Surface/Catchment

The characteristics of the topographic surface influences many of the internal attributes. Important characteristics and their role include:

- Size of the catchment (volume of water transported);
- Length, shape and relief (rate of water transport - discharge);
- Underlying lithology and soils composition (structure of channel network, channel density and form, groundwater storage and sediment availability); and
- Vegetation (slope stability).

The topographic surface is the route for energy input to the system in the form of precipitation (rainfall and snow) and also losses from the system in the form of evaporation.

Important processes on the topography include, weathering of solid bedrock to supply sediments downslope, rain-splash, sheet, rill and gully erosion, infiltration to provide groundwater flow and surface run-off, which can erode and transport unconsolidated soils and sediments.

A11.4.2 River Network

The network of rivers, streams and channels is the primary route for the transport of water and sediment downstream out of the river basin and into the estuary.

The form of the river network can be varied in terms of their length, density, shape (straight, meander or braided), slope, composition and cross-section. The network density is regarded as a fundamental characteristic of a drainage basin since it provides a measure of availability of channel flow (and hence total discharge) which is more efficient than surface or groundwater flow. The form of a river network can therefore be considered as one, which maximises discharge within the context of the topographic and geological constraints and under equilibrium conditions channel form tends to be morphologically stable (in regime).

The form of individual channels is a direct response to the flow received from upstream. This differs from the estuarine morphology where discharge through any one section is coupled to the form of the channel.

An important property of the water transported within the drainage basin is the low concentration of solutes. This property of freshwater prevents flocculation of fine sediments until exchange with saline water (in order of 2ppt) within the estuarine environment.

Key processes within the channel network primarily include those of sediment transport (erosion and deposition).

A11.4.3 Tidal River

The lower reach of a river network that accepts tidal and fluvial flow is an important feature as it represents the transition between fluvial and estuarine processes. Its form will reflect the gradual transition between the fluvial environment where form is dependant on discharge and the estuary where form and discharge mutually co-adjust.

A11.4.4 Flood Plain

The flood plain is the area of relatively flat land adjacent to the river network. It functions as a temporary sediment store as sediment moves downstream and can also accommodate floodwater storage during periods of extreme discharge.

Two processes are responsible for the formation of flood plains:

- Lateral accretion; and
- Overbank deposition.

Within a meander channel, deposition naturally occurs on the convex bend to create point bars during periods of low flow. During high flow erosion occurs on the concave side of the bend. This deposition and erosion cycle accommodates the lateral movement of a channel through the floodplain primarily during below bank flow conditions.

During overbank conditions, where water volume exceeds channel capacity the flood plain is inundated and deposition of suspended sediment occurs across the flood plain or locally to form levees.

It has been noted that the frequency of overbank stage is relatively uniform (typically 1:1-1:2 year event) for a range of rivers in differing regions (Leopold *et al*., 1964). Coupled with the knowledge that channels do not become progressively deeper as floodplain deposition occurs, implies that under equilibrium conditions the channel form adjusts to accommodate the typical basin discharge and that the floodplain can adjust to accommodate more extreme discharges.

Definition of an estuarine floodplain as a separate morphological form is perhaps unwarranted since as a river channel merges into the coastal setting it can be regarded as part of a continuum. However, there is a transition between dominance of tidal over fluvial processes in a downstream direction and the scale of the river channel increases, as does its stability, and these factors will alter the relationship between the channel and the floodplain.

Where the watershed input to the fluvial system is responsible for overbank conditions in the drainage basin, it is tidal waters that are responsible for flooding of the estuarine floodplain (although this can be in-combination with high river discharges).

A11.4.5 Vegetation

Vegetation plays an important role in the drainage basin. Vegetation cover determines the exposure of soil cover, the stability of sub-surface soils (through root structure) and the magnitude of modification of precipitation processes at surface. It therefore can modify the net input to the system (interception and transpiration), affect storage and influence rate at which water and sediments are transmitted through the system.

A11.5 General Behaviour

The importance of the behaviour of a drainage basin and its component systems lies in its function of transporting water and sediment into the estuary.

An understanding of the lithology of the basin, soil composition and land use informs on the type and quantity of sediment load input to the estuary. Knowledge of the discharge characteristics tells us something about the total volume discharged into the estuary and its distribution through time.

Both sediment and water volume can have an important influence on estuarine dynamics where such inputs are in sufficient proportion to estuarine flows or occur at sensitive periods in time. For instance, fluvial sediment can be an important component of the estuarine sediment budget and extreme water discharges can influence upstream estuary morphology.

The likely influence of the drainage basin on estuarine processes and morphology can be inferred from the ratio between river discharge and tidal prism, although the same analysis for extreme events can indicate the potential for influence on estuary morphology.

A11.6 Forcing Factors

The major forcing factor on the system is the climate that controls precipitation and temperature regimes, and together with the inherited geology, these determine the sediment yield, river network structure and vegetation cover.

A11.7 Behavioural Timescales

A11.7.1 Short-Term (Responses Within a Year)

The nature of river discharge for one gauging station, for instance at the tidal limit is expressed by a flood/storm hydrograph. This shows several important characteristics, including, peak flow, peak flow, total run-off and the rate of discharge rise and fall. When the rainfall is plotted on the same graph, the lag time to peak flow can be determined.

Flood hydrographs will clearly vary according to season for any particular drainage basin as a function of precipitation, temperature, lithology, soil composition and vegetation cover. Over the short-term variations in precipitation will be the dominant process that determines channel discharge and inputs to the estuary.

A11.7.2 Medium-Term (Responses Over Decadal to Century Scale Changes)

Much of the work within a drainage basin is accomplished by intermediate frequency, moderate magnitude events (extremes) of perhaps only a few times per year. With a long enough time series of discharge measurements annual extreme events can be identified and their relationship to estuary tidal prism understood.

Annual extremes or those over a longer period (shown by a flood frequency curve) may be particularly influential for estuary morphology under equilibrium drainage basin characteristics. Inputs of sediment may have functional importance for the estuarine sediment budget and discharges may alter inner estuary morphology.

Over the decadal period anthropogenic changes in the drainage basin may be important in influencing the interaction with the estuary. Changes to land use such as through agriculture may alter the availability of sediments. Whilst urbanisation and other associated interventions including, bank stabilisation and protection and canalisation is likely to significantly alter the drainage characteristics. Urbanisation reduces surface permeability thereby reducing the lag time of the flood hydrograph and increasing the flood peak and frequency of overbank discharge.

A11.7.3 Long-Term (Responses Over Century to Holocene Timescales)

Over longer timescales, erosion of the drainage basin surface will act to lower its relief and climatic factors will be important for evolving the drainage basin characteristics. Changes in precipitation and temperature regimes coupled with subsequent changes to vegetation cover may evolve the channel network to a new quasi-equilibrium state and result in altered discharge and sediment volume input.

Over this time frame the influence of sea level rise will become important. Changes to relative sea level will influence the tidal regime and hence will play an important role in modifying estuary morphology. Where an estuary has sufficient (unprotected) flood plain then sea level rise can be accommodated by migration of the estuary form both laterally and towards the rive basin at the head of the estuary.

A11.8 Interactions With Other Geomorphological Elements

A11.8.1 Estuary Floodplain

In the context of a rising and falling tide it is the intertidal surface that can be considered as the estuary floodplain with flooding on a twice daily frequency (for semi-diurnal tides). In the estuary, overbank condition can be considered as occurring when the tidal elevation exceeds the subtidal channel and water movement occurs laterally across the intertidal.

In an estuary where there is sufficient unconfined accommodation space, then more extreme tidal ranges will overbank the typical high water boundary and flood adjacent land in a manner more analogous to fluvial flooding. However, whilst the fluvial floodplain behaves more as a temporary sediment store for downstream transport, the estuarine floodplain does not over the short timescale appear to have this role, although can accommodate lateral channel movement.

Over long timescales the estuary floodplain can accommodate sea level rise by allowing space on the hinterland for the estuary form to migrate laterally.

A11.8.1 Estuary Channel

The focus of the earlier discussion has been on the interaction between the drainage basin and the estuary. This interaction by way of the tidal river element provides a source of fluvial discharge and sediment (bedload and suspended) into the estuarine setting.

The importance of the suspended load imported into the estuary for other geomorphic elements (mudflats, saltmarsh and estuary channels) will be dependant on the scale of the drainage basin. The scale of the contribution to the estuarine sediment budget from sediment load derived from the drainage basin, will be determined by, amongst other factors, the geology of the basin.

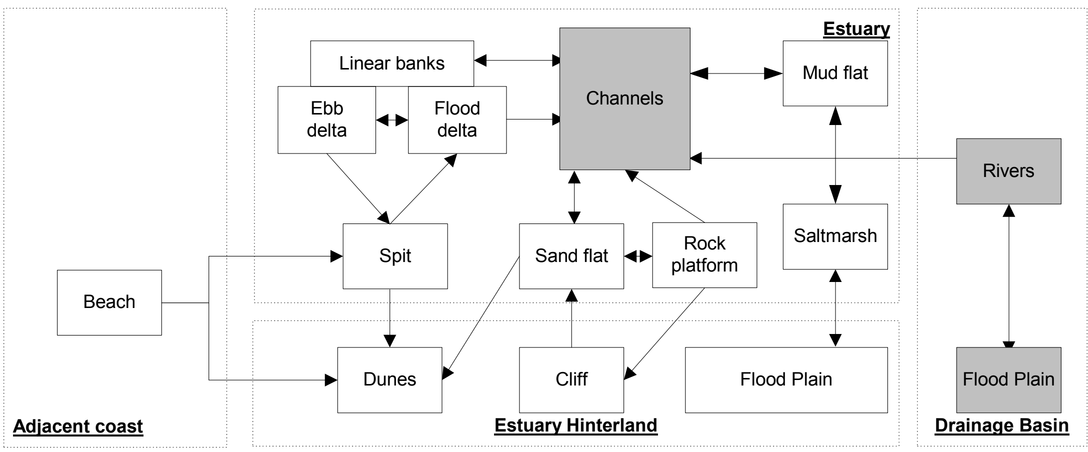

Figure A36. Interaction with other elements - Drainage Basin

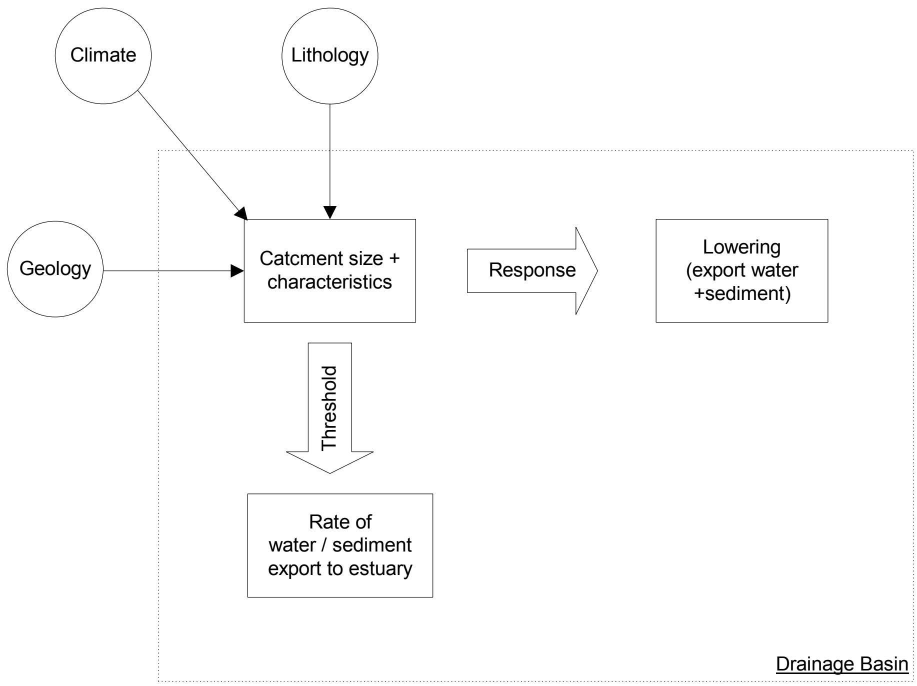

Figure A37. Short to medium term system diagram - Drainage basin

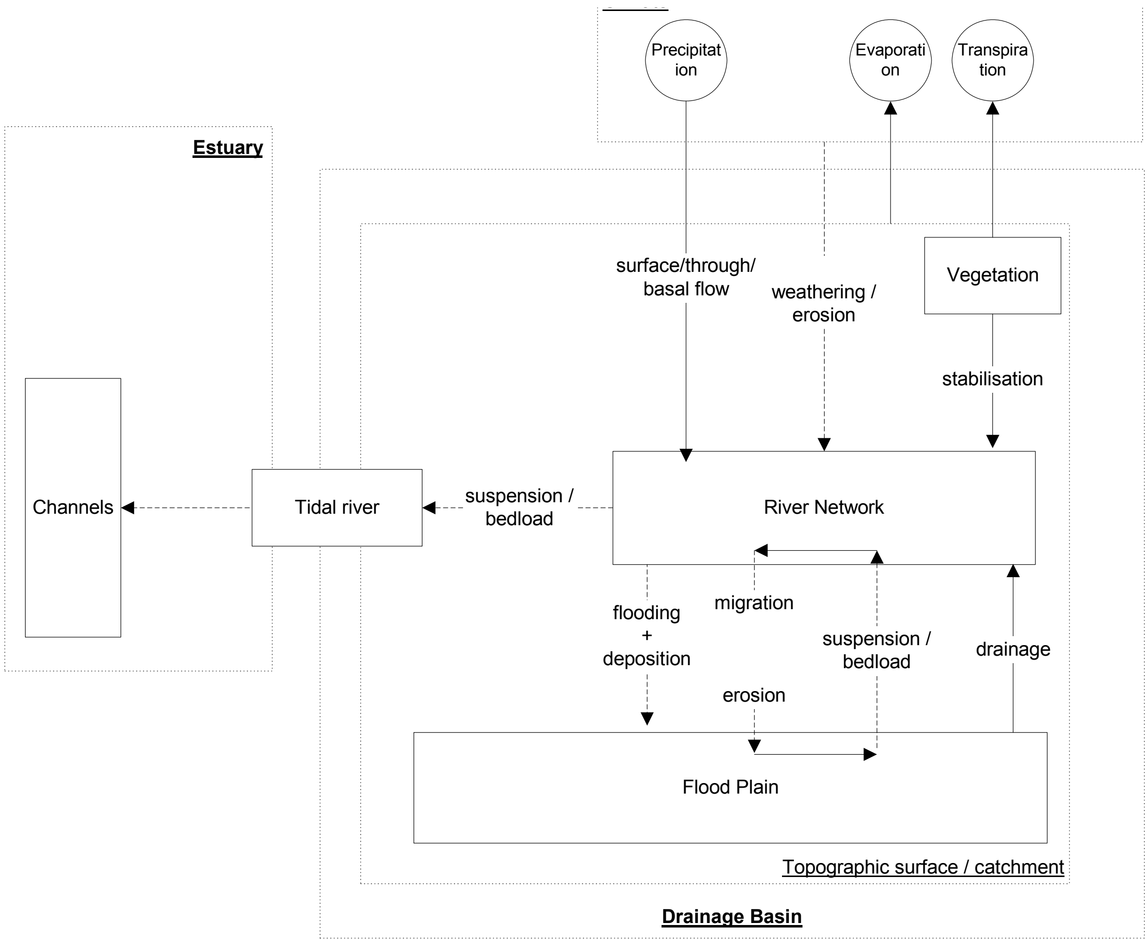

Figure A38. Medium to long-term system diagram - Drainage basin

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APPENDIX B. MANAGEMENT QUESTIONS

B1. Management Questions Consultation Exercise

A targeted and focussed consultation exercise was carried out which engaged with key stakeholders, identified and agreed in advance with Defra's project officer. Sixteen consultees responded from a variety of organisations and roles, which were summarised as policy, regulatory, research and operational; another seven people who were contacted decided not to participate. The specific roles are listed in Table B1. The aim of the consultation exercise was to gather opinions from those people concerned with estuary management on three main areas, identified below:

1) The use of existing management tools, their ease of use and presentation;
2) Familiarity with the concept of 'System Mapping' as a tool for estuary management; and
3) Importance of existing and future legislation as drivers for estuary management.

A summary of the consultation responses to each question is presented here.

Table B1. EstSim Consultees

Organisation and Department (Where Applicable)	Role
Environment Agency, Flood Risk Management Head Office	Environmental Policy Advisors
Environment Agency, Flood Risk Management Head Office	Policy Advisors
Environment Agency, Flood Risk Management Head Office	Policy Advisor - Shoreline Management
Environment Agency, Flood Risk Management Head Office	MSfW Policy Advisor
Environment Agency, Flood Risk Management	Operations
Environment Agency, Science	R&D Project Officer
Environment Agency, Policy Development	
Environment Agency	Estuary Manager
Environment Agency, Science	Project Manager
Defra	R&D Dissemination
Defra, Marine Environment Science Division	Head
ABP, Sustainable Management	Manager
ABP, Port	Assistant Port Manager
Tyndall Centre for Climate Change Research/ University of Southampton	Lecturer/Researcher
Natural England	Maritime Team

B2. The Use of Existing Management Tools, Their Ease of Use and Presentation

The consultees were asked about existing tools, with the aim of addressing issues of the usability of the Prototype Interface. The two interfaces that were discussed were Futurecoast and FloodRanger, however, most of the consultees were not familiar with FloodRanger and so this has not been included in the reporting.

All consultees had heard of Futurecoast, although most had not used it in their current roles. However, it was reported as an important reference tool, used by different groups of people from policy makers to students, often for specific issues, rather than the broad scale. Consultees stated that Futurecoast gives a useful impression of the coast and provides a good geomorphological basis for decision-making, and it has also provided information with which to compare new modelling work. One consultee pointed out that it was developed for coastal consultancies and as such was thought to be 'fit for purpose'; although it is now also used for other reasons, some of which, perhaps, it was not designed for. The Environment Agency may use it more in the future in their revised role incorporating coastal protection, but at the moment, an Environment Agency consultee responded that they rely on the consultancy companies carrying out coastal work on their behalf to use it appropriately.

One consultee stated that Futurecoast represented a small but very important step in shoreline management planning; in the past everything was driven by an engineering approach, but it was recognised that conceptual views and qualitative modelling are very important, bringing together all knowledge of the coastal system.

It has also proved to be a useful tool in stakeholder engagement; more than one consultee used the aerial photographs within Futurecoast to show people the estuaries in which they live and to highlight flood risk issues. In this context, the map presentation was felt to be useful, rather than sole use of text. Although in contrast, another consultee felt the map resolution was disappointing.

Issues that arose surrounding Futurecoast included that it seemed to have limited interactivity for option development; the Futurecoast concept does not include the functioning of the whole coast, i.e. both open coast and estuaries. Areas where Futurecoast was felt to be lacking were in areas of the coast where there are recognised issues (which were not included) and where numerical modelling is difficult, and incorporating these areas into an assessment of the whole coast.

The format of Futurecoast was not thought to be very intuitive and the three CDs required to use it was considered time-consuming and perhaps outdated.

The timing of Futurecoast was considered to be a fundamental issue. Futurecoast was produced at the end of the first round of SMPs and intended for use in SMP2s, which were then delayed. Since then some of the information has been superseded by other studies. As SMP2s progress it should become apparent how useful Futurecoast is.

The use of public domain data and the subsequent issue of such data within tools like this is a consideration for other such tools. Free sources of data should be considered, such as MDIP, Magic, SPIRE/INSPIRE, when there are charges associated with data from British Geological Society (BGS), Ordnance Survey and Seazone/UKHO.

The results of this element of the consultation exercise were intended to be used within the development of the Prototype Interface; however, due to time constraints this was not possible. However, these findings could be used in future developments of the Interface.

B3. System Mapping and Whole Estuary Management

The results of this element of the consultation focussed on the management of estuaries both ideally and in practice. All consultees recognised the need for estuaries to be managed as a system, with some consultees extending this to include both rivers and the coast. However, although most felt that they considered or tried to consider the whole estuary in their own role, they did not feel that in practice this is how most estuaries are managed, for a variety of reasons. It was stated that it is Defra policy to take a holistic approach, or an ecosystem approach, and to try to understand the whole system.

In addition, considering the estuary and coast as a whole is difficult, for instance, Futurecoast does not do this. Estuary modelling should also include coast and rivers, as the estuary is usually constrained by the surrounding coast. Rivers should also be considered, perhaps to a lesser extent, as fluvial influence is often less than tidal influences in UK estuaries, although it is often important for habitats.

Some felt that their work requires the consideration of the whole system, especially in terms of research and development and scientific aspects. Often, in the whole estuary, broader aspects are considered first. In particular, certain elements of legislation, including the Habitats Directive and also licensing (e.g. for dredging) require estuaries to be considered as a whole, but it may then be necessary to examine local or site specific aspects as well. For example, in terms of environmental impact assessment for works, including compensation sites, or for port management and site assessment, the whole estuary approach is the starting point, but the locally specific detail must follow.

In terms of practically managing an estuary as a whole, one consultee stated that they felt that there are currently serious limitations in estuary wide impact assessment, and that generally we are lacking in tools, although another consultee felt technology now made this possible. However, they felt that they were currently moving towards it and existing examples of whole estuary management given included the assessment of compensation/managed realignment sites as part of the Humber Flood Risk Management Strategy.

It is a requirement of CFMPs and SMPs that the system including the estuaries is managed as a whole, and this is also the case for policy development, nature conservation and flood risk, and also for the Habitats Directive. One area mentioned in which holistic estuary management would be very important is pollution and contamination, which can spread widely within an estuary system.

Several consultees stated that the Humber Estuary is an excellent example (and perhaps the only example) of an estuary that is managed in a holistic way. The Humber started with a solid foundation of using state of the art science and considering the whole estuary, but in other estuaries this is not the case, and each estuary would need to develop its own framework, choosing the relevant components from the Humber work. The Humber example could be used as a basis for an Estuary Management System.

The hope was expressed that Marine Spatial Planning will include estuaries, and in contrast it was thought that the WFD, in identifying status may split estuaries, and may split estuaries from the coast. The Marine Bill is also examining stakeholder engagement to encourage whole estuary management, but as highlighted on the Essex coast recently, stakeholders do not consider generally the whole estuary; they consider the specific area relevant to them.

One example of where the local or site specific view is still required is for engineering applications, although this must still fit in with the systematic approach.

Reasons given for not managing estuaries as a whole included lack of motivation, politics (in terms of between stakeholders) and also a failure to understand management interventions. Also, there was felt to be a possible lack of experience amongst estuary practitioners in considering the whole estuary, and importantly there were still thought to be limitations in the understanding, particularly of the integration of different factors and that system-wide issues still cannot be properly assessed. Other obstacles were land ownership, commitment and belief in the science e.g. sea level rise, inertia (e.g. Southampton Water has been managed for navigation for a hundred years and it takes time to adapt to a new management approach), and an apparent lack of technical tools and the capacity to inform. If technical information is not available, it can be used as an excuse to avoid considering some options and to only consider specific options or places where there is more information. Politics is often a barrier, where parochial attitudes can override the 'bigger picture'. However, a combination of policies, appropriate structures and tools to support both would help. Procedures also need to be more flexible; to ensure consistency of approach does not have to mean that everywhere is treated in the same way.

B4. Importance of Existing and Future Legislation as Drivers for Estuary Management

Within the context of the importance of existing and future legislation as drivers for estuary management each consultee was asked two main questions:

- What current legislation is/do you see as your main driver/controlling factor for estuary management (in your role)? and
- What changes in estuary management requirements are there going to be as a result of the Water Framework Directive (in terms of hydro-geomorphology)? (or any other changes to legislation that you are aware of)?

A summary of the consultation responses is presented here.

The responses focussed strongly on a few pieces of legislation, the Habitats Regulations (arising from the Habitats and Birds Directives), the Water Framework Directive and the future Marine Bill. The possible implications of the Marine Bill are summarised in EstSim Consortium (2007). There was interest in other Directives where it is not known yet what the impacts will be and the management issues that arise from transposing these Directives into UK law as required. These EU Directives are currently adopted or proposed and include the Marine Strategy Directive, the Floods Directive due for adoption in late 2007, and the Environmental Liability Directive, due to be incorporated into UK law during 2008.

Environmental legislation, in terms of the Habitats Directive and Birds Directive and the Habitats Regulations were recognised as very important for the UK's estuaries. Consultees stressed that the Birds and Habitats Directives and the Natura 2000 network tend to constrain all other management activities and legislation, and although one consultee stressed that the Directive is not as inflexible as it is often thought to be, it does tend to override/supersede other legislation. There was a view that the way that the Directives were implemented as the Habitats Regulations was wrong in the case of estuaries and that much more flexible boundaries are needed. One consultee felt that the Habitats Regulations precede the time of general acceptance of climate change and hence now require updating to accommodate a changing world. This view has also been expressed in a recent review of spatial planning policies under a changing climate (Piper *et al*., 2006).

It was felt that the Defra Strategy 'Making Space for Water' could have significant impacts on estuaries, and River Basin Management Plans will apply to estuaries. However, the extent of the influence of these Plans is not yet known.

Although there are not many specific details, the Marine Strategy Directive may become significant in the future, but it was thought that it should come from a marine spatial planning point of view, which needs to consider other uses of the marine environment and impacts on them, including impacts on resources.

The levels of appraisal required for the SEA Directive (the assessment of the effects of certain plans and programmes on the environment, European Directive 2001/42/EC) and Environmental Impact Assessment Directive was also an issue for one consultee.

The Floods Directive ('Directive on the Assessment and Management of Floods') through the required flood risk management plans has a requirement for biodiversity targets, which will impact on flood risk management. There is also overlap with the WFD.

The aim of the WFD is to establish a framework for the protection of inland surface waters, transitional waters (estuaries and brackish waters), coastal waters and groundwater. The principal objective is that such water bodies should achieve good ecological status by 2015. In order to achieve such a status, the impacts of actions in flood and erosion risk management, and other activities, must be considered, for example, how works affect habitats and sedimentation patterns.

It has become obvious through the consultation that most of the consultees are not aware of what the WFD will mean in practice for the management of estuaries and how it will impact on estuary management in the future; although there is recognition that it will have an impact and the extent of the impact will depend on how the process is managed. There is a need for more information and more technical understanding at the level of government, but also users such as the port authorities. River Basin Management Plans are a requirement of the WFD and these will include estuaries, however, it was felt that the work that is currently being done on the WFD is focussing on rivers, and has not extended to estuaries.

However, it was also believed that the WFD could help estuary management, as the introduction of new EU legislation could provide an opportunity to streamline current UK legislation, for example the Coast Protection Act (1949) and the Water Resources Act (1991); it could also encourage a more holistic view, where linkages within the system must be recognised.

The port authorities are in the process of establishing the requirements of the WFD for estuaries where large ports are located. For example, in the Humber, historic pollution may affect the programme of measures in relation to priority substances in dredged materials and could have a huge impact on the disposal of dredged material and the remediation ('the polluter pays').

Specifically, for port activities the Habitats Directive was thought to be of primary significance at the moment and the chance of judicial review for losses of designated habitat. However in the future the WFD will also be important, as above, as will the introduction of the requirement for strategic impact assessment for maintenance dredging (as a recognised as plan or project), the revision of the Waste Framework Directive (potentially important for the disposal of dredged material at sea, if classified as waste) and the Marine Bill. It was not thought that the Floods Directive would be significant in the context of port management.

Consultees were also asked about the significance of Integrated Coastal Zone Management (ICZM) in estuary management. It appears unlikely that an EU Directive will follow, however, within the UK it was felt that the principles of ICZM are being incorporated into current shoreline management planning, by linking with Regional Spatial Strategies and Local Development frameworks, partly through Making Space for Water.

B5. References

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APPENDIX C. MATHEMATICAL FORMALISATION

The following three approaches have been considered in the review of alternative approaches for mathematical formalisations of defined relationships:

1) The Boolean Approach, developed by University of Plymouth (Karunarathana & Reeve, 2007);
2) The Network Dynamics Approach of UCL (Seymour, 2005);
3) The ASMITA Approach, developed by WL | Delft Hydraulics and Delft University of Technology (Stive *et al*., 1998; Stive and Wang, 2003; Kragtwijk *et al*., 2004; Van Goor *et al*., 2003).

This document summarises the review. First the three approaches have been briefly described (Section C1) and then a comparing discussion has been given in (Section C2).

C1. Brief Description of the Approaches

C1.1 Boolean Approach

An estuary is schematised into a number of geomorphologic elements. The state of each element is described by a Boolean variable, low=0, high=1. The same description is for the state of hydrodynamics (tide, wave). The state of an estuary at a certain time is thus described by a vector of Boolean variables.

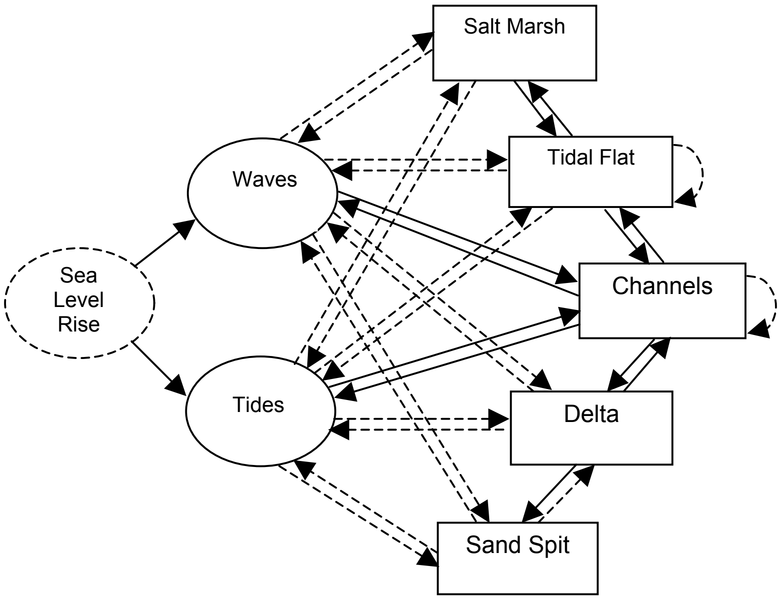
A Boolean function for each variable is derived by combining Boolean variables within a logical framework, for the simulation of the evolution of the estuary.

The approach can best be illustrated by the example given in the document of Karunarathna & Reeve (2005). The schematisation of the system is shown in Figure C1. For each of the 5 morphological elements (marshes, flats, channels, delta and sand spit) and the 2 hydrodynamic forcing (waves and tides) a Boolean variable and a corresponding Boolean function are defined (see Table C1).

Table C1. Boolean Variables Describing the Elements & Their Corresponding Boolean Function

Network Element	Boolean Variable	Boolean Function
waves	*w*	*W*
tides	*t*	*T*
salt marsh	*sm*	*SM*
tidal flats	*tf*	*TF*
channels	*cc*	*CC*
delta	*dd*	*DD*
sand spit	*ss*	*SS*

The Boolean functions describe how the Boolean variable variables (and possibly itself) as indicated in Figure C1.



Dark arrows and broken arrows in the network represent positive and negative feedback respectively.

Figure C1. Boolean network for a generic tidal inlet (little or no sediment flow from outside)

$$\left.\begin{array}{lr}
W = sm' \vee tf' \vee cc \vee dd' \vee ss' & \text{(a)} \\
T = sm' \vee tf' \vee cc \vee dd' \vee ss' & \text{(b)} \\
SM = (w' \wedge t \wedge tf) & \text{(c)} \\
TF = ((sm \vee cc) \wedge t) \vee (tf' \wedge w') & \text{(d)} \\
CC = (w \vee t) \wedge (tf \vee dd) \vee cc' & \text{(e)} \\
DD = (w' \vee t') \wedge ss' \vee (t \wedge cc) & \text{(f)} \\
SS = (w' \vee t') \wedge dd & \text{(g)}
\end{array}\right\} \quad (1)$$

Table C2 shows some examples of the evaluation of the Boolean functions according to Equation 1. The framed row indicates an equilibrium state, as the output is exactly equal to the input according to the Boolean functions.

Table C2. Some Selected States From the Boolean Matrix for Tidal Inlet With Constrained Sediment Inflow

	w	t	sm	tf	cc	dd	ss	W	T	SM	TF	CC	DD	SS
1	1	1	0	1	1	1	0	1	1	0	1	1	1	0
2	1	0	1	1	1	1	1	1	1	0	0	1	0	1
3	1	0	0	1	1	1	1	1	1	0	0	1	0	1
4	1	1	0	0	1	0	1	1	1	0	1	0	1	0
5	1	1	0	1	0	1	0	1	1	0	0	1	0	0
6	1	1	0	0	1	0	0	1	1	0	1	0	1	0
7	0	1	1	1	1	1	1	1	1	1	1	1	1	1
8	1	1	1	1	1	1	1	1	1	0	1	1	1	0
9	0	1	0	1	1	1	1	1	1	1	1	1	1	1

C1.2 Network Dynamics

The state of an estuary is described by a vector of state variables. Each of the state variable xi ≥0 describes the state of a node in the network. The links between nodes indicate influences between the nodes: structure of the network. Mathematically the structure of a network (of n nodes) is expressed in a (n x n) matrix W of connection weight (-1, 0, or 1).

The net influence of the network on the node is defined as:

$$w_i(x) = (xW)_i = \sum_j x_j w_{ji} \qquad (2)$$

Evolution of the state of a node xi in time is determined by xi it self and by the net influence of the network on the node:

$$\dot{x}_i = R_i(x_i, w_i(x)) \qquad (3)$$

The response function R is calculated as follows:

$$R(x,w) = \varphi(x)F(w) \text{ if } x > 0,\ w \geq 0, \qquad (4a)$$
$$R(x,w) = -x\varphi(x)F(-w/x) \text{ if } x > 0,\ w < 0. \qquad (4b)$$

The two functions φ and *F* can be chosen but the need to satisfy a number of requirements. Both functions cannot take negative values. φ is a monotonously non-increasing function and F is a monotonously increasing function with F(0)=0 and F(∞)=1. Typical examples of the two functions are shown in Fig. 2.

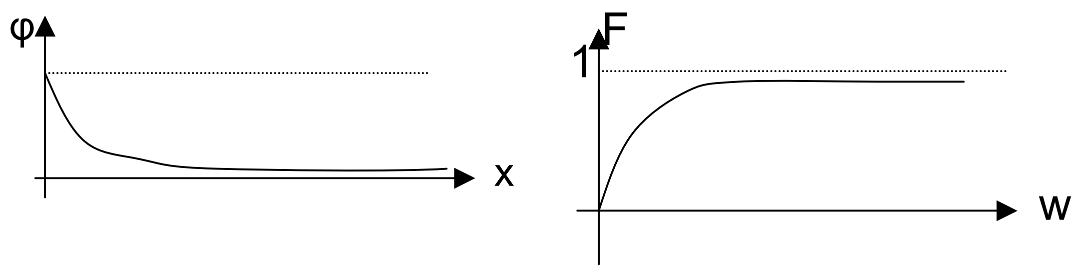


Figure C2. Examples of φ and F functions

Figure C3 shows an example of network, given in Seymour (2004).

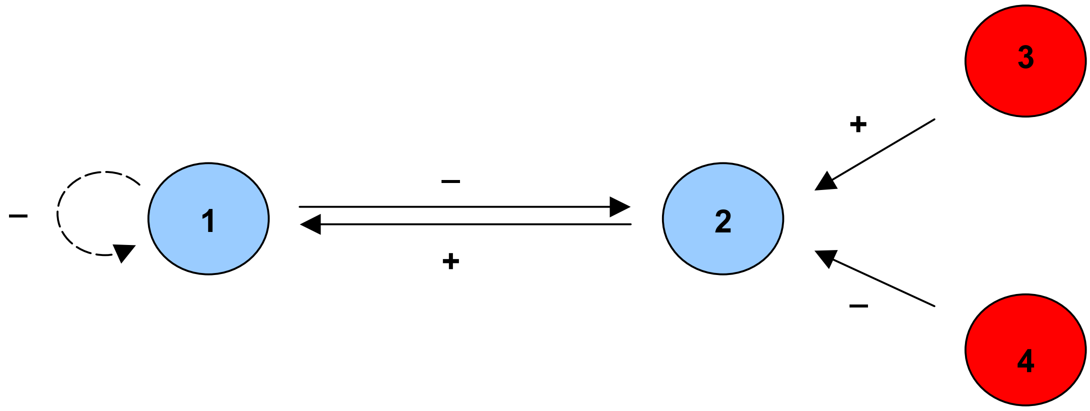


Figure C3. Example of a network

The structure of this network is mathematically represented by the following matrix:

$$W = \begin{pmatrix} -\varepsilon & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix} \quad (5)$$

So the net influence vector can be calculated as:

$$(w_1, w_2, w_3, w_4) = (x_1, x_2, x_3, x_4)W = (-\varepsilon x_1 + x_2, -x_1 + x_3 - x_4, 0, 0) \quad (6)$$

In this example the nodes 3 and 4 are external nodes and their net influence by the network is zero, so they do not change in time (as F(0)=0). Figure C4 shows examples of the possible evolutions of the two internal nodes 1 and 2.

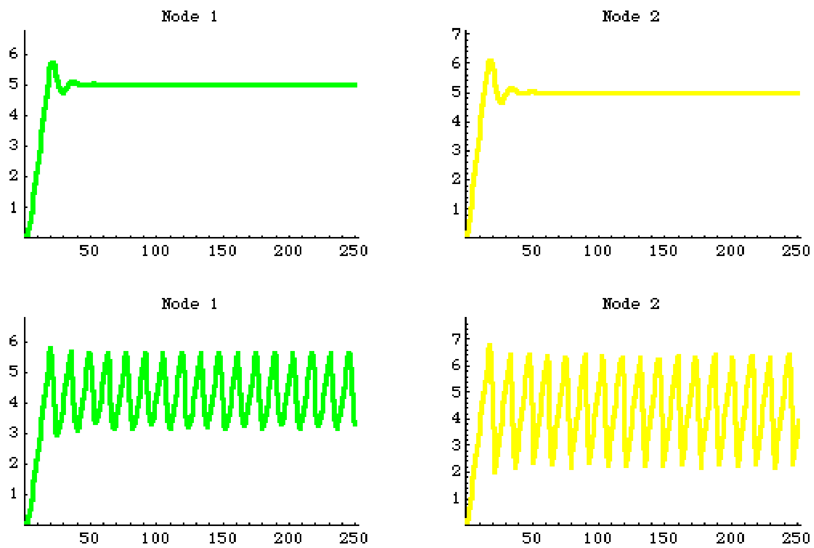


Figure C4. Examples of the possible evolution of internal nodes, 1 and 2

C1.3 ASMITA

ASMITA is a semi-empirical model for the long-term morphological development of tidal inlet systems (Stive *et al.*, 1998, Stive and Wang, 2003, Van Goor *et al.*, 2003, Kragtwijk e*t al.*, 2004).

C1.4 Common Examples

C1.4.1 The Problem

In order to better illustrate the various approaches all three approaches are applied to a common problem. Consider the morphological development of an estuary / tidal inlet under influence of tide and (accelerated) sea level rise. For simplicity reasons the morphological state is schematised with a single variable, e.g. the averaged depth.

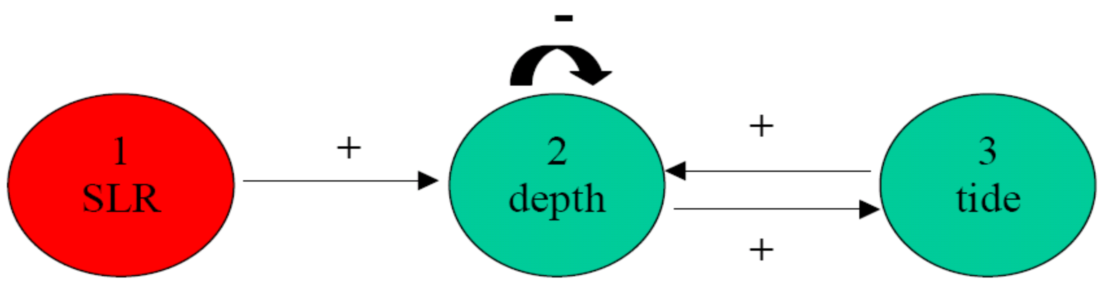


Figure C5. Network representation of the morphological development of an inlet under the influence of tide and sea level rise

Figure C5 shows the network representation of the problem. Sea level rise causes a direct increase of the depth. An increase of depth can cause more tidal intrusion in the system, which in turn can cause increase of the water depth. When the water depth is too large it can cause deposition again, therefore there is a negative feedback of the depth to itself.

Note that Figure C5 can be used as basis for the Boolean approach as well as for the network dynamics approach. However, there is an essential difference in using such network schemes in the two approaches. In the network dynamics approach the positive and negative influences as indicated in the figure is interpreted into the influence matrix in a fixed way. In the Boolean approach, on the other hand, these influences are represented in the Boolean function not according to a single way. In other words, the figure is sufficient to determine the behaviour of the system in the network dynamics approach, but is not sufficient in the Boolean approach.

C1.4.2 Boolean Approach

The sea level rise is an external node and is considered as given. The Boolean variables for the two internal node and the corresponding Boolean functions are defined as follows:

Table C3. Definition of the Boolean Variables and Functions

Network Element	Boolean Variable	Boolean Function
depth	d	D
tides	t	T

$$D = d' \vee t$$
$$T = d \qquad (7)$$

As there are only two Boolean variables, there in total 4 (=2^2) possible state of the system. These 4 state and the responses according to the Boolean functions (7) are given in the following table.

Table C4. States and Responses According to the Boolean Functions

State	d	t	D	T
1	0	0	1	0
2	0	1	1	0
3	1	0	0	1
4	1	1	1	1

It is interesting to notice that state 4 is a steady equilibrium and states 2 and 3 form a cyclic equilibrium. State 4 is the end state only if it is the initial state. In all other cases the system ends with the cyclic development 2⇔3.

C1.4.3 Network Dynamics

The network as show in Figure C5 is represented by the following matrix:

$$W = \begin{pmatrix} 0 & 1 & 0 \\ 0 & -1 & 1 \\ 0 & 1 & 0 \end{pmatrix} \qquad (8)$$

so the net influence vector becomes:

$$(w_1, w_2, w_3) = (x_1, x_2, x_3)W = (0, x_1 - x_2 + x_3, x_2) \qquad (9)$$

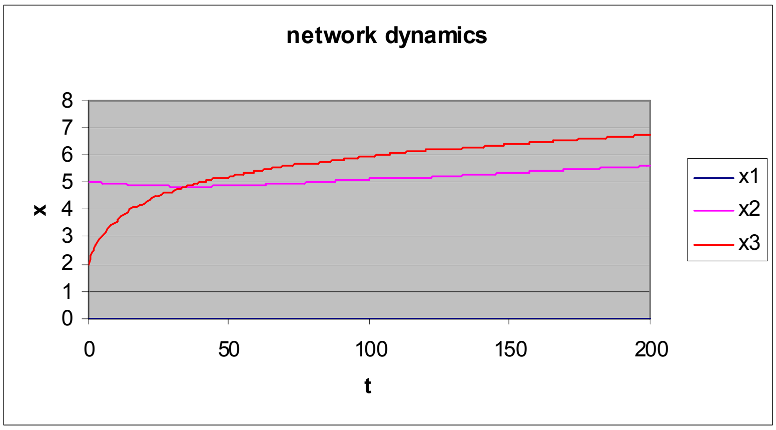


Figure C6. Network model results

Using the following choices for *F* and φ and with the initial state (x_2=5, x_3=2) the model results as shown in Figure C6 are obtained.

$$F(w) = \tanh(w)$$
$$\varphi(x) = \exp(-x) \qquad (10)$$

The results in Figure C6 suggest that both tide and water depth in the estuary is increasing in time.

C1.4.4ASMITA

The results of the single element ASMITA model are shown in Figure C7. The simulation starts with an estuary in equilibrium, before the sea level rise starts at t=0. The volume under moving sea level increases to a higher new (dynamic) equilibrium value. At the end state the sedimentation (decrease of the volume under fixed level) exactly balances the sea level rise.

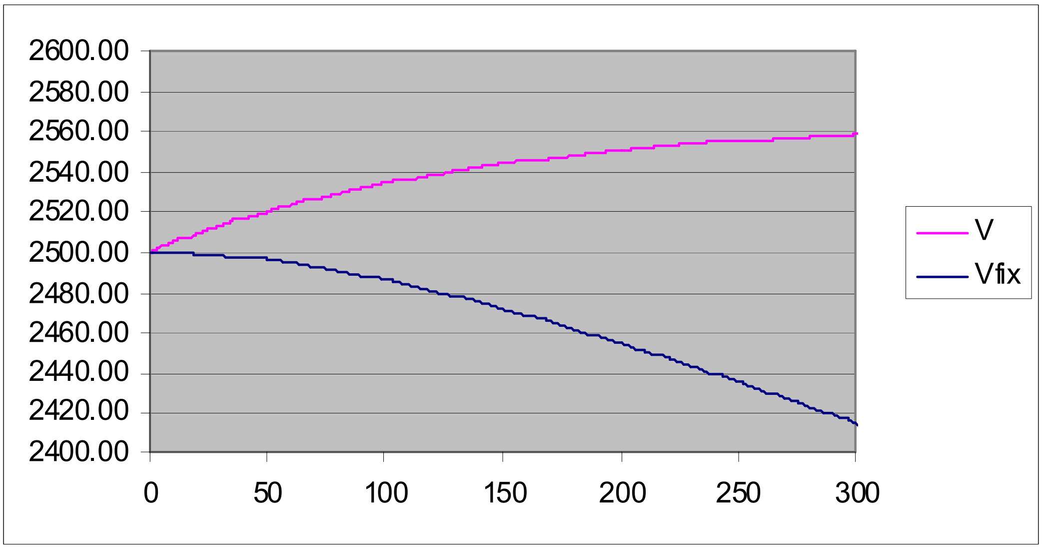


Figure C7. Development of the volume of the estuary under moving sea level (V) and under (fixed) initial sea level (Vfix) simulated by the single element ASMITA model

C2. Concluding Discussions

The three approaches under consideration are in fact almost totally different from each other. The only thing is common is the schematisation of an estuary into a "small" number of "large" elements. Nevertheless an attempt is made to compare the three approaches in Table C5 by looking at the INPUT/OUTPUT of the approaches, by considering their behaviours, and by evaluating the known applications in the estuarine modelling so far.

As indicated in Table C5, the input and output of the Boolean approach are qualitative. Also the time step in the development is qualitative. Therefore the interpretation of the output of the model is very important in this approach. A whole story needs to be told on the basis of a series of Boolean vectors. The other two approaches use quantitative input and output. However there is a difference between the two methods concerning the physical meanings of the state variables. The state variables in the ASMITA model are in principle measurable physical quantities. The (uniform) way of treating all the node variables in the network dynamics implies that all these variables must have the same dimension. In practice this means that they should be dimensionless. Furthermore it is noted that the absolute values of the node variables are not important because of the (so called) scaling behaviour of the approach. By scaling behaviour it is meant that an equilibrium state (represented by a vector of non-negative real numbers) multiplied by any constant positive number remains an equilibrium state. It seems therefore that the physical meanings of the node variables and the way in which they should be made dimensionless are not clear. Another interpretation of this observation is that although the input and output of the network dynamics approach are quantitative in the mathematical sense, they are qualitative in the physical sense.

The qualitative character of an approach also makes it more flexible in applications. It is e.g. much easier to include an element or a process (as an example to extend an existing morphological model by including ecological influences) of different category in a Boolean approach than in ASMITA.

The real estuarine system is too complex to be fully described by any of the considered approaches. Due to the differences between the methods and due to our restricted understanding of the system we the three approaches should be considered as complementary rather than competitive to each other.

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APPENDIX D. GLOSSARY OF TERMINOLOGY USED IN THE MATLAB CODE OF THE PROTOTYPE SIMULATOR

Coastal-Estuary Features

Ocean waves	Presence of offshore waves
Littoral sand	Presence of sand available to be transported by littoral drift
Inlet	Presence of an opening in the coast i.e. an estuary or tidal inlet
Spit	Presence of an extended sand barrier caused by littoral drift which partially blocks an inlet/estuary entrance
Dunes	Presence of sand dunes
Wind	Presence of dune-inducing wind
updrift beach	Presence of beach which provides a source of material to the inlet/estuary
downdrift beach	Presence of beach which is a sink for sediment material to the inlet/estuary
marine_sand/marine_mud	Presence of sand/mud as a sediment source
macrotidal/mesotidal/microtidal	Tidal range

Outer Estuary Features

ebb delta	Presence of a sedimentological feature occurring just outside the mouth of an estuary or inlet
flood delta	Presence of a sedimentological feature occurring just inside the mouth of an estuary or inlet
prism	Presence of a significant tidal volume
accommodation_space	Presence of significant channel depth in the estuary
linear banks	Presence of a sand bank system outside the mouth of an estuary
outer flood dominance estuary	Presence of landward residual transport in the outer
outer estuary swell	Presence of swell cause by offshore waves
outer estuary waves	Presence of significant locally generated waves in the outer estuary
outer subtidal sands	Presence of sand overlying the channel bed
outer sand flat/outer mud flat	Presence of sand/mud flats in the outer estuary
outer marsh low/outer marsh high	Presence of saltmarsh in the outer estuary near the Low Water/High water margin
Outer flood plain	Caused due to the presence of flood defence and represents the area that is being protected by the defences

Inner Estuary Features

Inner estuary flood dominance	Presence of landward residual transport in the inner estuary
inner estuary subtidal deposits	Presence of sand or mud overlying the channel bed in the inner estuary
inner estuary waves	Presence of significant locally generated waves in the inner estuary
inner sand flat/inner mudflat	Presence of sand/mud flats in the inner estuary
inner marsh low/inner marsh high.	Presence of saltmarsh in the inner estuary near the Low Water/High water margin
Outer flood plain	Caused due to the presence of flood defence and represents the area that is being protected by the defences
river_discharge	Presence of significant fluvial discharge
river_sand/river_mud	Presence of significant fluvial sediment input of sand/mud

Interventions

Seawall	Presence of sea wall
Groynes	Presence of groynes - affects longshore drift
sea level rise	Presence of sea level rise
Hold the line	Management option to maintain current flood defences
Realign	Management option to remove flood defence
Inner flood defence/Outer flood defence	Management option to remove flood Defence in the inner/outer estuary
Inner Dredging/Outer dredging	Presence of dredging (deepening) in the inner/outer estuary
Barrage	Presence of a barrage which reduces tidal range in the inlet

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