A GIS framework for probabilistic modelling of coastal erosion and flood risk

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Abstract

The Coastal Zone is a complex and dynamic environment that is often highly developed with valuable property and businesses located within close proximity of the coast. Beaches can vary rapidly over time; their dynamic nature ultimately influencing the risk of coastal erosion and flooding of the Coastal Zone. Traditionally, deterministic models are used to investigate the evolution of the shoreline. Occasionally the results from one model are used as input to a complimentary model. Such approaches can be time consuming and tend to be used to explore a small number of predefined scenarios over short spatial and temporal scales. Probabilistic approaches can be employed to explore the potential outcomes that may occur due to natural variability in the climatic or stochastic forcing conditions. Such approaches allow the Coastal Zone Manager to understand the uncertainty associated with any management intervention that may be undertaken. By coupling chains of nearshore probabilistic models together it is possible to explore the potential impact of uncertainty on downstream processes. This paper presents a generic GIS based framework for integrated modelling of the coastal zone and presents a recent application of the framework to perform coupled probabilistic coastal evolution modelling.

> **Keywords**
>
> Coastal Zone Management; Probabilistic shoreline modelling; Coastal Erosion; GIS; Integrated modelling

Introduction

The Coastal Zone is often highly developed with valuable property and businesses located within close proximity of the coast. In addition, the Coastal Zone itself provides a valuable commercial and recreational resource. It is however a particularly dynamic environment where complex and interactive processes occur. Beaches can vary rapidly over time; perhaps fluctuating seasonally, and often losing or gaining volume over a longer time period. Their dynamic nature ultimately influences the risk of coastal erosion and flooding of the Coastal Zone. For the Coastal Zone Manager, it is important to

understand the systems and their responses to nearshore processes, normal and extreme coastal events, and any management interventions that are employed.

Traditionally, deterministic models are used to investigate the evolution of the shoreline under a predicted set of forcing conditions. Occasionally the results from one model are used as input to a complimentary model. Such approaches can be time consuming and tend to be used to explore a small number of predefined scenarios over short spatial and temporal scales.

The development of integrated modelling capability is a relatively new art. Various methods for linking and managing models which reflect varying processes are being trialled within the UK flood and coastal defence engineering community; each method carries its own set of advantages and disadvantages, and each has arisen and been adapted from a basic need to address the same issue: why and how to link models together.

For example, the Regional Coastal Simulator (Pearson *et al.*, 2005) has its origins in the development of the soft-cliff erosion model (Walkden et al. 2000), and the potential of such a model to expand in to the realm of flood-risk assessment was identified by the researchers where the need to evolve some form of model linkage arose. At the same time, rapid advances in processing power were also taking place and with the establishment of the Tyndall Centre for Climate Change Research during the same period, model linkages formed (Dawson *et al.*, 2005 and Koukoulas *et al.*, 2005) to allow wave models to link to morphological, flood-spread and economic damage models. Output from these models is presented within GIS.

In parallel to the development of the Regional Coastal Simulator, the FluidEarth (OpenMI) initiative (eg Fotopoulos et al. 2010) has arisen. This methodology adopts a standard format for the exchange of data between models. Further, should the models operate in different time-steps, the FluidEarth central management system is able to control the running order of the different models which have been "wrapped" within the system. Wrapped models, perhaps developed at different institutions, have all been modified to conform to the standard format of data exchange adding value to independent developments by collation and management.

Meanwhile, Shoreline Environment Analysis and Management Tool (SEAMaT) (Stripling *et al.*, 2007) examined an alternative approach to coordinating the running and linking of numerical models of coastal processes within a GIS framework. With coastal and flood-risk engineers and managers in mind (who may or may not be specialist modellers), the approach emphasised straightforward and rapid operability – with a series of linked numerical models installed locally on laptops, for example, to allow broad-scale strategic-level interventions to be examined. Stripling and Panzeri (2009) presented the feasibility of such a system in supporting the assessment of coastal erosion- and flood-risk.

Recently the SEAMaT modelling framework has been extended to include the integration of probabilistic nearshore, coastal erosion and flood risk models. The validated numerical models are easy to operate by the Coastal Zone Manager allowing him to explore the uncertainty in coastal evolution, cliff erosion and flood risk associated with varying wave climates, river sediment fluxes and management options. Such an approach allows for more informed decision making and better management of the coast. This paper presents the integrated modelling method, and an example of the integrated model applied to coastal management.

SEAMaT

The SEAMaT Framework was originally conceived in 2002 under a research contract for the Regional Coastal Authority of Calabria, (Italy) to provide a straightforward means for their staff to synthesise nearshore wave climates from offshore measured wind data for any location along their 750km coastal jurisdiction. Since then it has been extended a number of times to incorporate different model types and has been exploited to deliver the modelling aspects for dozens of consultancy and research projects for coastal regions in Italy and the UK.

The SEAMaT coastal modelling framework is depicted in Figure 1. It contains a number of modular components which are based around a generic interface and shared datamodel. This common approach provides for a significant amount of flexibility in accommodating the addition of complimentary models which can be coupled together to give a seamless user-experience of modelling in the nearshore environment. The models can be run using data from a variety sources ranging from historic and synthesised data to real-time measurements. In addition, the results from the model simulations are stored in the same underlying database that stores the input data enabling the model coupling to be achieved; results from one model can simply be input to another. The user-experience is enhanced by the graphical user interface (GUI) which is embedded as a toolbar inside a map of the coastal zone using the geographical information system(GIS), ESRI ArcMAP. The user chooses which models to run and which input parameters to use via a series of forms and clicks in the map. On completion of the model simulations, the results are added to the coastal zone map enabling the user to directly visualise the key findings of the model run. The following sections describe the key elements of the SEAMaT GIS modelling framework, after which some results from recent application will be presented and discussed.

The SEAMaT Datamodel

Traditionally, model input data and boundary conditions are held in a series of bespoke files. The results from models are written to bespoke output files. A further set of files are used to supply the calibration parameters and simulation control settings. Each model program has its own variety of input, output and control file formats making it difficult to run model programmes in sequence due to the requirement for translation of results from one model to the input data format for another.

In addition to this, when running an investigative study, thousands of results files may be generated in a relatively short space of time, making management of the different scenarios and their results a difficult task. Comparison of differences between scenarios can be challenging to identify and quantify.

To address these shortfalls in modelling technique, a datamodel has been developed to support the integration of coastal zone models. Key to the datamodel is the concept that all models use the same underlying format for input, output and model configuration settings. This supports the vision that a single set of tools can be developed to run all models which have subscribed to the underlying datamodel. This set of tools is embodied in the SEAMaT GIS Framework, which provides a single GUI for the operation of all subscribing models and manages the translation of the required data from the datamodel into the bespoke model file formats needed for any particular simulation. It subsequently translates the bespoke results files and stores them back into the datamodel where they can take advantage of generic plotting tools and the GIS front-end.
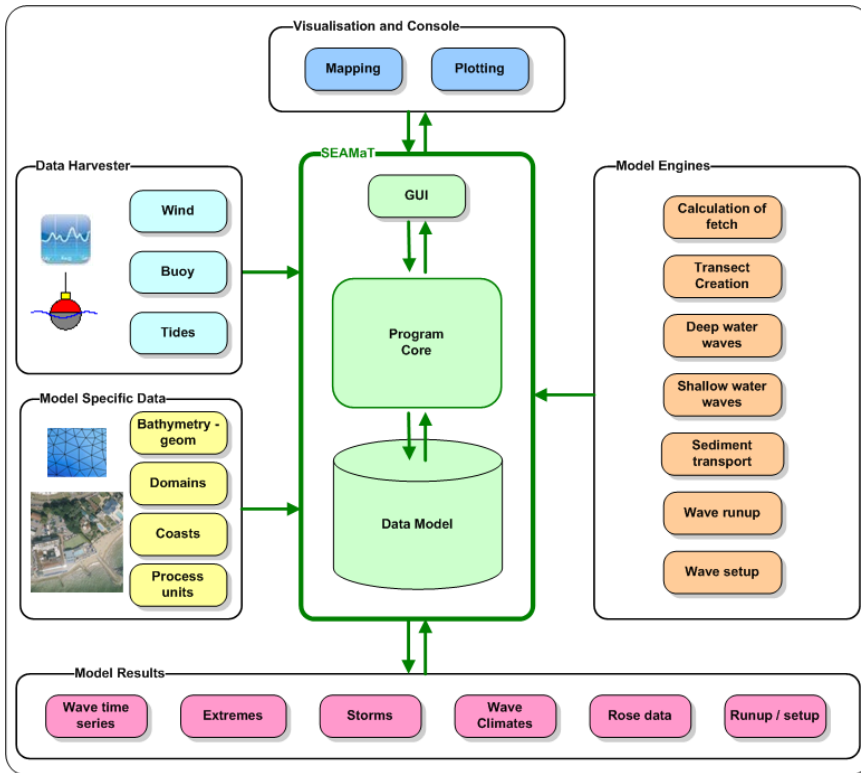
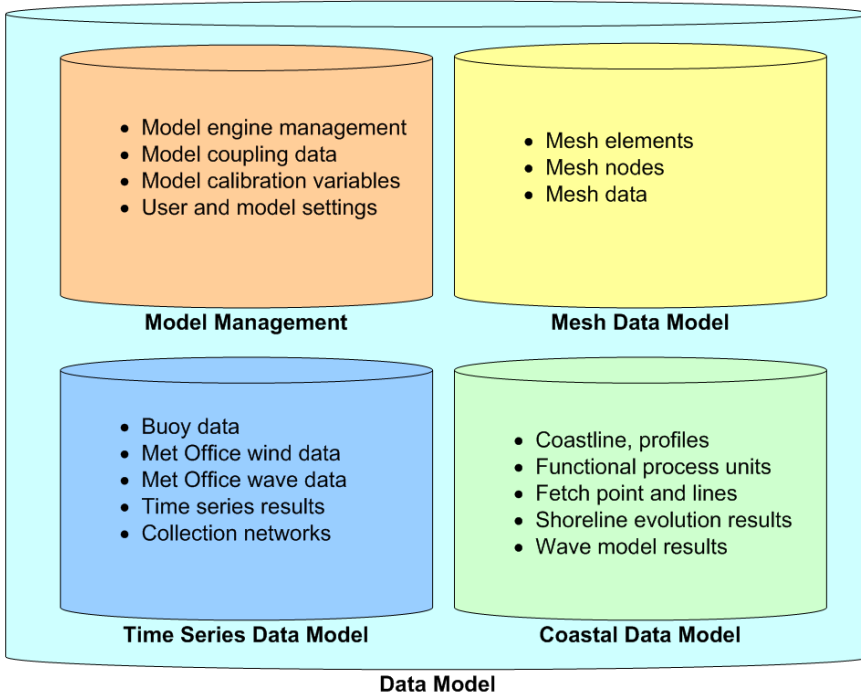Figure 1: The SEAMaT GIS modelling framework

Figure 2. Overview of the SEAMaT datamodel

The datamodel, summarised in Figure 2, contains four main components, which function as follows:

- The Model Management component contains a series of tables used to define the numerical model engines programmes for a particular simulation, the data exchange files, the default parameters for the models, and what is done with the results files. It is also used to record a full list of input parameters and model engine versions used for each model run such that a detailed provenance exists for all model results.

- The Time Series datamodel is a generic datamodel for storing spatial times series data. It is incorporated within SEAMaT since it provides a very powerful concept to the software; by storing measured data, synthesised data and model data within the same logical table structure the models are able to run seamlessly from any source of data without any knowledge of their origin or native formats. Data harvester programmes have been developed for the Time Series datamodel, enabling the automated storage of real-time data against which the numerical models in the suite can be run or compared

- The Mesh component stores results from numerical models based upon unstructured mesh spatial domains for efficient display and analysis. The datamodel stores the mesh geometries independently from the variables enabling the data to be rapidly queried through time and space.

- The Coastal Data component is used to store all of the spatial data associated with the coastal models, such as coastlines and cliff behavioural units, beach profiles and shoreline evolution results.

The datamodel has provided a consistent and robust framework upon which the SEAMaT software can be efficiently developed. It provides a structured environment for hosting the modelling data while allowing for rapid uptake of future modelling methods due to the standardised data structures that have been established. In practice, when a project is commenced, a new implementation of the datamodel is created and used to store all of the data for that particular modelling study, enabling all of the results and metadata to be held in a single database.

Building a model

Creation of a model is achieved initially by making a new instance of the database (in ESRI GeoDatabase format) and populating tables relating to Model Management. There are a number of tables used to define key aspects relating to the modelling process. These include;

- The models that will be available
- Which program files (model engines) will be run for each of the models
- Which input files are required for each model engine and what their formats are
- Which output files are produced by each model engine and what their formats are
- What the spatial domains or extents of the models are

The above information is used by the SEAMaT software to determine which models and options are required. Thanks to the flexibility that this approach offers, the functionality of the software is altered without the need to change the SEAMaT source code.

After updating the Model Management tables, the input data need to be stored in the database. These may include for example time-series data streaming from offshore wave buoys, wind data from numerical models, coastal bathymetry and sediment information. Next, the model configuration variables must be populated in the database. These define all of the settings and calibration factors

that should be used. They can be generic for all instances of a model engine or specific to a particular domain. Finally, a GIS project file is created which provides the contextual mapping to the models, adding aerial photography, satellite imagery, topographical mapping, maintenance records, residual life of structures, or any other data which could give more insight into the area of interest.

Adding new models to the suite is straightforward. If the new model engine uses input or output files with different file formats to those previously used then it is necessary to write up to three new types of code classes to core SEAMaT programme. One class is used to perform the extraction of input data from the database and to write the input files. A second is used to read the results and store them in the database and the third is to add model specific tabs to the GUI. In addition code classes may be added to provide new plot types or model preparation tools

After these tasks have been completed, the SEAMaT database and software can be provided to a relatively novice modeller who is able to perform scenario testing covering larger regions of the coast with ease.

The SEAMaT GUI

The SEAMaT software exists as a toolbar within ArcMap. The toolbar provides access to tools which provide four different functions;

1. Framework configuration; provides tools to select the SEAMaT modelling database
2. Input data creation; provides tools to exploit the GIS for automating the creation of model input data for specific models in the suite. Examples include a fetch calculation tool and a beach profile extraction tool.
3. Running the models; a context specific form which is used to run all of the model engines in the suite. The form filters choices to those models which are present for the desired location and presents the appropriate tabs required for specifying the model settings for the chosen model engine.
4. Plotting tools; although most results are presented in the coastal zone map, graphs are often necessary to understand certain trends in results. Rose and xy graph windows are used to explore the multi-dimensional nature of the results.

The function of the components is described in more detail in the following section.

The SEAMaT user-experience

In order to operate the framework, following installation of SEAMaT, the user opens the ArcMap project document. This displays all of the contextual data for the coastal zone region of interest in the map view. The SEAMaT toolbar is turned on and the user runs the configuration tool to specify which project database to use for the session. The user is now able to build model input data, run models and view results of previous simulations from the chosen project database.

The model build tools are provided to enable rapid creation of input datasets for the model engines. These are simple to run, and will generate input files in seconds which would otherwise take hours or days to produce. The data are displayed in the map and are stored straight into the project database ready for immediate input to the model engines.

The "run model" form is used to start a model simulation. Upon opening the form, the user specifies the model type and model engine from those available and clicks in the map to specify which area they are interested in. Certain models will run for the exact location where the click was made while others will run for the specified model domain that covers the click location. Once the engine and model location have been specified, tabs are added to the form for the user to input settings which are specific to the particular model engine chosen. The tabs show only those variables that the user can alter, while other variables, such as calibration settings are read directly from the database and are not presented on the form. The user enters a unique name for the model run and a description, both of which are recorded in the database, along with all model run settings, ensuring detailed provenance information is recorded.

The last set of tools in the toolbar provides plotting capability. There are tools to display interactive roses for wind or wave data as well as xy plots for runup, setup, bathymetric cross-sections or extremes. Figure 3 presents a SEAMaT screenshot showing a wave rose and a plot of wave runup and setup.
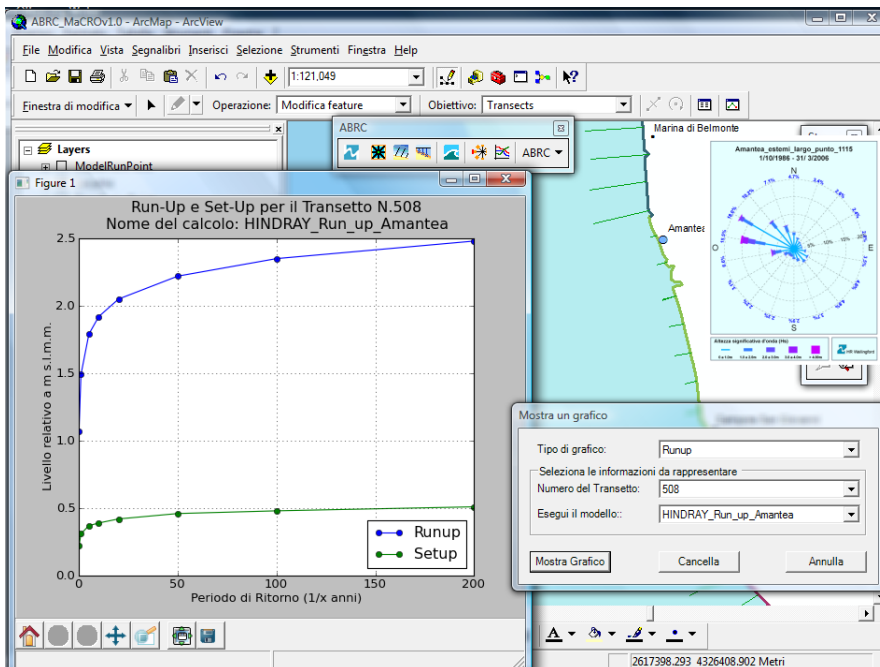

Figure 3 The SEAMaT Tool; results from runup and wave models displayed over the Coastal Zone map

Case Study: Calabria, Italy

The Region of Calabria is a long and narrow peninsula at the southern tip of the Italian mainland. The regional government, Autorità di Bacino Regione Calabria, has approximately 750km of coast to manage with many different types of foreshore and backshore settings. The Regione use the modelling framework presented here to help them with this challenging task of managing their entire coastline. Figure 3 shows some of the functionality of the Regione's integrated modelling suite, including extreme runup and wave setup values at the coast.

Past and present human interference with natural river systems, in particular reductions in the amounts of sand and larger sediment previously delivered to the coast, has resulted in widespread problems of beach erosion around Italy. Such problems can increase the risk of coastal erosion and flooding of the hinterland.

The Fiume Savuto is one such river that has been subject to aggregate extraction. As a result, sediment supply to the coastline has reduced, giving rise to coastal erosion and subsequent management of the coast (Plate 1). A study has been undertaken using the integrated modelling suite to run a probabilistic one-line model of the coast in the vicinity of the river to investigate the neighbouring coast's sensitivity to changes in the fluvial sediment supply. In the study it was not necessary to establish a high degree of confidence in the calibration of the model since the objective was to demonstrate the application of the probabilistic methods. The comparisons made are relative and not representative predictive outcomes.

Wave conditions at the site were derived from a regional-scale shallow-water wave propagation model described by Stripling and Panzeri (2009), which were filtered to provide morphologically-averaged conditions. Estimates of the 'present-day' distribution of fluvial sediment load for a range of flood events were made. A loading event is sampled from these estimates based on its likelihood of occurrence during each day. The majority of the samples will return a zero supply volume since the Fiume Savuto supplies sediment to the coast during rare flood events.

Plate 1. Management of the eroding coastline near Fiume Savuto

Figure 4: Sensitivity of the coastline to variation in sediment discharge from River Savuto, Italy.

Figure 4 presents the outcome of two probabilistic simulations. The solid lines show the shoreline evolution during 20 years of simulation with the fluvial sediment loading from the Fiume Savuto at the present day level. The dotted lines indicate the shoreline evolution which may occur should the fluvial sediment loading be increased to ten times the present day value, perhaps through river management techniques. Neither set of values necessarily occur concurrently, with the mean shoreline position after 20 years, its maximum (ie furthest seaward) and minimum (ie furthest landward) positions being derived from the entire set of probabilistic realisations.

Figure 4 suggests that the present-day sediment loading from the Fiume Savuto is not sufficient to prevent erosion of the coastline. There would still be insufficient beach building material arriving at the coast in the event that river re-profiling was carried out to significantly increase the loading.
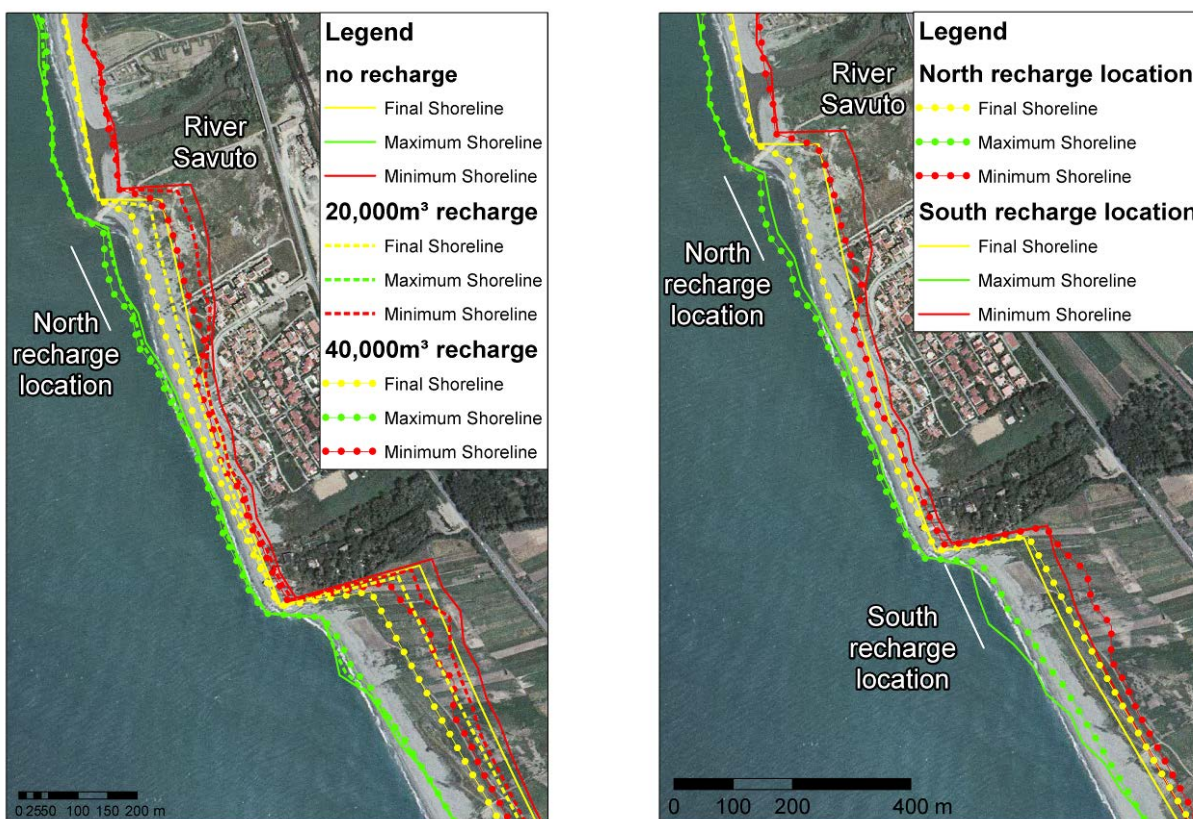
Figure 5: Investigation of volume (left) and placement (right) of nourishment near River Savuto, Italy.

The integrated model facilitates an examination of erosion mitigation management programmes. One such possible mitigation is to nourish the beaches. Figure 5 shows the statistical response of the coastline to variant beach nourishment options immediately south of the Fiume Savuto. The volume and location of nourishment options are examined. The dotted lines should be compared to the solid lines to ascertain the relative value of each management option. One interesting result from the investigation was the observation that nourishment at the north recharge location also performed very well at protecting the beach in the vicinity of the southern recharge location. Other scenarios have shown that the timing of any proposed nourishment is not critical to the probable response of the shoreline, indeed, the model results showed that 40,000m³ per year of nourishment introduced every May at the north recharge location had the same effect as introducing the same volume gradually over the whole year. Whilst this is, in any case, an intuitive outcome, the modelling provides a useful quantification of that intuition, allowing for effective scheduling and budgeting for coastal management in that area. Many other nourishment scenarios, such as nourishing every 3 years for example, can also be assessed.

Case Study: Holderness, UK

The Holderness coastline is a 60km stretch of coast resembling an elongated S-shape between Flamborough Head and Spurn Point on the East Coast of the UK. The beaches are typically narrow and backed by glacial sea cliffs of between 5 and 35m in height. With a long fetch to the north east and deep water relatively close to the shore there is little attenuation of the wave energy which is able to easily erode the soft cliffs. This coastline historically has very high rates of erosion. Cliff recession is known to have continued over hundreds of years and shows no signs of abating. Approximately 1,000 hectares have been lost in the last 900 years. One of the most comprehensive studies of the rate of recession of the Holderness cliffs was made by Valentin (1971) who suggested that the average recession rate was 1.2m per year.
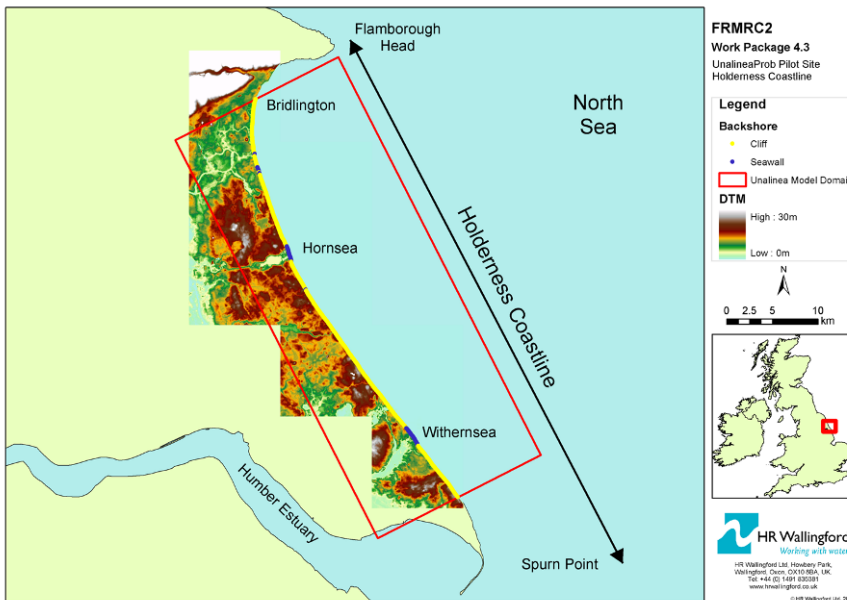

Figure 6. Pilot site for integrated coastal erosion and flood risk modelling using the SEAMaT framework at Holderness, UK (from Stripling. et al 2012)

Along this length of shoreline there are a small number of low lying villages and towns which are protected from coastal flooding by sea defences. A recent study was undertaken for the Holderness coast to demonstrate the potential benefit of coupling coastal erosion and flood risk models together. The domain of the coastal model is shown in Figure 6, a length of approximately 40km of the Holderness coast.

The study extended the coastal one-line model to include the consideration of soft cliff erosion and coastal flood defences. During probabilistic application, it tracks the vertical movement of the sediment at each length of flood defence in order to produce a distribution of beach toe-levels for every year of the simulation. Next, the SEAMaT framework was extended to include a probabilistic flood risk model for Hornsea; one of the low lying towns that is protected by coastal flood defences. The flood risk model samples from the distributions of beach toe levels and estimates an associated overtopping rate for every flood scenario realisation. The overtopping rates are spread across the floodplain where depths and associated damages are captured for every wetted cell. Figure 7 shows results from the two integrated models within the GIS.
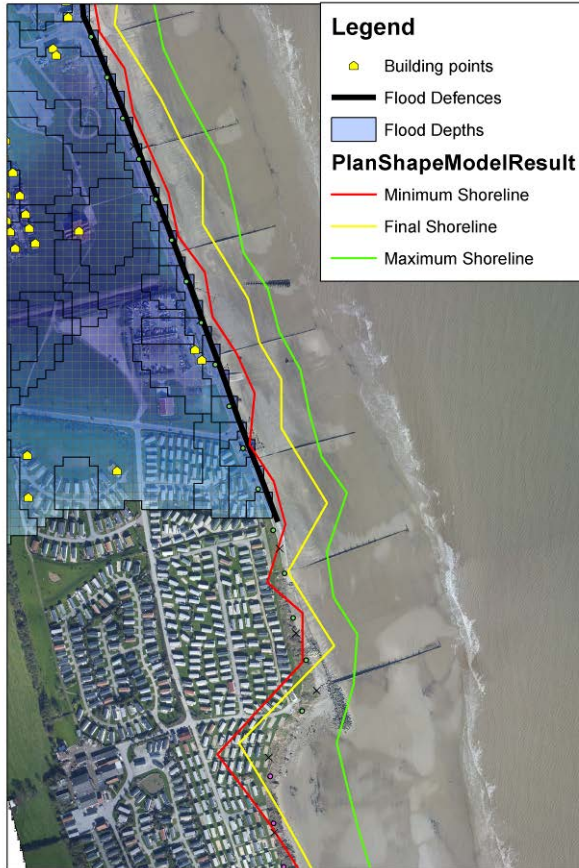
Figure 7 An example map from the integrated coastal erosion and flood risk modelling pilot site at Hornsea, UK

The results from the model are recorded to the SEAMaT database and displayed in the map as mean beach planshape positions, final cliff positions, along with histograms of defence toe-levels, overtopping rates, flood depths, damage given return period and finally expected annual damage (EAD) to property. The tool allows for a more joined-up approach to flood and coastal erosion management to be undertaken by providing quantitative assessment of the flood risks associated with certain shoreline management scenarios. It also enables flood risk managers to investigate alternative options to flood risk management such as beach recharge or other beach volume management options. Further detail of the integrated coastal erosion model and flood risk model, and the pilot testing at Holderness are presented in Stripling et al 2012.

Conclusions

Modelling methods capable of supporting the flood-risk management community through regional-scale assessment of erosion- and flood-risk remain relatively few and, particularly with regard their general applicability, the expertise required to exploit them and the time required to examine scenarios is often prohibitive. As a result, regional-scale assessments tend to be carried out with limited support from process-based numerical models and continue to rely heavily on qualitative geomorphological assessment.

The notion of integrated flood and erosion risk management is at the core of policy yet a practical and credible integrated modelling capability, designed to support holistic assessment, is not yet in the domain of practitioners and decision-makers. This paper has presented research and development of an integrated probabilistic coastal erosion- and flood-risk modelling technique, with particular regard to the broad-scale behaviour of the shoreline and how such modelling can be effectively and efficiently managed within the ArcMap GIS.

The method is readily applicable to site-specific cases, and is flexible so that it can be extended to consider additional processes such as cliff-recession, overtopping and flood spreading. The data model development has allowed the significant quantities of data that arise from probabilistic model runs to be managed efficiently and effectively, facilitating the management and onward use of coastal numerical model related data. The models are run via a simple GUI which is accessed from a toolbar within ArcGIS enabling the modelling system to be operated by inexperienced modellers and experts alike.

Acknowledgements

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