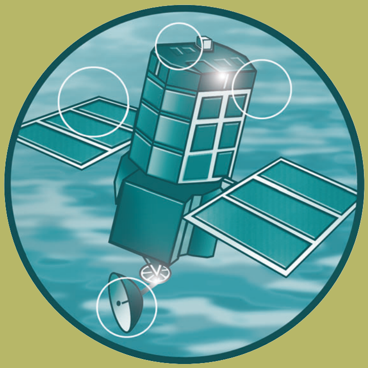
Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme

Development and Demonstration of Systems Based Estuary Simulators (EstSim)

Pilot testing: Performance evaluation of prototype simulator

R&D Technical Report FD2117/PR7



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Pilot testing: Performance evaluation of prototype simulator

Prepared by HR Wallingford Ltd for the Estuaries Research Programme (ERP Phase 2) within the Defra and Environment Agency Joint Broad Scale Modelling Theme

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Contract Statement
This report describes work commissioned by Defra under Project FD2117 Development and Demonstration of Systems Based Estuary Simulators (EstSim). The Funders Nominated Project Officer was Kate Scott Environmental Agency. (Email: Kate.Scott@environment-agency.gov.uk.). The HR Wallingford project number was DDS0211 and the Project Manager at HR Wallingford was Richard Whitehouse (Email: r.whitehouse@hrwallingford.co.uk).

Collaboration Statement
This report was prepared by HR Wallingford as part of the EstSim Consortium comprising: ABP Marine Environmental Research Ltd (lead), University of Plymouth (School of Engineering), University College London (Coastal & Estuarine Research Unit), HR Wallingford, WL | Delft Hydraulics and Discovery Software.

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EXECUTIVE OVERVIEW OF FD2117: DEVELOPMENT AND DEMONSTRATION OF SYSTEMS BASED ESTUARY SIMULATORS (EstSim)

Pilot testing: Performance evaluation of prototype simulator, July 2007

Purpose

The Broad Scale Modelling Theme of the Defra/EA Joint Thematic R&D Programme for Flood & Coastal Defence has funded three contracts under the Estuaries Research Programme, Phase 2 (FD2107, FD2116 and FD2117). FD2117 (EstSim) started in April 2004 and has the following headline aims:

- To extend the ability to simulate estuary response to change.
- Facilitate knowledge exchange through accessibility of simulation results.

The Project

ABPmer, University College London, University of Plymouth, HR Wallingford, WL | Delft Hydraulics and Discovery Software are undertaking the project. The project is of just over 3 years duration (April 2004 - June 2007) and has nine Scientific Objectives as follows:

1. **System Conceptualisation**: Boundary setting and focusing of research effort.
2. **Development of Management Questions**: Rationalisation of management questions that can be informed through application of systems approach.
3. **Development of Behavioural Statements**: Formal definition of estuarine system in terms of systems approach and behavioural statements.
4. **Mathematical Formalisation**: Development of behavioural statements into a logically consistent mathematical framework.
5. **Development of System Simulation**: Development of architecture for estuary simulation based on the mathematical formulation of the system definition.
6. **Manager System Interface**: Explore the use of decision support systems and visualisation techniques for proof of concept testing.
7. **Pilot Testing**: Performance evaluation of estuary simulator.
8. **Dissemination**: Increase awareness of function and utility of research.
9. **Peer Review**: Ensure research lines deliver against Scientific Objectives.

This report delivers item 7 on the performance evaluation of the EstSim prototype estuary simulator developed in the project through mathematical formalisation of the system based description of estuary behaviour.

The results of this pilot testing have been taken forward in drafting a model description for use by the project, including input/output requirements and statements on validation, range of applicability and accessibility.

Contact Details

For more details of the pilot testing contact Richard Whitehouse at HR Wallingford (r.whitehouse@hrwallingford.co.uk). For information on the project please contact the FD2117 Project Manager Alun Williams (awilliams@abpmer.co.uk) or the Funders' Nominated Project Officer Kate Scott (Kate.Scott@environment-agency.gov.uk).

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1. INTRODUCTION

1.1 Background

This report describes work undertaken by HR Wallingford as part of Defra R&D project, FD2117, 'Development and Dissemination of System Based Estuary Simulators'. The work described in this report consists of pilot testing of the EstSim prototype simulator developed during the project.

The EstSim approach builds on the modelling methodology set out by Karunarathna and Reeve (2005) and extended by French and Burningham (2007). It describes a set of rules encapsulated in a network based model of an estuary system with feedbacks between components described in terms of Boolean logic. For any estuary the model represents the presence or absence of a forcing and of different features or elements in the estuary by a "1" or a "0". The modelled estuary passes through a number of intermediate states before reaching a stable end state. The results are presented in the form of a table (e.g. Table 1) in which the steps are represented by numbered columns and the estuary features are distinguished in the rows of the table and distinguish between the estuary/coast interface and the inner and outer estuary.

1.2 Objective

The objectives of this part of the project were twofold:

- To evaluate the performance of the simulator against present and emerging knowledge of estuary processes, i.e. how well these estuaries can be represented by the EstSim simulator; and,
- To provide a critique of the simulator's ability to help address an identified range of management issues.

These objectives are achieved by applying the EstSim simulator to two different estuaries: the Thames and the Teign (Devon). The ease of using EstSim and interpreting the results is also assessed. The testing used the MatLab© code Version 3.03 (estsim3delay.m) with ESTSIM Boolean Function Library version 12, provided by Dr Jon French of University College London (http://www.geog.ucl.ac.uk/ceru/projects.htm). The delay terms used were 3 times steps for rapid change and 5 time steps for slow change (French and Burningham, 2007). A web-based version of the simulator will be made available following completion of the project.

Specifically, this report will comment on:

- The capabilities of the EstSim approach to determine emergent properties of an estuary;
- The capabilities of the EstSim approach to determine the sensitivities of an estuary to change;
- The capabilities of the approach to determine the constraints on estuary evolution;
- The ability of EstSim to provide a basis for evaluating quantitative models (e.g. to confirm the direction of change following a change in forcing).

These issues were identified in the report on management questions prepared by ABPmer (2007).

1.3 Report structure

This report comprises a further four chapters. Chapter 2 describes the use of the EstSim prototype simulator for the Thames Estuary. Chapter 3 presents the use of the simulator for the Teign Estuary. The results of these applications are discussed in Chapter 4 and conclusions of the report are presented in Chapter 5.

2. THAMES ESTUARY

2.1 Generic funnel-shaped estuary

The Thames estuary is described as a funnel shaped estuary in FutureCoast (Dyer, 2002) and in EstSim (ABPmer, 2004) and a coastal plain estuary by JNCC (1997).

The evolution of a generic funnel shaped estuary in the simulator is shown in Table 1. The estuary evolves from starting conditions of ocean waves, littoral sand, marine sand, marine mud, macrotidal (tidal range), inlet, wind, prism, accommodation space, river discharge, river sand and river mud. These variables are defined in the glossary (Appendix 1). 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 and 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 sand flat, inner mudflat and inner marshes. Accommodation space is lost because it is taken up by intertidal features in the outer estuary. In the inner estuary there is a switch between flood and ebb dominance as intertidal features appear.

Table 1 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 simulator (French and 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 Estuary.

2.2 Adjusting generic funnel-shaped estuary for the Thames

2.2.1 Flood defences

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 2).

Table 2 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 (Table 2, step 1) are the same as the generic funnel shaped estuary (Section 2.1) 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, prism is turned off which it did not do in the simulation of the generic estuary of which the results are shown in Table 1.

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 EstSim use of outer flood defences may not be appropriate here. Table 3 shows the evolution of a funnel shaped estuary with inner flood defences only.

Table 3 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 4) 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 mud flats 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 (Section 2.3.1).

In addition, it was noted that outer estuary swell is not present in the Thames Estuary 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 (Section 2.3.2).

Table 4 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

2.3 Changes to function libraries for Thames Estuary

2.3.1 Addition of "encroachment" term

New terms can be added to the function libraries to allow morphologies for specific estuaries to be represented more accurately. To add a term to the existing library, it is first necessary to edit the number of variables on line 7 of the function library. The function name can then be added to the list, selecting the most appropriate place in relation to the other functions. The new function definition and extended variable name description are added to the relevant sections ensuring that these are in the same relative position as in the name list. 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. To make this work it is important to edit the number of variables and to insert the function in the same relative position it occurs in the function library.

2.3.2 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)
```

2.4 Thames specific setup

Using the changes to the generic funnel shaped estuary derived from experience with initial testing (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 5). The results were saved in a new version of the function library (version 13) that was sent to Dr Jon French at UCL.

Table 5 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

This model set up is used for all modelling experiments of the Thames Estuary reported in the remainder of this report.

2.5 Thames Estuary experiments

Various experiments 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.

2.5.1 Barrage

The effect of including a barrage on the Thames was simulated using the steady state condition for Thames specific setup (Section 2.4, Table 5) with the addition of a barrage feature in the Outer Estuary (Table 6).

Table 6 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 sand flats and linear banks present before for the barrage 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 depend 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 7) is similar. However, the inner flood defences breakdown, allowing sand and mud flats and marshes to develop. This draws attention to the use of management intervention policies in the version 12 function library – each policy applies everywhere in the system. Separate policies for the inner and outer estuary and coastal sub systems would be useful.

Table 7 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

2.5.2 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 8) and outer and inner dredging (Table 9).

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 Estuary, 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 8), 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 5) 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 8 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 9), 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 9 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

2.5.3 Reclamation

The Thames Estuary has undergone extensive reclamations in the past, particularly in the inner estuary, making it necessary to include the inner encroachment term (Section 2.3.1) 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 10 shows that 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 and 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 enough in the Version 12 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 10 Evolution of Thames Estuary 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

2.5.4 Realignment

The effect of managed realignment is simulated by removing the flood defences. In Table 11 the effect of removing flood defences has been simulated using the steady state conditions for the undisturbed Thames specific setup (step 11, Table 5) as the starting conditions. This can also be done using a realign policy. However this causes a delay of 6 time steps before the flood defences are removed.

Table 11 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

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 Version 12 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 which develop following a realignment intervention.

2.5.5 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 12. Adding sea-level rise for the Thames estuary has no impact on the processes or on the steady state morphology.

Table 12 The evolution of the Thames Estuary 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 13) the evolution is similar to the simple realignment scenario (Table 10) 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 13 Evolution of the Thames Estuary 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

3. TEIGN ESTUARY

3.1 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 the EstSim project (ABPmer, 2004), 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 14. Starting conditions include ocean waves, long shore power, littoral sand, marine sand, marine mud, mesotidal, 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, down drift beach, dunes, ebb and flood deltas, outer subtidal sands, outer sand and mud flats, inner subtidal deposits, inner sand and mud flats 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 14 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

3.2 Teign specific setup

A Teign specific estuary definition file was created based on the generic spit-enclosed estuary. It was adapted (Table 15) to include:

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

The general procedure for doing this was the same as that followed for adding the encroachment term in the Thames (Section 2.3.1). In the Teign specific case reed beds form in the inner estuary and the absence of marine mud prevents outer-mud-flats 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. The Teign estuary is strongly ebb dominant.

It should be noted that there are no obvious “inner” and “outer” sections within the estuary and this adds some uncertainty to the conclusions arising from the application of the generic estuary template. It may be that the outer estuary is only a very short section between the narrow mouth and Shaldon Bridge about 1km up-estuary.

Table 15 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

3.3 Teign experiments

A number of modelling experiments 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 3.2, Table 15), unless otherwise stated.

3.3.1 Flood defence

Flood defences were imposed in the outer estuary (Table 16), inner estuary (Table 17) and both outer and inner estuary (Table 18). 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 sand flats are lost.

The inner estuary is unaffected by the outer flood defences.

Table 16 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

Flood defences in the inner Teign Estuary had less effect on the overall morphology of the estuary (Table 17). 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 17 Evolution of the Teign Estuary with inner_estuary_defence

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 18 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 18 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

3.3.2 Dredging

The effect of dredging in the outer estuary (Table 19), inner estuary (Table 20) and both inner and outer estuary (Table 21) was simulated using the Teign specific setup.

The comments made in Section 2.5.2 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. In general this greatly over-emphasises the effects of dredging.

The predicted effects of outer dredging (Table 19) 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 3.2 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.

Table 19 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

With inner dredging only (Table 20), the evolution of the outer estuary is the same as for the undisturbed case. The down drift beach, accommodation space and flood and ebb deltas are unaffected by inner dredging. In the inner estuary, inner subtidal deposits are removed. The inner mud flats, marshes and reed beds remain.

Table 20 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 21 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 21 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

3.3.3 Realignment

This simulation uses the steady state conditions from simulation with inner and outer flood defences as the starting point (step11, Table 18). The defences are 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 22).

Table 22 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

3.3.4 Groynes

The effect of groynes on the updrift coast was investigated by adding groynes to the Teign specific steady state conditions. Table 23 shows that there is no response to adding groynes in the absence of additional forcing.

Table 23 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 24 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 down drift beach and dunes. Ocean waves now penetrate the estuary resulting in outer estuary swell. The behaviour of the inner marsh becomes cyclic.

Table 24 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

3.3.5 Sea-level rise

Table 25 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 26). 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 25 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 26 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 27). Following the break down 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 27 Predicted evolution of the Teign Estuary 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

4. SIMULATOR USABILITY

The MatLab script of the EstSim prototype simulator was found to be relatively easy to use and quick to run. The results files are output in text file format which can be imported into a spreadsheet in order to present the results as colour coded tables (e.g. Table 27) (as was done in the present testing using Microsoft Excel).

The generic estuary scenarios can be run without additional knowledge. Both the function libraries and estuary definition files may need modification in order to accurately represent specific estuaries. This task requires a good knowledge of estuary geomorphology and processes as well as familiarity with numerical modelling.

Estuary definition files required modifications to forcing variables so that estuary specific morphologies evolved during simulations. Changes to the generic estuary definition files include switching on or off forcing associated with the generic type and inclusion of additional forcing or morphologies from the function libraries. Both types of change are easily done, but it is important to insert additional parameters in the correct position in the definition file (definition file should be in same order as library).

Changes to the function libraries were also relatively simple to achieve. New functions need an abbreviated name, function definition and a full name. Defining the function and ensuring it has the correct interaction with other functions and morphology requires some thought and knowledge of estuary systems, but implementing the function in the library should be straight forward.

5. DISCUSSION

5.1 Overall performance and emergent properties

A major benefit of the EstSim prototype simulator was that it was straightforward to use from the MatLab code with the generic estuary definitions and existing rule-based function library. As part of the present pilot testing study application of the code to the Thames Estuary and estuary of the River Teign was investigated. In general, minor modifications to the generic estuary definitions allowed the observed features of the Thames and Teign estuaries to emerge. For the Thames estuary this required changes to the generic funnel shaped estuary specification and an addition and modification to the EstSim function libraries to reproduce the observed morphologies. These changes in the code were relatively simple to make but required a good understanding of estuary processes and morphology. Following the modifications, the simulation produced a morphology that represented the Thames Estuary reasonably well.

For the Teign Estuary, changes were limited to minor alterations to the estuary specification to make it case specific. In general the results were satisfactory with morphologies resembling those found in the real estuary; however the simulator predicted 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 causes other effects which in turn lead to morphologies that are not seen to develop in the real system. This point was acknowledged in the EstSim Development Report (French and Burningham, 2007) which suggested that the problem could be overcome with an increase in the model complexity. While this could be seen as a longer term goal, in the meantime clearer definitions of the morphologies and processes are needed.

On the subject of interpretation of the results, 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 the present study this was assessed largely by trial and error and the interpretation of the simulator performance required a high level of expert knowledge to know what the expected outcomes should be and how these differed from the model assessment. Therefore the initial stages of the simulator application were similar to any modelling exercise, namely that the model 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 model to answer specific questions about the system function.

A number of the logical relationships within the Boolean model, as it currently stands, appear to require modification. This report has not sought to modify these aspects unless absolutely necessary (as in Section 2.3.2), 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 marsh elements, have *on themselves* appears to be the cause of the cyclical behaviour observed in French and Burningham (2007) and in this report.
- 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 – 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 sand flats 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 (Table 8) and for the estuary to be both microtidal and mesotidal as a response to a tidal barrage (Table 7).

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

5.2 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 medium for estuary description.

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 estuary system. In other cases, we noted 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 mud flats and salt marsh. 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 sand flats were also lost.

5.3 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. For example, in the present version of the simulator the management policies apply equally to the inner, outer and coastal sub-systems. A refinement could be made to enhance the function library which allows for selective application of management policies to the different sub-systems.

5.4 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 will provide 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. 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.

5.5 Other remarks

From the pilot testing described in this report it is apparent that a prototype estuary simulator has been developed which 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 model can be refined until it captures the essential elements.

The simplicity of the model is attractive. It combines complex (subjective) geomorphological concepts in a simulator and is quick to run; both of these aspects are major advantages. The simulator would be 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 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 within the model. In addition, more extensive testing with specific estuary setups is necessary to determine the range of behaviours that may be experienced. The results of these tests should be documented such that an objective set of information exists from which improvements can be driven

As with any model, the EstSim prototype simulator requires good/expert knowledge of estuary morphology both to set up the model 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.

Future development of the simulator should consider the difficulties that validation of the model predictions presents. 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) in estuaries. Deciding whether this sort of estuary property has been correctly predicted by the model is a value judgement which may be open to significant uncertainty depending on the quality of data available and the experience of the person making the judgment. A means of making this evaluation process more rigorous would be valuable both for the future development of the model and for its subsequent use.

6. CONCLUSIONS

The EstSim prototype simulator implemented in MatLab by University College London (French and Burningham, 2007) has been evaluated through pilot testing. The following conclusions have been drawn:

1. 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 code was able to reproduce the observed features of two UK estuaries (the Thames and Teign) following specific modifications to the generic estuary specifications and some changes to the EstSim code. It is quite likely that other interpretations are possible and may be required for specific purposes.

2. 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 exercise identified a number of shortcomings with the existing model which means that further improvement, possibly including increased complexity, and validation of the model is required.

3. 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.

4. The simulator may be useful for evaluating quantitative models by providing information on the direction of change. The simulator predicts an evolutionary path but the “all or nothing” binary approach and inherent lack of time scale makes comparison difficult. The model 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.

5. 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 model to distinguish between large and minor effects, which results from the Boolean architecture of the model. This makes it inappropriate for use as the only source of information with which to inform decisions regarding regulation and development.

6. 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 model 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 of the model needs to be extended further and extensive testing with a wider range of specific estuary setups is necessary to determine the behaviours that may be present in real estuaries.

7. The results of this pilot testing have been taken forward in drafting a model description for use by the project, including input/output requirements and statements on validation, range of applicability and accessibility.

7. THE WAY FORWARD

A project team meeting was held at ABPmer offices on 11 June 2007 to disseminate the findings of the Pilot Testing Objective (7). The results of this Objective have been incorporated into the Interface, together with an interpretation of the results and performance of the approach in each test situation, i.e. the Thames and the Teign, Devon. In addition a decision was made to document how to make changes to model (inclusion of inner reed bed and encroachment elements), as these elements were necessary to enable the estuaries to function.

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Appendix 1

Glossary

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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