Paper to be presented at the
Flood and Coastal Erosion Risk Management Conference 2007
Tuesday 3rd July to Thursday 5th July 2007
University of York

INTEGRATED COASTAL SIMULATION TO SUPPORT SHORELINE MANAGEMENT PLANNING

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Key words: coastal simulator, shoreline management, regional assessment

Abstract: Shoreline Management Plans (SMPs) in the UK are currently at a key stage with most now being updated for the first time. These SMPs need to be technically robust, integrating flood risk and coastal erosion in the context of climate change, spatial planning, habitat protection and the need for stakeholder engagement. The Tyndall Centre for Climate Change Research, in partnership with the Environment Agency, is developing a coastal simulator that addresses these complex questions. The simulator provides information on the possible future states of the coast under a range of climate and socio-economic futures and shoreline management options. Currently, it is mainly focused on cell 3 (East Anglia) and sub-cell 3b, in particular, but the method is designed to be generic. The approach is based on a series of linked models within a nested framework which recognises three spatial scales: (1) global; (2) regional (e.g. North Sea); and (3) the simulator domain (a physiographic unit such as sub-cell 3b). The linked models describe climate (waves, surges and mean sea level), sand bank morphodynamics, wave transformation, shoreline morphodynamics, the evolving built environment, ecosystem change, and erosion and flood risk, while shoreline management scenarios are developed with relevant stakeholders. The simulator includes a dedicated user interface which allows a wide range of queries, making the results available in the preparation of SMPs. The initial results demonstrate important linkages for shoreline management, such as the interaction between erosion management and flood risk within a sub-cell. Delivering improved shoreline management raises important social and political issues which the Tyndall Centre is also addressing.

1. Introduction

Coastal zones are important in social, economic and environmental terms. They attract settlements and economic activity, and include natural habitats that provide valuable services and functions. However, the coast is vulnerable to climate and other changes. Sea-level rise and more intense storms could increase coastal erosion, raise flood risk and adversely affect ecosystem structure and functioning, especially along low-lying coasts (Lee, 2001; Holman *et al.,* 2005; Thorne *et al.,* 2007). Importantly, the coast is an integrated system, and interventions in one sector may influence the impacts for another sector.

A universal "hold the line" policy in the face of increasing climate pressures is unsustainable (DEFRA 2004; 2005; 2006). Hence, future management policies are likely to include more use of "managed realignment" and "no active intervention" options, while also aiming to be in line with the Government's policies to reduce risks to people and their properties, and promote sustainable development by maximising benefits to environment, society and economy. Taking into account climate and socio-economic futures with coastal processes within an integrated framework helps to focus on the real choices that we face in developing appropriate long-term shoreline management policies. Consequently, a linked system capable of simulating a range of coastal processes (in the broadest sense of the word) and their feedbacks is a valuable tool for the scientific community and coastal mangers to investigate the full range of management options and their wider implications. Such an integrated system can also be useful as a platform for knowledge transfer including communication with non-specialised stakeholders.

The coastal simulator being developed by the Tyndall Centre for Climate Change Research addresses this challenge by providing a framework to link a system of models, which collectively capture a range of processes and impacts, and provide access to the results. These include erosion and flood risk, ecosystem change and land-use change in the face of climate change and different shoreline management choices. A dedicated Graphic User Interface (GUI) allows easy interaction between the user and the underlying model outputs and provides effective visualisation and statistical reports. This challenging task required early consultation with main stakeholders, including the Environment Agency, and a mutual understanding and continuous contacts across all the institutions involved in the project. This paper describes the work that has been carried out to date, including the overall design of the coastal simulator and the coastal process modelling procedures, with the ultimate goal of providing a decision support tool that makes best use of the available science.

2. The Study Sites

To date, the research has been mainly focused on sub-cells 3a and 3b in East Anglia. The work on sub-cell 3b has focused on cliff erosion between Weybourne and Happisburgh, and its implications on flood risk to the south in the low-lying Norfolk Broads and environs (Figure 1). Historically, the easily-eroded chalk and till cliffs have retreated at an average rate of up to 1 m/yr (Clayton, 1989), releasing large quantities of sand and gravel that have maintained downdrift beaches. However, this has been affected during the last century by shoreline management; with large stretches of the cliffs being protected. As a result, the supply of beach sediment has been significantly reduced, increasing the risk of coastal flooding in the Broads (Hall *et al.* 2005). Extreme flood events, such as the 1953 storm surge have also led to progressively more protection of the low-lying land between Happisburgh and Lowestoft, culminating in the construction of offshore breakwaters at Sea Palling.

Sub-cell 3a in north Norfolk is the main focus of ecological development for the coastal simulator. The area comprises spits, barrier islands, saltmarshes and mudflat with inter-tidal channels, some of which have been reclaimed and protected from coastal flooding by embankments (Brown, 2006). This coast contains inter-tidal and grazing marsh sites with significant biodiversity resources potentially affected by climate change and shoreline management decisions.

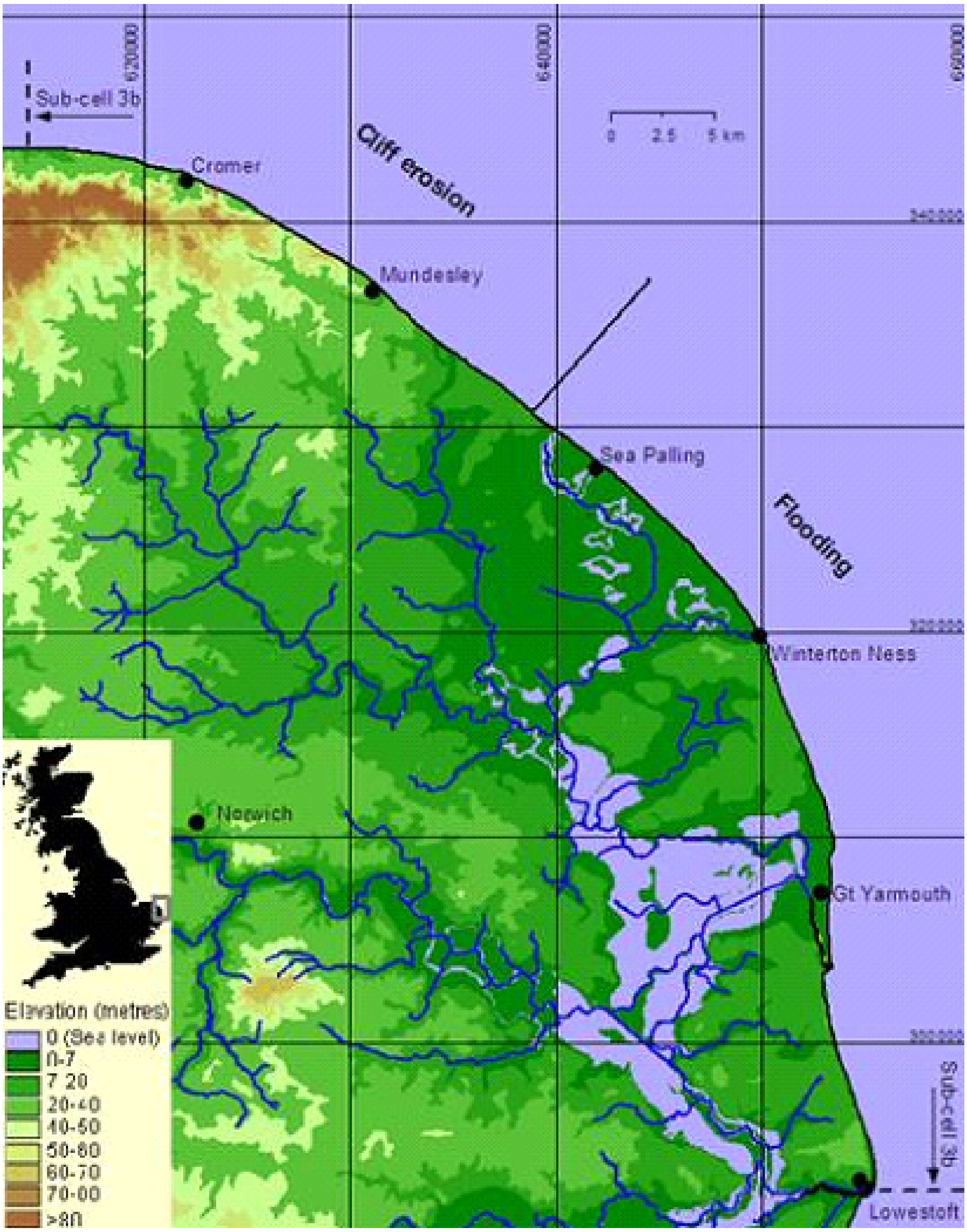

Figure 1. Sub-cell 3b: Topographical map showing the cliffed coast from Weybourne to Happisburgh and the coast subject to flood risk to the south-east, especially Happisburgh to Winterton.

3. Modelling activities and framework of development

The coastal simulator is a means of investigating the impacts of future climate pressures on coastal processes and land use using a series of linked models (Figure 2) (see also Walkden, 2005). The model explicitly recognises three scales of analysis. The global domain provides boundaries to the regional (North Sea) domain, which in turn provides boundaries to the simulator domain, which is defined as a coherent physiographic unit (e.g. sub-cell 3b). Hence, an assessment of coastal change during the 21st century is conducted under possible future changes in mean sea level, surge and wave climate, socio-economic scenarios (built environment) and management policies.

At the global scale, the socio-economic futures drive the emissions and hence the climate change (e.g., Thorne et al., 2007). The Hadley Centre General Climate Model (GCM) is downscaled to the regional scale using a Regional Climate Model (RCM). Analysis from 2000 to 2100 has been completed for the A2 and B2 emission scenarios, based on UKCIP02 (Hulme et al., 2002), and is underway for the A1B emission scenario, based on UKCIP08. The storm surge modelling follows the work of Lowe and Gregory (2005), while the wave modelling is considering changes in the Atlantic, and then the North Sea in more detail, using a similar method of nested models to that of Wolf and Flather (2005) for a hindcast of the 1953 floods. Collectively, these model results provide boundary conditions to the simulator domain.

At the scale of the simulator domain, the onshore propagation and transformation of the waves is important (Kuang and Stansby 2004), and this is influenced by extensive sand banks off sub-cell 3b, which themselves are potentially dynamic under changing climate. Therefore, sandbank sedimentation and erosion processes due to extreme wave and current action are being analysed. These effects are being numerically modelled for the area of investigation for periods of several years (up to about 50 years) using the finite element code of the TELEMAC System. This consists of a TOMAWAC module for wave action propagation; TELEMAC-2D module for tidal flows and the SISYPHE module for morphodynamics. Nearshore wave climate provides input to the SCAPE cliff erosion model below (Stansby et al. 2006).

The morphological evolution of the coastline from Weybourne to Winterton (Figure 1), has been predicted using the process-based SCAPE (Soft Cliff and Platform Erosion) model with a probabilistic model of cliff top position (Pearson *et al.,* 2005). At present, the outputs from 45 climate change and management scenarios are available in the form of maps, dynamic visualisation and descriptive statistics of key parameters such as cliff toe and cliff top positions (Koukoulas et al., 2005). Additionally, the SCAPE model is coupled with a coastal flood risk model for the adjacent coastal lowlands, which considers flood risk under temporal changes in loading conditions and floodplain development (Nicholls *et al.* 2005a). Ultimately many more climate and management scenarios will be simulated, with an explicit consideration of uncertainty.

Where process-based morphological models are unavailable (e.g. sub-cell 3a), geomorphological analysis uses an outcome-driven approach which builds on FutureCoast (Burgess et al., 2002) and incorporates expert knowledge and understanding. This identifies broad patterns of shoreline change, such as narrowing of beaches and barriers, in response to changes in sea level and sediment supply and assigns a likelihood of occurrence to each possible change based on the understanding of the coastal system (Nicholls *et al.,* 2005b; Hanson *et al*., 2007). A similar approach is utilised by the ecosystem modelling which identifies the possible range of habitat and species outcomes associated with the outcomes of the geomorphological modelling (Sutherland, 2006). One advantage of implementing such an approach is the possibility of providing solutions to the problems of imprecision, uncertainty and partial truth associated with environmental modelling.

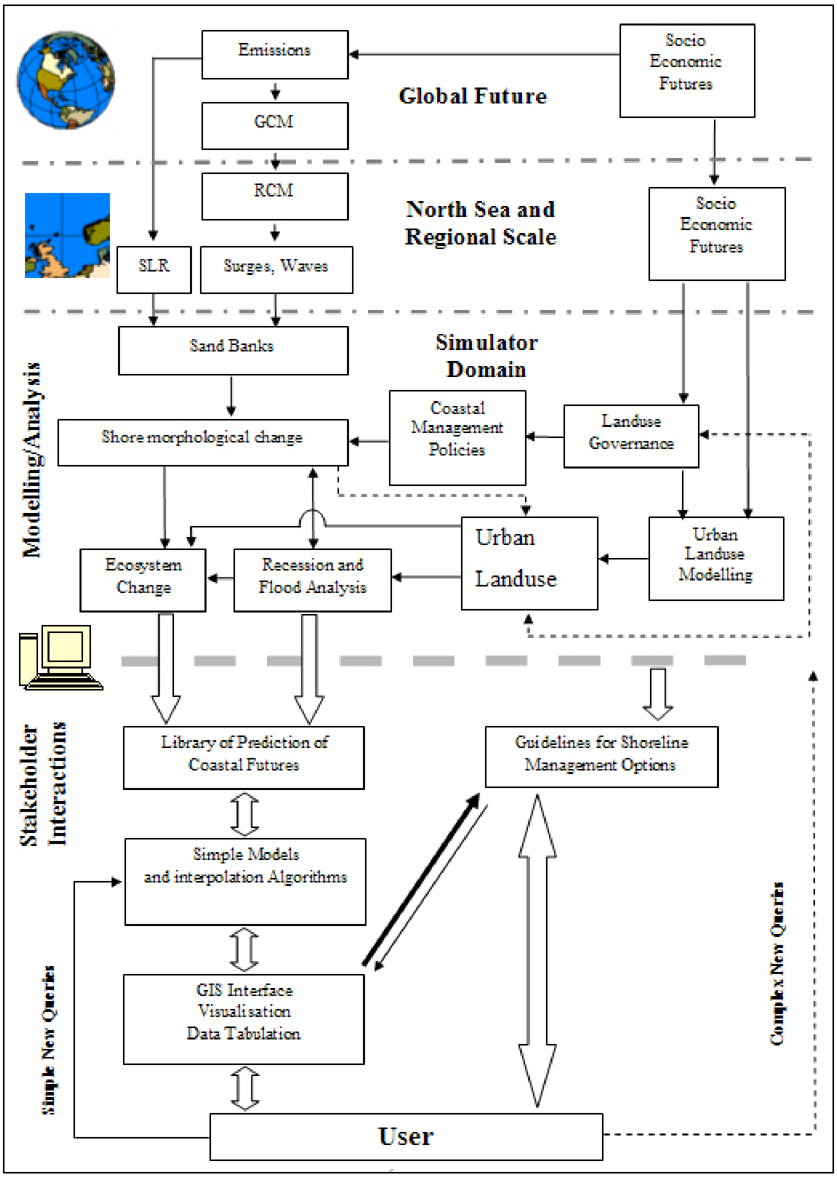

Figure 2. The integrated framework for developing the coastal simulator, distinguishing the different scales of analysis and the user interface.

Whilst previous studies (e.g. Holman *et al.*, 2005) have applied socio-economic scenarios based on informed expert judgement, the coastal simulator is using scenarios of the built environment produced by an innovative Agent-Based Model (ABM). The ABM distributes housing demand through a series of algorithms that describe interacting agents (households, planners, etc) at the local, regional and national levels whilst also taking account of differing socio-economic futures. The resulting scenarios subsequently influence the magnitude of erosion and flood risk. A wide range of shoreline management scenarios are also being developed in conjunction with the Environment Agency.

4. The coastal simulator interface

Initial investigation identified that a GIS environment is an ideal platform for developing the Graphic User Interface (GUI) of the coastal simulator as it is able to handle and visualise outputs from all the models involved (Koukoulas *et al*., 2005). The ArcGIS Desktop environment is being used because it is readily available and has powerful spatial analysis tools, visualisation capabilities and an open system for development.

A key aspect of the simulator is that it should allow users to explore and query the modelling results so that it can be used as a decision support tool. This requires the modelling results to be communicated to users in an understandable manner. To achieve this, the simulator is not only being designed to incorporate a traditional 2D GIS mapping interface and tabulated results (Figure 3), but building on previous Tyndall Centre research (e.g. Brown *et al.*, 2006; Jude *et al.*, 2006) it will also contain 3D visualisations, which have been found to be powerful communication tools (Figure 4).

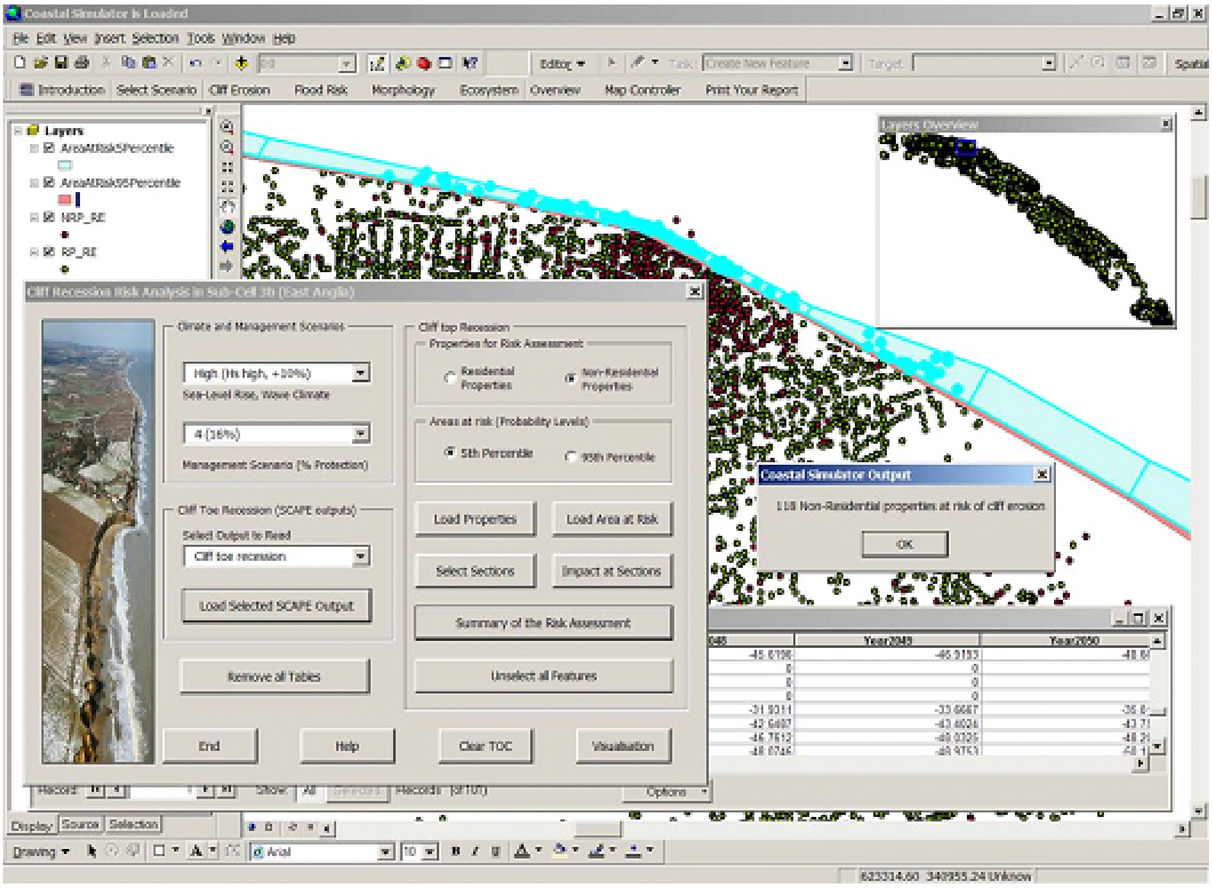

Figure 3. Exploring the impacts of future cliff recession using the Coastal Simulator in ArcMap.

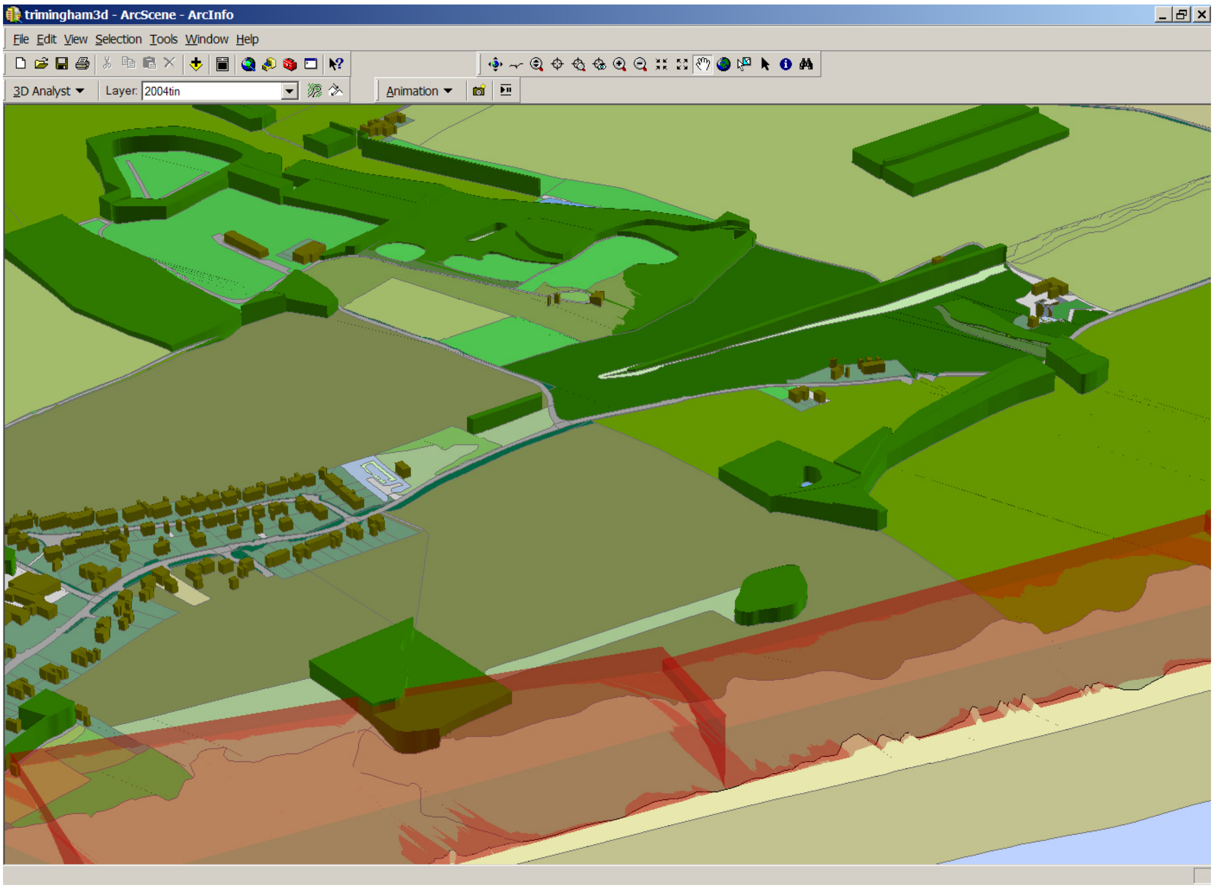

Figure 4. Viewing the future cliff recession risk zone using the 3D visualisations incorporated in the coastal simulator.

Three types of visualisation are envisaged; (1) standard time series (e.g. lines representing cliff recession over time); (2) 3D visualisation of coastal futures; and (3) uncertainty representation. Users will be able to access the visualisations through the standard 2D Simulator map interface, by interactively selecting individual settlements or SMP management units. Instead of using specialist visualisation tools (e.g. Brown *et al.*, 2006), the simulator will utilise the 3D visualisation capabilities provided by ESRI ArcScene/3D Analyst. This not only enables the 3D representation of coastal features (e.g. terrain, buildings and risk zones), but also provides users with interactive navigation and query tools via a familiar GIS interface. A further innovative aspect of the coastal simulator interface is that it is being designed to make the uncertainties associated with predicting coastal change explicit. This requires the development and testing of new methods for expressing uncertainty.

Initially, the coastal simulator will contain pre-modelled data that the user will be able to display and query via the visualisation interface (e.g. risk zones). However, in the longer term it is planned to add real-time links to some of the models contained in the simulator, especially those with short run times (e.g., the agent-based model for built environment, or the ecosystem models) to enable users to explore a richer set of model outputs and make their own assumptions about socio-economic change.

5. The simulator in action: exploring erosion and flooding in sub-cell 3b

A prototype simulator has been developed for sub-cell 3b using coupled erosion and flood models (Pearson et al., 2005; Nicholls et al., 2005a). The 45 scenarios (Table 1) used comprise a range of sea-level rise scenarios (from 0.2 to 1.2-m rise over the 21st Century), and wave scenarios (comprising no change, up to an increase in winter wave heights of 10%, and changes in direction of ±10^{o} as a sensitivity analysis). Management scenarios of the cliffed coast range from no protection to total protection, with more realistic intermediate protection options of the existing situation (Management scenario 2), and two further options with reduced protection by 2030. Additionally, there are four distinct socio-economic scenarios concerning changes to the built environment, corresponding to the global responsibility, local stewardship, national enterprise and world markets socio-economic storylines that were used in the OST Foresight: Future Flooding project (Thorne et al., 2007).

Table 1. Summary defining the 45 scenarios used in the analysis in terms of relative sea-level rise, wave conditions (indicated by H_s low, etc.) and management approach.

Management Scenario (% of cliffed coast protected)	***Relative sea-level rise scenario (2000 to 2100)***								
	Low (0.2-m rise)				**Mid (0.45-m rise)**	**High (1.2-m rise)**			
	H_s low (no change)	**H_s high (+10%)**	**H_s high + (+10% & +10°)**	**H_s high – (+10% & -10°)**	**H_s mid(+7%)**	**H_s low (no change)**	**H_s high (+10%)**	**H_s high + (+10% & +10°)**	**H_s high – (+10% & -10°)**
1 (100%)	1	2	3	4	5	6	7	8	9
2 (71%)	10	11	12	13	14	15	16	17	18
3 (34%)	19	20	21	22	23	24	25	26	27
4 (16%)	28	29	30	31	32	33	34	35	36
5 (0%)	37	38	39	40	41	42	43	44	45

The wave climate is transformed onshore as input to the process-based SCAPE model (Walkden and Hall, 2005; Pearson *et al.*, 2005). SCAPE determines how the shore profile is reshaped and retreats in response to waves, tides and sea-level rise, longshore exchange of sediment and shoreline management interventions (Dickson et al, 2005; 2007). Shore recession proceeds through cycles of storm-induced beach lowering, shore profile erosion, cliff toe retreat and the release of beach sediments from the cliff and platform. SCAPE models cross-shore sections 500 m apart, linked by a bulk longshore sediment transport approach. The cliff top recession is predicted using a probabilistic model (Hall *et al.*, 2002), where the predictions of the cliff toe from SCAPE are inputs in order to define erosion hazard zones. Recession distances corresponding to the 5^{th} and 95^{th} percentiles of the probability density function (accounting for the uncertainty of the angle of the cliff slope only) are calculated to define the area at risk.

The coastal flood risk analysis is conducted to analyse the implications of future climate under the four socio-economic scenarios of the changing built environment, but assuming no additional flood risk management measures (Figure 5). As beaches are directly linked to longshore supply from updrift cliff erosion, the morphological impacts connected to cliff erosion within sub-cell 3b are considered, aiming to analyse the interactions between cliff erosion and flood risk within the sub-cell. A systems model of shoreline evolution is coupled with a reliability model of dike systems, thus capturing the variability in beach level associated with different cliff management scenarios and its subsequent influence on the failure probability of coastal flood defence structures. The reliability analysis is driven by joint probability distributions of loading and a rapid flood inundation model is employed to generate flood risk estimates (full details can be found in Nicholls *et al.*, 2005).

The results stress the erosional nature of the cliff coast (Figures 3 & 4) and confirm that erosional losses increase with increasing sea-level rise and decreasing protection (Dickson et al, 2005; 2007). Wave conditions also influence the losses, but to a lesser degree than the other factors. Importantly, the economic losses due to erosion are always small when compared to the economic losses due to flooding (Hall *et al.*, 2005). The results also show that if we protect the entire coast, or even maintain the present situation, the shore platform will continue to lower in front of the cliffs, necessitating continued investment in defence upgrade and maintenance. Furthermore, the downdrift beach volumes will continue to decline increasing the flood risk in the low-lying areas – this assumes the defences are not upgraded. In contrast, if the defences are removed along stretches of the cliffed coast, the release of sediment as a result of erosion considerably reduces the expected annual economic damages from flooding in the low-lying areas of the Broads (Figure 6). A fuller treatment of these results is available in Nicholls *et al.* (2005a), Pearson *et al.* (2005), Dickson *et al*. (2007) and Dawson *et al.* (in prep).

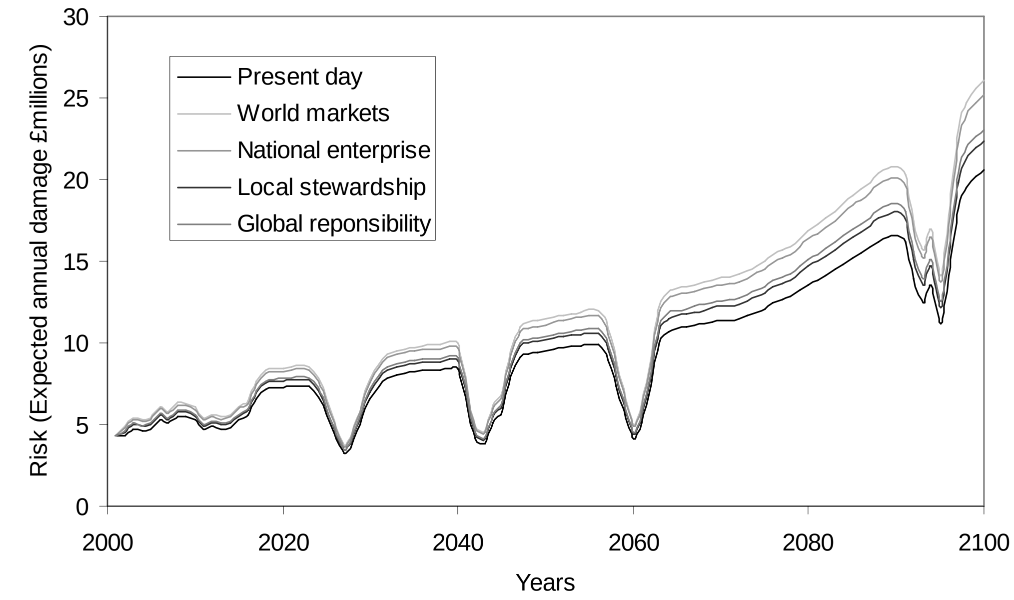

Figure 5. Flood risks over the 21st century under future socio-economic scenarios, assuming moderate climate change and no change in cliff management (Scenario 14 in Table 1). The temporal fluctuations in risk represent oscillations in beach volume predicted by SCAPE – their validity is being tested, (Source: Nicholls *et al.*, 2005a).

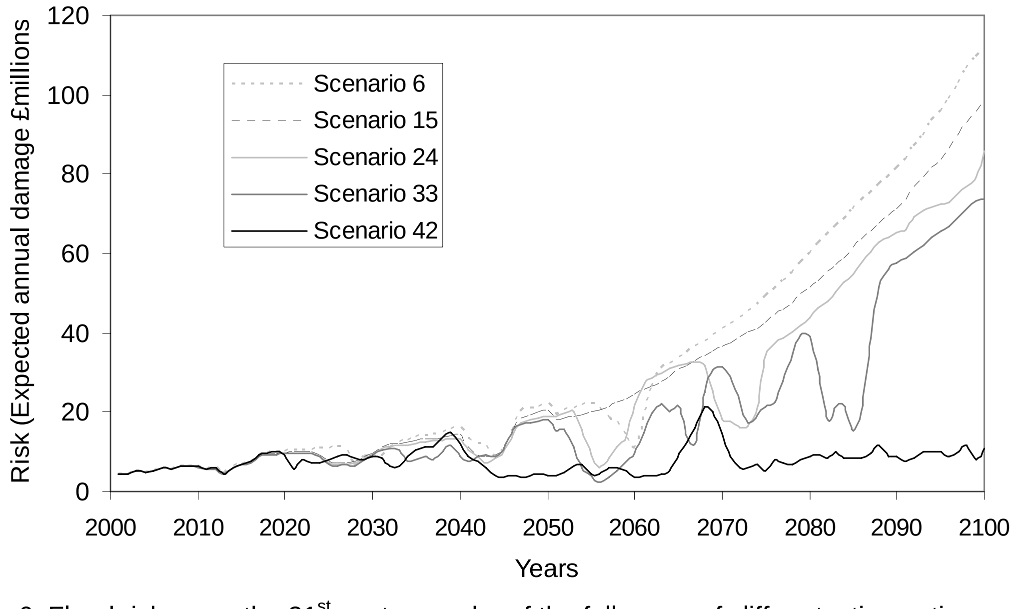

Figure 6. Flood risks over the 21st century under of the full range of cliff protection options and high sea-level rise (Scenarios 6, 15, 24, 33 and 42 in Table 1) with constant (present day) socio-economics (Source: Nicholls *et al.*, 2005a).

An important element of the simulator is the inclusion of the social science dimension within the simulator domain (Figure 2); key inputs relate to the socio-economic scenarios and shoreline management policies, both of which have a major impact on risk, as is illustrated in Figures 5 & 6 for coastal management. Our analysis thus allows us to derive insights into some of the fundamental socio-economic drivers of flood risk, together with climate change, within an interactive framework. There are two key elements here that we are trying to capture within the simulator framework that relate to stakeholder interaction. The first relates to the whole area of governance and how it impacts on the formulation and delivery of responses (O'Riordan et al. 2006) and the second relates to stakeholder participation and participatory techniques (Jude et al. 2006). Both of these are seen as critical in defining the response framework within the simulator and draw on experience from the pilot

Phase 2 SMP for sub-cell 3b.

6. Conclusions

The development of the coastal simulator to date has shown that a linked set of models of the coastal system can be designed, applied and accessed from a single user interface to give a more integrated picture of the impacts of both climate change and management decisions. While such integration requires significant additional effort when compared to more traditional analyses, this approach delivers quantitative results of direct relevance to the Shoreline Management Planning process that would not be available without this effort. The user-friendly interface presents information on a range of parameters in a form which can be easily accessed and understood by the non-specialist user, while communicating the associated uncertainty. Hence, different management decisions can be explored and tested against a wide range of criteria. In this way, the simulator provides a methodology that can support better shoreline management planning.

For the Norfolk coast, early quantified results demonstrate that management decisions for the cliffed coast significantly influence the magnitude of down-drift beaches which form a protective barrier for large areas of low-lying land. This has consequences for the management of these areas and in particular the effectiveness of flood defences. This key finding quantifies previous more qualitative understanding of the coastal system and justifies the widespread interest in moving shoreline management towards reduced cliff protection. Implementing such a policy raises important social and political issues which are also being addressed as part of this research effort.

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