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Project identification

1. Defra Project code: FD2117
2. Project title: Development and Demonstration of Systems-Based Estuary Simulators (EstSim)
3. Contractor organisation(s):
   ABP Marine Environmental Research Ltd (Lead Contractor)

   University of Plymouth;
   University College London;
   HR Wallingford
   Deltares
   Disovery Software
4. Total Defra project costs (agreed fixed price): £ 235,000
5. Project: start date .... 01 April 2004

   end date .... 30 June 2007

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Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

FD2117 'Development and Demonstration of Systems-Based Estuary Simulators' (EstSim), has been completed as part of the joint Defra/Environment Agency R&D Programme. This research forms one of the contracts completed under Phase 2 of the UK Estuaries Research Programme (ERP). The three phases of ERP seek to improve our understanding and prediction of morphological change over the medium to long term, thereby facilitating strategic and sustainable decisions regarding flood and coastal defence

FD2117 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 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 detailed consideration be given to the capabilities and limitations of the Prototype Simulator prior to any application of the approach.

This report includes the following:

- An overview the scientific context and objectives of the research;
- A review of the systems approach and the formal definition of UK estuaries;
- 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;
- Conclusions and Recommendations for further work; and
- A model summary providing a description of the key aspects of the Prototype Simulator;
- Details of the accessibility of the research outputs (including the web-based interface, the Matlab research code and further project outputs).

Project Report to Defra

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:

- the scientific objectives as set out in the contract;
- the extent to which the objectives set out in the contract have been met;
- details of methods used and the results obtained, including statistical analysis (if appropriate);

- a discussion of the results and their reliability;
- the main implications of the findings;
- possible future work; and
- any action resulting from the research (e.g. IP, Knowledge Transfer).

1. INTRODUCTION

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.

This is the FD2117 Project Report to Defra. Further details of the study can be found in the R&D Technical Report (FD2117/TR).

Aims

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.

Purpose

The effects of natural change and anthropogenic interventions on an estuarine environment require 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.

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).

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).

Scientific Objectives

The research 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 a 1-day workshop at the University of York (2^{nd} 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.

The project involved providing a formal definition of estuary systems through mapping of the system components (via production of systems diagrams) and providing an understanding of how these components interact (via the production of behavioural statements). This definition of an estuary system maps a set of influences between the morphological and process components. This component of the work is detailed in Sections 2 and 3 of this report. The project then formalised this definition using a Boolean network approach. The Boolean approach is mathematically straightforward, an estuary is conceptualised as a set of morphological features (inlet channels, tidal flats, saltmarshes, spits etc.) and processes (waves, tides, sediment supply etc.), which can be represented in the form of a network of interconnected components. At any time, a given morphological feature is either present or absent (or 'on' or 'off' in a logical sense) depending on the status of the other components with which it interacts. This Boolean formulation has been used to develop a *proof-of-concept* estuary system simulator. The prototype simulator incorporates linked sub-systems for inner and outer estuary zones, and for the interaction between the estuary and the open coast, and includes additional variables to represent engineering interventions (e.g. coastal groynes, seawalls, dredging). The prototype simulates the evolutionary trajectory in terms of the state of each of the components within the system. The development of the prototype simulator is discussed in Section 4 of this report. The pilot testing of the prototype is discussed in Section 5. This prototype simulator has been developed into a web-based interface. This provides full simulation functionality through an easy to use Graphical User Interface (GUI) and provides a means to promote systems based knowledge and understanding. The details of the interface and how to access it are provided in Section 6. This is followed by the conclusions and recommendations from the study. Appendix A then provides a 'model summary' summarising the key aspects of the prototype simulator including its applicability and theoretical background.

2. THE SYSTEMS APPROACH

The systems approach involves separating out sub-systems and their interactions in order to understand the system organisation and define its behaviour. Thus it 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.

A system-based approach is necessarily an abstraction of the real system, focussing on the scale and aspects of the system that are of interest to the user. To this end, 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 estuary processes and the ways in which these are expressed. The objective of defining systems diagrams is to represent the interactions between system components. Ideally this should capture the behavioural attributes of the system and inform abstraction and aggregation to different system levels.

Behavioural / Qualitative Modelling

The systems approach and the use of systems diagrams can be used to map the system components (elements and interactions) at a specified level of interest. However, attempting to model this detailed system is limited by current mechanistic understanding of the underlying processes, which is one of the reasons why the behavioural systems approach was 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 (e.g. sediment), 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 that exhibits the same behaviour, but which does not need to have any specified 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). 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 one or more of these units are likely to change.

3. DEFINITION OF UK ESTUARIES

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 using systems diagrams and behavioural statements 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.

Estuary Classification

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

In terms of geomorphological elements, Table 1 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 1 then identifies which geomorphological elements are potentially present in the different types of estuary.

Table 1. 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.

In order to test the typology presented in Table 1, a rule base was set-up and applied to the estuary data from EMPHASYS, Futurecoast and the JNCC inventory. This gives results that are reasonably consistent with previous classifications.

Application of the typology to classify all UK estuaries allowed for the development of behavioural statements and systems diagrams that are applicable to the range of estuarine types found in the UK. In doing this, application of the classification ensured the behavioural relationships explored, developed and applied throughout the research could be compared within a consistent framework.

Behavioural Statements and Systems Diagrams

The development of behavioural statements has facilitated (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.

High-level descriptions of each of the seven identified estuary behavioural types in the UK (Table 1) including identification of the component geomorphic elements, using a systems diagram, were developed. In addition, textural descriptions were generated for each of the eleven geomorphic elements identified from the typology as being present in UK estuaries (Table 1). Each geomorphic element is represented by a systems diagram, which covers the short to medium-term and medium to long-term.

These behavioural statements and system diagrams capture, in a qualitative sense, the components and linkages at different levels within generic estuary systems in order that these definitions could be formalised to develop a behavioural model.

4. DEVELOPMENT OF A PROTOTYPE SIMULATOR

The project then developed a mathematical framework to capture the formal definition of estuary systems as represented by the systems diagrams and behavioural statements. 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. However, 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.

The formal system definition described was then developed into a mathematical framework. The approach adopted for this mathematical formalisation involved the use and development of a Boolean network approach.

The Boolean Network Approach

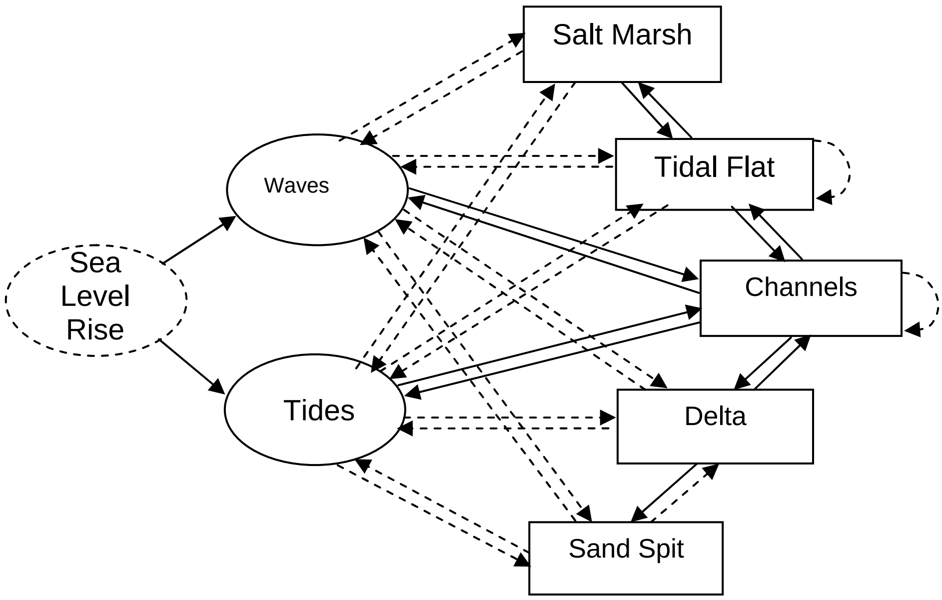
The Boolean network approach was described by Nicolis (1982) in a pioneering application of the technique to climate dynamics; and has since been developed with applications to different fields including seismology, climatology and meteorology (e.g. Ghil *et al.,* 1987, Wohlleben & Weaver 1995; Saunders & Ghil 2001; Zaliapin *et al.,* 2003). It provides a modelling framework that is particularly suited to the mathematical formulation of conceptual models of systems that exhibit threshold behaviour, feedbacks and time delays.

Within the EstSim project, a Boolean approach has been used to develop a 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' (i.e. as provided by the formal system definition) to be encapsulated and manipulated in a rigorous manner.

Boolean networks were initially constructed for each behavioural estuary type (Table 1). 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.

Once the elements of the Boolean network have been defined based on the estuary system diagram, feedback loops between geomorphological elements and external forcing that drive the morphological evolution of the estuary are developed from the behavioural description and the system diagram of the geomorphological elements. 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.

Once the network is completed, a Boolean variable is assigned to each element in the network and 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 the computed by solving the logical expressions for Boolean functions, giving Boolean states corresponding to various combinations of Boolean variables and resulting Boolean functions. The concept is illustrated for a simplified-representation of a generic tidal inlet in Figure 1. The geomorphological rules for that network are defined by the statements contained in Equation (1).



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

Figure 1. Boolean network for a generic tidal inlet (little or no sediment flow from outside).

$$\left.\begin{aligned}
W &= sm' \vee tf' \vee cc \vee dd' \vee ss' && \text{(a)}\\
T &= sm' \vee tf' \vee cc \vee dd' \vee ss' && \text{(b)}\\
SM &= (w' \wedge t \wedge tf) && \text{(c)}\\
TF &= ((sm \vee cc) \wedge t) \vee (tf' \wedge w') && \text{(d)}\\
CC &= (w \vee t) \wedge (tf \vee dd) \vee cc' && \text{(e)}\\
DD &= (w' \vee t') \wedge ss' \vee (t \wedge cc) && \text{(f)}\\
SS &= (w' \vee t') \wedge dd && \text{(g)}
\end{aligned}\right\}(1)$$

The following notations stand for the variables used in Equation 1:

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*

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 will change.

Prototype Simulator

This initial development of the Boolean network approach was extremely useful as a proof of concept exercise. The challenge was then 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.

The formal system definition was 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 sedimentary 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 sets out the spatial arrangement of the major morphological components and various external and internal influences on their evolutionary behaviour. Three broad types of system component are distinguished:

- External (imposed) forcing and interventions;
- Process state variables; and
- Morphological components (similar to the geomorphological elements derived from the estuary typology with a number of minor modifications).

Boolean functions were developed to define, within the network model, the linkages between each of the above variables for the coast-estuary interface, outer-estuary and inner-estuary sub-systems. In applying what is essentially a 'rule-base' approach at this level of detail, it is recognised that the translation of a qualitative understanding of geomorphological elements, and their interaction with processes, into Boolean functions represents a significant challenge.

To provide an illustration of the extension of the initial Boolean network model, as described above, an example Boolean variable and function within the Outer Estuary sub-system is presented below in Table 2, together with the rationale for the specific function. The extended Boolean network described above is referred to as the Prototype Simulator.

Table 2: Example of a Boolean Variable and associated Boolean, to illustrate 'Rule Base' approach of Boolean network model

Sub-System	Outer Estuary
Boolean Variable	OUTER_MARSH_LOW
Boolean Function	(~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)))))
Descriptive Rationale	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.

Notes: Boolean Functions are defined here using logical AND (& in MATLAB), OR (|) and NOT (~) operators.

5. PILOT TESTING

Several phases of testing were completed as part of the development process. The first test of the Prototype Simulator model was whether or not it is capable of discriminating between the seven generic estuary types defined as part of the project. In addition, 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).

In addition to this testing undertaken as part of the development process, 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 Thames and Teign). The pilot tests were essential in providing a robust evaluation of the Prototype Simulator.

In order to ensure the research was targeted and tested against present and relevant management drivers a review of management questions was also undertaken. This was used to steer the scenarios used to pilot test the prototype simulator.

The results from this review were 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. These scenarios were 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. The scenarios tested in the pilot testing exercise included imposed sea level rise, flood and coastal defence scenarios and development activities (such as port development and dredging).

Strengths and Weaknesses of Network Models Formulated Using Boolean Functions: Discussion

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. There are some consequences of adopting a discrete binary logic, 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 has been shown within the research 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 (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.

Capabilities and Limitations

Experience from the pilot testing exercise provided assessment and guidance regarding the capabilities and limitations of the prototype simulator.

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 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 are 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.

6. ACCESS AND DISSEMINATION

The project developed a web-based interface to host the prototype simulator and various documentation disseminating the systems based approach.

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.

The preferred and developed 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 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.

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 discussed, 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.

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.

As a simple standalone tool, the MATLAB-based simulator is intended to supplement the web-based interface.

The web-based interface is available through:
http://www.discoverysoftware.co.uk/EstSim/EstSim.html.

The MATLAB research code is available through:
http://www.geog.ucl.ac.uk/ceru/EstSim

7. 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. 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.

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 Environment 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.

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.

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.

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.

APPENDIX A: PROTOTYPE SIMULATOR ‘Model Summary’

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.

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.

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.

Background

The EstSim Behavioural Statements report (ABPmer, 2007) 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.

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.

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.

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.

Validation

The EstSim method has been applied to the Ribble Estuary and Southampton Water and to the Thames and Teign. 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. 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 during the pilot testing exercise to a limited extent concluding 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.

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 be observed prior to any application of the approach.

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).

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.

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References to published material

9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.

Journal Articles / Papers:

Williams, A., Townend, I, H., French, J., Reeve, D., Whitehouse, R,J., Zheng, W,B., Morris, K., Surendren, S. 2008. Development and Demonstration of System Based Estuary Simulators: EstSim. Proceedings of the 43rd Flood and Coastal Management Conference, 2008. July 2008.

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Web Publication:
http://www.discoverysoftware.co.uk/EstSim/EstSim.html
http://www.geog.ucl.ac.uk/ceru/EstSim
In addition, details of the EstSim project can be found on the Estuary Guide website:
http://www.estuary-guide.net/
This website includes copies of each of the PowerPoint presentations from the FD2117 dissemination workshop held at York University.