Super Work Package 4: Infrastructure Management

Work Package 4.3: Broad Scale Integration of Coastal Flood and Erosion Risk Models

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Statement of Use
This report is intended to be used by researchers and practitioners working in the field of coastal erosion- and flood-risk assessment/management. It describes enhancements to the modelling methods available for examining erosion- and flood-risk at regional and local scale. The developments presented are focused on research in the UK, but also include application abroad.

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Summary

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 report presents research and development of an integrated coastal erosion- and flood-risk modelling technique which enhances the RASP methodology. In particular the broad-scale behaviour of the shoreline (both beach and cliff systems) is included into the RASP assessment, as a dynamic element, rather than a static user input.

Key advances within the research include:

1) **Development of a stable numerical scheme for broad-scale beach planshape modelling** - Based on investigations into various numerical schemes for modelling the morphodynamic change of the shoreline at broad-scale (including time-stepping, spatial discretisation, accuracy and stability of numerical solvers) a preferred approach (trading off runtime, stability and accuracy) has been proposed and incorporated into UnaLinea.

2) **Efficient characterisation of the driving storm conditions to support regional scale and long term coastal risk modelling** - The need to maintain very rapid computer processing times in the face of some advanced process- and stochastic-based modelling methods. Even in the light of continually increasing processor speed, there is a requirement that numerical simulations are performed as efficiently as possible. Whilst this is inherently linked to the numerical solution method, the filtering of input data is also investigated.

3) **Efficient temporal and spatial representation shoreline change** - The dynamic response of the shoreline, and how that is influenced by the character of the backshore is considered. By representing the behaviour of the shoreline in a statistical fashion, the influence on the beach by event-based loading such as that which occurs from the erosion of soft cliffs or fluvial sediment loading can be examined.

4) **Development of cliff recession model coupled with the beach planshape model.** – In many coastal environments, significant sources of natural beach nourishment must be considered if the model is to perform adequately. A simple probabilistic cliff erosion model has been developed, enabling the consideration of cliff recession and beach nourishment from cliff material to compliment the beach planshape model.
5) **Stochastic and coherent integration of flood and erosion risks within RASP** - The exploitation of Monte Carlo simulation in the examination of morphodynamic behaviour. The rapid and stable numerical simulation techniques that are presented in this research and development document are critical to the integration of the erosion-risk modelling procedure with the flood-risk modelling procedure. This research provides an erosion-risk modelling capability which integrates with the RASP flood-risk assessment models through exploitation of stochastic modelling.

6) **Efficient data management and data model compatible with RASP** - Development of a database system capable of managing the significant quantities of data that arise from probabilistic model runs. A data model has been built which facilitates the management and onward use of coastal numerical model related data. The database is populated through a GIS, from which the modelling system is operated and queried. The coastal modelling database is standardised so that it conforms with the range of RASP models already in existence.

7) **Forward propagation of epistemic uncertainties** - Enhancement of the RASP-SU (structured uncertainty) set of models to allow the integration of the new probabilistic shoreline evolution modelling technique with the existing RASP suite of models. The RASP overtopping model has been enhanced to allow beach levels at the toe of a seawall to be considered as a histogram rather than a single value. This allows uncertainty in the toe level to be grasped by the RASP model.

The completion of this programme of research has clarified some of the potential that this innovative morphodynamic modelling technique, linked with system risk models such as RASP can offer. Though not examined in great detail in this report, scenario-testing of defence options and how those options perform on a cost/benefit scale will readily follow.
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1 Introduction

Defra’s ‘Making Space for Water’ (MSW) places emphasis on integrated management of flood-risk at broad-scale. Ecological, environmental, socioeconomic, geomorphological and morphological factors are all to be part of the integrated approach to management which should fit in with the EU Water Framework Directive and Floods Directive.

As a result there is a perceived need for new and broader approaches to decision support systems and modelling. Whilst such systems and models span a wide range of scientific disciplines associated with flood-risk at broad-scale, the model development reported here under WP4.3 relates to the holistic approach to managing coastal flooding and erosion emphasised by MSW.

Under the Defra/EA Modelling and Risk (MAR) Theme, commission FD2118 ‘Broad Scale Modelling for planning and policy’ has recently been completed, and presents a vision of how integrated management of flood-risk at broad-scale might be achieved. The vision places Broad Scale Modelling (BSM) within a Drivers-Pressures-States-Impacts-Responses (DPSIR) framework. Emphasis of FD2118 recommendations is on exploiting existing state of process knowledge (according with Defra’s ‘Coastal Vision’ that small increases in understanding will not enhance greatly our ability to manage flood-risk).

The Source-Pathway-Receptor model used within RASP (Sayers and Meadowcroft, 2005) fits within the DPSIR BSM framework under the ‘States’ element, and when “solved” is considered to lead to an assessment of flood risk. Enhancement of the RASP methodology, with regard the consideration of the coast as a dynamic rather than static defence, was initiated through work previously carried out under FRMRC1 WP4.2 into shoreline and foreshore change. A proof of concept model was produced; namely a standalone systems-based modelling system embedded within GIS software.

The research and development carried out in FRMRC2 WP4.3, and reported here, has taken the systems-based modelling investigated during FRMRC1 WP4.2 and extended its functionality and applicability such that erosion risk and flood risk can be considered within one modular modelling framework.

1.1 Project description and overview

WP4.3 has extended the research carried out within FRMRC1 WP4.2 to link the broad-scale behaviour of the beach to the reliability of shoreline defences, whether structures, soft-cliffs or the beach itself. This has enhanced the assessment of coastal flood risk via the RASP framework (as enacted within the NaFRA, Steel et al, 2009, and MDSF2, McGahey et al, 2007, applications, Gouldby et al, 2010) and supports the evaluation of different beach management operations.

In particular, the research has linked the probabilistic change in the volume and position of the beach with the risk of flood. The change in the beach as a coastal defence (reflecting the predicted change in beach level and incident wave and water level conditions) has been used within the RASP framework to assess flood risk and a new approach has been established to assess erosion risk. The treatment of erosion...
risk as a stochastic phenomenon has enabled the link to flood-risk to be formed. In addition, the basic framework proven in FRMRC1 WP4.2 has been extended to incorporate the use of databases in managing the model data.

1.2 Aims and objectives
The summary objective of this research is to provide a step change in our ability to programme and manage defended coastlines in an integrated manner taking account of both erosion and flood risks. The aims were, more specifically, to:

- Incorporate a stochastic representation of soft-cliff erosion taking into account beach change and performance of toe defences.
- Accommodate barriers to longshore drift and how those barriers might influence shoreline evolution.
- Represent changing toe levels within the modelling framework in the assessment of floods resulting from coastal defences overtopping or breaching.
- Develop the RASP framework to include the impact of changes in toe level on coastal flood and erosion risk.
- Develop a pilot proof-of-concept broad-scale systems-based model to explore coastal flood and erosion risk.
- Quantify damage.

The research outlined above has facilitated the evolution of a broad scale integrated erosion- and flood-risk model within the RASP framework, and conforms to the flood risk management DPSIR framework, as well as maintaining links to ongoing research programmes such as NaFRA, PAMS, SAM, MAR, FLOODsite, MDSF2.

1.3 Deliverables
The user-focused measurable output from this research is documented as:

“D4.3: A report demonstrating an improved ability to assess, at a broad-scale, coastal erosion and flood risks (and explore management interventions), and associated proof-of-concept software (runtime version) for the pilot study site to demonstrate functionality.”

This report, therefore, constitutes part of the main deliverables of the project. The runtime software has been independently tested for the Holderness pilot site and comments from the reviewer can be found in Appendix D.

1.4 Report structure
The report is structured as follows:

- Chapter 1 – provides an introductory background to the research and development carried out and presented in this report.
- Chapter 2 – describes the current methods adopted to establish erosion and flood risk at Shoreline Management Plan, or Strategy Study level.
- Chapter 3 – establishes the basis upon which the development was carried out.
- Chapter 4 – presents the modelling principles adopted in more detail.
- Chapter 5 – introduces the pilot study software, and demonstrates the capability of the development to date.
• Chapter 6 – concludes the report, and provides recommendations for future possible study and application.

The target audience for this report is flood risk management researchers and practitioners whose primary background is scientific or engineering. The language and terminology used in the report reflects this target audience.
2 Current practice for assessment of erosion- and flood-risk

2.1 Introduction
In order to make successful management decisions on the coast, there needs to be an understanding how the beach and backshore are likely to change, together with the resultant implications for the level of future flood and erosion risk. Improving our ability to understand and predict long-term change along coastlines has a direct influence on future investment choices (Wells et al., 2010).

The coastal system is in a constant state of flux (over varying time-scales and distances) due to the physical processes acting upon it (see Figure 2.1). There are also a number of interactions and feedbacks within the coastal system, which makes it very difficult to predict the net impact of a change in any one parameter.

However, in order for future coastal management schemes to be viable and publically accepted, some estimate of future change is needed. Issues such as beach loss, cliff recession or foreshore changes are obviously very important to the people who live along or use the coast.

Figure 2.1 Principal components involved in coastal morphodynamics (after Pye and Blott, 2008)

There have been a number of other studies that have looked generically at the various approaches available to coastal managers, such as the Shoreline Management Plan (SMP) Guidance (Halcrow, 2002), which provided an Appendix on appropriate tools for a high-level open coast study; EMPHASYS (EMPHASYS Consortium, 2000), which looked at tools specifically to appraise estuary systems, and the Defra/EA project – Predicting large scale coastal geomorphological change (SC060074) (Whitehouse et al., 2008; Defra/EA, 2009 a, b), which appraised the tools and approaches that could be used in coastal studies, and assessed the main limitations with each approach. Most recently, DEFRA/EA have commissioned the CoaEST
project to “improve our capability to predict long-term and regional-scale change on the coasts and in our estuaries.” Phase 1 of this project reviewed research reports and coastal plans to outline the status of existing tools and research needs, and is reported in Wells et al. (2010).

All of these studies indicate that a wide range of tools and techniques are available to help coastal managers understand how the coast has changed in the past, how it currently responds to the forces imposed on it, and therefore how it is likely to change in future, under various futures. In brief, these include:

- top-down rules and relationships developed from data analysis, empirical evidence and behavioural understanding. This approach recognises that useful information can be obtained from simple models that seek to represent general behaviour without the need to understand the detailed processes;
- process-based models that seek to replicate physical processes of water and sediment movement;
- hybrid approaches that seek to couple process models and top-down methods; and,
- systems-based approaches that recognise the limitations of process-based ones and seek to inform on long-term behaviour via the concept of reduced complexity.

There is, however, currently no single method or model that can answer all of the questions that coastal managers have. In addition, frequently there are financial or data availability constraints which mean that many of these tools are not appropriate for the assessments undertaken in support of SMPs or Coastal Strategy Studies (Wells et al., 2010).

This report section focuses on the various methods that are actually used in developing Shoreline Management Plans and Coastal Strategy Studies, rather than discussing the methods available, which have already been fully explored in the various texts mentioned above.

2.2 Shoreline Management Plans

2.2.1 Introduction

Shoreline Management Plans (SMPs) set out the long-term (100 year plus) vision for the coast and provide a “route map” for decision makers to move from the present situation towards the future. As such, a key output is the assignment of shoreline management policies to discrete sections of coast for three time periods: up to 20 years, 20 to 50 years and 50 to 100 years. The four policies that can be recommended are Hold The Line (HTL), Advance The Line (ATL), Managed Realignment (MR) and No Active Intervention (NAI) (Defra, 2006).

There are 22 SMPs for the coastline of England and Wales, and therefore these documents cover significant distances, which, whilst allowing more cohesive decisions to be made, does mean that appraisals remain high-level. As such, SMPs sit at the top of the hierarchy of plans that support coastal decision-making (see Figure 2.2).
The current SMP guidance (Defra, 2006) advocates the adoption of a “behavioural systems” approach, which involves the identification of different elements (geomorphological units) that make up the coastal system and the development of an understanding of the relationships and interactions between these various elements over a range of temporal and spatial scales.

The SMP guidance also suggested that the SMP reviews (SMP2 - undertaken between 2006 and 2010) should build upon the knowledge already produced as part of Defra’s Futurecoast project (Halcrow, 2002), which provided a vision of how the coast may evolve over the next 100 years for two hypothetical scenarios: ‘with present management’ and ‘unconstrained’.

2.2.2 Morphological tools and techniques applied
The most recent review of SMPs mainly relied on desk-based studies, reviewing existing data and information, rather than the acquisition of new data or detailed modelling. This was due to the high-level nature of the reports and also due to time and financial constraints. Also, in some areas, strategy studies, which had carried out more detailed coastal process appraisals, had already been recently undertaken in the SMP areas.

The main approach to assessing geomorphological evolution in the majority, if not all, of the SMP2s has therefore been expert judgement. The SMP2s have generally
adopted a “systems-based” approach, using the behavioural systems method outlined in the SMP guidance. This involves a tiered breakdown of the coastal units into: large scale units, termed Coastal Behavioural Systems (CBS); medium-sized units called Shoreline Behaviour Units (SBUs), which are discrete stretches of coast whose platform evolution appears to be governed by various controls and influences, through a combination of different linkages; and finally geomorphological elements such as cliffs, beaches, barriers, coastal dunes, tidal flats, marshes or shore platforms. Although some SMPs did not retain the same terminology as Futurecoast, the general concept of cascading units, has been applied across the SMP2s.

A common theme within the SMP2s has been the desire to work with natural processes wherever possible. Future prediction of coastal evolution has therefore recognised the benefits of allowing coastal cliffs to erode in order to provide sediment to fronting and downdrift beaches. Similarly many SMP2s have acknowledged the potential disadvantage of holding the line in terms of falling beach levels and decreasing beach widths.

The various SMP2s produced tended to use a limited range of techniques to support this approach, including:

- historical trend analysis – this tended to be undertaken at a very broad-scale, generally using historical OS map analysis undertaken by Futurecoast, new appraisal of historical maps and charts, review of cliff-top measurements, review of beach profile data and appraisal of anecdotal information;
- development of conceptual models for each large-scale process unit, using expert-led assessment; considering the key coastline characteristics in terms of morphology and sediment types, key controls and influences on coastal form, key processes operating and sediment budgets;
- estimation of future erosion rates based on expert geomorphological assessment of existing knowledge and previous estimates (typically as a banded estimate for soft cliff shorelines). This also utilised the cliff assessments undertaken as part of Futurecoast;
- application of the Bruun Rule, where considered appropriate, to take account of projected future sea level change; and
- use of the SCAPE model (e.g. Kelling to Lowestoft Ness SMP2) to predict rates of coastal erosion.

The development of coastal behaviour understanding was then used in the SMPs as a basis to assess the response and implications of different management scenarios over the three epochs.

2.3 Coastal strategy studies

2.3.1 Introduction

Strategy studies sit within the second tier of the hierarchy of coastal plans (see Figure 2.2). Whilst the SMPs provide the risk framework for management of the coast, strategy studies provide a more detailed assessment of particular frontages. The aim of a strategy study is to identify appropriate schemes to implement the policies set by the SMP. As such, strategies explore in more detail the practical implications of
alternative management actions for discrete coastal frontages, with the key outcome being a business case for investment in capital schemes.

A strategy therefore tends to require a more comprehensive assessment of the physical and natural environments in order to enable the:

- identification of a series of preferred options for the management of discrete coastal frontages over the next 100 years, taking account of implications on people, heritage and natural environment;
- assessment of the key risks of implementing the proposed options;
- identification and assessment of habitat creation sites on an opportunity basis and for offsetting FCERM habitat losses; and
- calculation of the economic justification for individual capital schemes.

2.3.2 Morphological tools and techniques applied

Strategy studies tend to cover much shorter stretches of coastal frontage than SMPs, and require a greater level of detail to fully appraise potential impacts of implementing the SMP policies. A variety of morphological tools and techniques are therefore used, depending on the nature and complexity of the study area.

The first stage of the study is commonly to undertake a scoping or baseline study of the environment and this tends to be a desk-based study of existing data and literature, using the SMP as a key resource. This stage should identify the need for any additional studies to improve confidence in the option proposals, and will tend to recommend the types of tools and techniques most appropriate for the issues to be addressed. Commonly, a strategy study will use process-based models to assess specific issues such as sediment transport, changes to beach profiles, risk of breaching and risk of inland flooding. It is recognised that the majority of process based models consider relatively short term processes in the order of days to weeks. The derivation of long term trends over years to decades is more problematical and subject to greater uncertainties. Thus, even where extensive modelling is undertaken, expert review of the model outputs remains an important component of the geomorphological appraisal. Commonly, a key stage of a strategy is the development of a conceptual model of coastal behaviour, which is used in the development and review of appropriate policies.

The recent Defra/EA CoaEST report (Wells et al., 2010) looked specifically at two FCERM Strategy Studies, in terms of the techniques used: the Folkestone to Cliff End Flood and Erosion Management Strategy (FoCE) and the Humber Flood Risk Management Strategy.

Within the FoCE Strategy the following tools were applied:

- expert geomorphological analysis of the entire study area through desk study and literature review; and
- one-line modelling of the beach plan-shape completed along the Lydd Ranges frontage (using the Halcrow Beach Plane Shape Model (BPSM)) to help predict future shoreline positions.
Within the Humber FCERM Strategy the following tools were applied:

- process modelling (Delft3D) investigating sea-level rise and the influence of the 18-year tidal cycle;
- modelling of proposed managed realignment; and
- Telemac-2D modelling to assess development of realignment sites in detail.

2.4 Summary
Whilst there have been significant advances in the development of models to address morphological change, there is no single method or model that can be universally applied to all coastal situations.

There is, however, a range of tools and techniques available to the coastal manager, but the use of these is often constrained by time, budget, complexity of the coastal situation, level of risk and data availability.

In both SMPs and Strategies, expert geomorphological appraisal therefore remains the main technique currently used, with a systems-based approach becoming more widely applied, in both types of studies, particularly following the guidance from Defra for SMPs (Defra, 2006). This appraisal often takes the form of a desk-based review of existing data and literature. Where more confidence is required, or a particular situation needs to be considered, process-based analysis may be used, but this is more common in strategy studies than in the SMPs. This may also involve the acquisition of new data to improve confidence in the modelling.

These appraisal techniques, and the relatively restrictive set of tools currently available, particularly in relation to universal application of models, indicate that there is indeed scope for investigations into modular integrated modelling techniques to be carried out.
3 Development of appropriate modelling techniques

3.1 Introduction
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. In parallel, 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, Bates 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 linked models is presented within GIS.

In parallel to the development of the Regional Coastal Simulator, the FluidEarth (OpenMI) initiative (REFERENCE) 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 are models, perhaps developed at different institutions, which have all been modified to conform to the standard format of data exchange adding value to independent developments by collation and management.

At the same time, GTI-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 (Figure 3.1). 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.

Figure 3.1 presents a schematic of various models which have all been incorporated within the GIS framework of GTI-SEAMaT. The naming of the individual models in this figure is not important, but essentially the framework facilitates the running and data management involved when using numerical wave propagation models, sediment transport and beach morphology models, as well as non-numerical parametric models and data analysis methods.

The present research has built upon the work presented by Stripling and Panzeri (2009) through two main routes. First of all, the principles of data management and presentation of model outcomes were modified to be centred on a database rather than
in “flat-files”. Secondly, there has been development of the modelling methods themselves to allow probabilistic application. This is a significant step which allows the summary objective of the research to be realised. Further, the underlying principle that the system must be straightforward to apply and rapid to execute has been sustained. The following sub-sections present these developments in greater detail.

Figure 3.1 The GTI-SEAMaT GIS modelling framework

3.2 Database development
Previously, input data and modelling results from the coupled models were held in flat files within a logical folder structure. The data were read, reformatted and shared where necessary by the models and the results files were saved into the logical folder structure. Consequently, a library of results files would grow. The key modelling outputs were read from the library of results into the GIS at the end of each model run sequence.
To manage this process more effectively, a data-model has been developed and implemented in the form of an ESRI Personal GeoDatabase. The datamodel, summarised in Figure 3.2, contains four main components, which function as follows:

- The Model Management component contains a series of tables used to define the run sequence numerical model engines, 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 Model Management component provides the ability to introduce new model engines to the software quickly and easily by simply adding rows to the database tables, and writing new code classes for any new data input file formats.

- The Time Series data model is a generic datamodel developed by HR Wallingford 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. Regardless, the Model Management component defines which data are needed by the engines in a model run sequence and the SEAMaT software extracts those data from the Time Series component and converts them to the model steering and input files. Furthermore, when the model run sequence is complete, the results are stored back to the Time Series component for better management of the data and for input into any-ongoing modelling processes that may be desired.

Figure 3.2  Overview of the SEAMaT data model
• The Mesh component was developed under HR Wallingford’s internal research programme to store results from numerical models based upon unstructured mesh spatial domains within a data model for efficient display and analysis within ArcGIS. The datamodel stores the mesh geometries independently from the variables enabling the data to be rapidly queries 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 could 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 data model 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.

3.3 “UnaLinea” 1-line model development

Previous development utilised the relatively process-rich sediment transport model COSMOS-2D (Stripling and Panzeri, 2009) in determining beach morphology. However, it was considered that, with the prospect of probabilistic application of the sediment transport model, a 1-line model would offer greater flexibility and computational efficiency.

In these models, the sand beach morphology is represented by a single contour, and such models are therefore often referred to as “1-line” models. Usually the x-axis is established approximately parallel to the coastline, and the y-axis directed offshore. The changes in the position of this contour, together with other parameters such as wave conditions, currents, and sediment transport rates, are functions of only longshore position (x) and time (t) and so the model is referred to as “one-dimensional”.

Predictions of changes in the beach and nearshore seabed plan-shape are produced. The beach profile is usually assumed to be constant, i.e. unchanging with time. A good starting point for those interested in the theory and application of beach plan-shape models is the paper by Bakker et al. (1970). This not only discusses the simplest “1-line” approach to such modelling but also takes the first step in the development of a model that allows some variation in profile along the shoreline.

1-line numerical models originated from analytical solutions to the diffusion equation for the small amplitude departures from a rectilinear coastline (Pelnard-Considere, 1956, Falques, 2003). There has been revived academic interest in the use of analytical solutions in recent years (Falques, 2003; Murray and Ashton, 2003; Reeve, 2006) but most 1-line modelling for coastal erosion management is likely to be performed using numerical models (e.g. Hanson and Kraus, 1989; Ozasa and Brampton, 1980) due to their flexibility in modelling realistic, non-idealised coastlines. Numerical 1-line models can include representation of seawalls and groynes.
Whilst extensive portions of coastline can be covered by rectilinear one-line models, the coverage is only extensive relative to, say, that covered by a coastal area model and is usually limited to a few tens of kilometres. This is mainly due to the basic assumption of the rectilinear one-line model that the coastline is infinitely long and straight not holding in general. Even in such cases where a curvilinear coordinate system is used, such as that presented by Jiminez and Sánchez-Arcilla (2004) where the evolution of the strongly curved Trabucador-La Banya spit complex (Spain) is simulated, the lateral extent of the model is often restricted to several tens of kilometres by an alongshore variation in wave climate induced by complex nearshore bathymetry.

A new 1-line model, referred to here as UnaLinea, has been written with the specific aim of probabilistic application. Whilst the utilisation of 1-line models to assist in making coastal management decisions does indeed date back 3 or 4 decades, recent interest in their value in probabilistic application has arisen (e.g. this report, Wang and Reeve, 2010). The spatial variation in wave climate over regional-scale coastline lengths, referred to above, has been managed through the specification of multiple inputs of nearshore wave climate, derived from the regional-scale wave propagation model already incorporated within SEAMaT.

The following sections outline the fundamental development of UnaLinea, and in some instances shed new light on 1-line model development.

3.4 Achieving a stable, rapid, and accurate 1-line solution for broad-scale application

Essential to the probabilistic application (ie multiple realisations) of the numerical 1-line model is the establishment of a reliable, accurate and rapid solution method, and these 3 characteristics of numerical models are intrinsically linked.

A rapid model can be achieved by keeping the 1-line model as simple as possible, by selecting an appropriate numerical solver, and by increasing the time step and grid spacing as much as possible. It is not sufficient just to accept the fastest solution method, and accurate plausible results must still ensue whilst stable operation is vital.

Numerical solution of the 1-line model equations is traditionally carried out using finite-difference schemes in either an explicit or an implicit manner. Explicit numerical schemes are generally considered to be conditionally stable (ie they are restricted in resolution of time and space in order to fulfil stability criteria). Implicit schemes, though more complex to code and theoretically more computationally demanding, are generally considered to be unconditionally stable thus allowing greater flexibility in time-step. There is, however, a restriction to implicit scheme time-step due to the possible introduction of numerical errors (Zacharioudaki and Reeve, 2010).

Experienced users and developers of 1-line modellers are aware that complicated infrastructure layouts and/or large spatial discretisation can induce instability, and although this can be managed in a single deterministic application, there is no tolerance for instability in a probabilistic application where possibly many thousands of individual deterministic runs may be realised.
To examine the issue of stability, a range of numerical schemes were implemented within the UnaLinea model, and these were tested using different combinations of time and space discretisation. It should be borne in mind that the aim here is to produce a rapid 1-line model capable of regional-scale and very long epoch applications.

In the following sections, these two issues are investigated.

3.4.1 The 1-line model: UnaLinea
The UnaLinea model is essentially a finite difference solution of the continuity equation which expresses the continuity of the volume of sediment moving along the shoreline as:

\[
\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0
\]  

where:
- \(Q\) is the volume rate of alongshore sediment transport,
- \(x\) is the distance along the shore,
- \(A\) is the beach cross-sectional area,
- \(t\) is time.

The basic equation can be modified to:

\[
\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} + q = 0
\]  

where \(q\) is used to express the volume of material brought onshore by wave action, added to the beach by artificial nourishment or removed from the beach by mining. By denoting the co-ordinate perpendicular to the beach by \(y\), the beach cross-sectional area, \(A\), can then be expressed by the product of \(y\) and a depth \(D\). If \(D\) (the depth of the active profile as defined by the summation of the closure depth and the berm height) is assumed not to vary with time, then equation (2) can be written:

\[
\frac{\partial Q}{\partial x} + D \frac{\partial y}{\partial t} + q = 0
\]  

Starting from some initial position, \(y = y(x)\), the model evaluates successive beach positions at time intervals \(\Delta t\), at points along the shore separated by \(\Delta x\). So for each ordinate \(x_i\) (separated from its neighbour \(x_{i+1}\) by \(\Delta x\)) we have \(y_i(0), y_i(\Delta t), y_i(2\Delta t)\) and so on. The model used is of a type known as '1-line', that is to say that the beach position is given by the location of a single contour which represents, normally the high water line.

An important factor in the accuracy of the model is the representation of the alongshore rate of sediment transport, \(Q\), which is dominated by the action of breaking waves. For waves of small unevenness in height along a beach with nearly straight contours, \(Q\) is usually approximated by the CERC formula with Osaza and Brampton (1980) term for variation of the wave height alongshore.
3.4.2 **Numerical schemes in 1-line models**

As mentioned above, several numerical solutions are traditionally used to resolve the continuity equation. These are:

- **explicit methods**: in which the shoreline position calculated essentially depends on the old values of the shoreline position;
- **implicit methods**: in which the solution essentially depends on the old values of the shoreline position as well as the new shoreline position.

Explicit methods available include Forward Euler and Runge Kutta 4\textsuperscript{th} order, while an implicit method would include the 3-level fully implicit scheme. This implicit scheme is unconditionally stable, which makes it very attractive to the model user, as the explicit methods go unstable at times, rendering the model unusable. However, the implicit method is more complex to code and takes more computational time. Therefore, the user needs to carefully select which method to use based on many factors, which include the stability criterion and the required discretisation in time, dt, and space, dx.

3.4.3 **Advantages and disadvantages of explicit and implicit schemes**

It can be shown (by using Taylor series, for example) that the Euler method has large errors. The true error is approximately proportional to the square of the step size, that is, as the step size is halved the true error gets approximately quartered. However, in practice we see that as the step size gets halved, the true error only gets approximately halved. This is because the true error being proportioned to the square of the step size is the local truncation error, that is, the error from one point to the next. The global truncation error is however proportional only to the step size as the error keeps propagating from one point to another.

According to Fletcher (1990) for diffusion equations (and many other equations), it can be shown the 3 level fully implicit method is unconditionally stable. However, the approximate solutions can still contain (decaying) spurious oscillations if the ratio of time step to the square of space step is large (typically larger than 1/2). For this reason, whenever large time steps or high spatial resolution is necessary, the less accurate backward Euler method is often used, which is both stable and immune to oscillations.

From the explicit schemes examined the most efficient (computationally) and accurate should be Runge-Kutta 4\textsuperscript{th} order. It should also allow the largest time-step. In the testing done, however, there was not a big difference in stability or accuracy between both explicit solvers mentioned (it was seen however that a second-order Adams-Bashford explicit solver, also tested, was more unstable and less accurate).

3.4.4 **Stability criterion**

The Courant–Friedrichs–Lewy condition (CFL condition) is a necessary condition for stability when solving hyperbolic partial differential equations (such as pure advection) numerically. In practice, the time step must be less than a certain value in time-marching computer simulations, otherwise the simulation may become unstable (Courant et al, 1967).
For example, if a wave is crossing a discrete grid in an explicit scheme, then the time step must be less than the time for the wave to travel across adjacent grid points. As a corollary, when the grid spacing is reduced, the upper limit for the time step also decreases. The time-step must be restricted to ensure that the fastest waves will not traverse more than one cell each time.

The linearised stability condition is:

\[ |C_{\text{cfl}}| \leq 1 \]  \hspace{1cm} (4)

where \( C_{\text{cfl}} \) is the Courant-Friedrichs-Lewy number corresponding to the maximum wave speed at each time level given by:

\[ C_{\text{cfl}} = \frac{1}{\Delta x} \frac{dQ}{dY} \]  \hspace{1cm} (5)

Due to the fact that the one-line equation has advection, diffusion and source properties it is very difficult for a catch-all stability criterion to be evaluated. To calculate the criterion within the models is not viable either as the criterion becomes over sensitive when the changes in \( y \) are small.

Other one-line models, like GENESIS (Krauss and Harikai, 1983), use the stability criterion for the approximation to the diffusion equation. This is explained in the section below for completeness, although the criterion misses the advection part of the equation and therefore is not exploited here.

### Stability condition from the diffusion equation

Krauss and Harikai (1983) set up the basis framework for the well-known 1-line model GENESIS. They defined the stability criterion for GENESIS from the approximation to the diffusion equation when the wave angle at breaking is small, and explained as follows.

The longshore transport \( Q \) is defined from the CERC formulation by:

\[
Q = K_1 \left( \gamma_s \right) E_b (nC)_b \left( \sin 2 \alpha_b - 2K_2 \frac{\partial H_b}{\partial x} \cot \beta \cos \alpha_b \right)
\]  \hspace{1cm} (6)

where
- \( K_1, K_2 \) are non-dimensional coefficients
- \( E \) is the wave energy density = 0.125 \( \rho g H^2 \)
- \( H \) is the significant wave height
- \( g \) is the acceleration due to gravity
- \( \rho \) is the water density
- \( \gamma_s \) is the submerged weight of beach material in place
- \( nC \) is the group velocity of the waves
- \( \alpha \) is the angle between their crests and the local depth contours
- \( \tan \beta \) is the mean slope of the beach face, and
- \( b \) denotes breaking wave conditions (where used as a subscript).
The angle between the breaking wave crests and the shoreline is expressed as:

\[
\alpha_b = \alpha_0 - \arctan \left( \frac{\partial y}{\partial x} \right)
\]  

(7)

where 

\(\alpha_0\) is the angle of breaking wave crests relative to the x axis and \(\frac{\partial y}{\partial x}\) is the local shoreline orientation.

The longshore drift can also be written as:

\[
Q = Q_0 (\sin 2 \alpha_b)
\]  

(8)

where

\[
Q_0 = K_i (\nu_s)^{-1} E_b (nC) \left( 1 - 2K_2 \frac{\partial H_b}{\partial x} \sin \alpha_b \cot \beta \right)
\]  

(9)

Assuming the breaking wave angle relative to the shoreline and the shoreline orientation are small, the longshore drift can be approximated to:

\[
Q = Q_0 \left( 2\alpha_0 - 2 \frac{\partial y}{\partial x} \right)
\]  

(10)

Assuming there are no sources or sinks in the model \((q=0)\) and if the amplitude of the longshore sand transport and the incident wave breaking angle are constant (independent of \(x\) and \(t\)) the continuity equation approximates to a diffusion type equation as:

\[
\epsilon \frac{\partial^2 y}{\partial x^2} = \frac{\partial y}{\partial t}
\]  

(11)

Where the diffusion coefficient \(\epsilon\) is given by:

\[
\epsilon = \frac{2Q_0}{D}
\]  

(12)

The following stability condition then holds:

\[
R_s = \frac{\Delta t \epsilon_{\text{max}}}{(\Delta x)^2} < \frac{1}{2}
\]  

(13)

Krauss and Harikai (1983) use this stability condition to choose between the implicit/explicit numerical scheme within the Genesis 1-line model. An alternative option is to utilise a practical grid convergence study as suggested by Roache (1998), and this is further explained below.
3.4.6 Grid convergence study – infinitely long groyne “AS1”

A systematic grid convergence study in the spirit of Roache (1998) has been carried out with the aim of choosing an appropriate time-step and grid spacing to aim for in a rapid 1-line model such that it would still provide acceptably accurate answers.

This study methodology includes:

1. Grid convergence: starting with the smallest possible grid size (which would be the reference, if an analytical solution is not available), keep doubling the grid spacing. Calculate the error and the computer time in order to determine the coarsest grid that gives satisfactory results in comparison with the reference grid.

2. Accuracy test: once suitable grid spacing has been chosen, the time-step is modified in order to find the largest value that gives acceptable results in comparison with a reference (very small) value.

The grid convergence study has been carried out for two cases:

1. Idealised case with an initially straight shoreline and constant waves. Extended to include an impermeable infinitely long groyne.

2. Idealised case with an initially straight shoreline and constant waves. extended to include a constant source at a single point (to represent a river, beach recharge or series of cliff-falls).

These cases have been compared to analytical solutions (Appendices 1 and 2) of the same problems.

The set up to allow the 1-line model UnaLinea to examine these test cases is presented in Table 3.1 below.

Table 3.1 Set up conditions used for the UnaLinea model convergence studies

<table>
<thead>
<tr>
<th>Numerical Models Input Conditions</th>
</tr>
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<tbody>
<tr>
<td>Depth at which waves are input, h</td>
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<tr>
<td>$D_{50}$</td>
</tr>
<tr>
<td>$K_1$</td>
</tr>
<tr>
<td>Depth of active beach</td>
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<tr>
<td>Epoch</td>
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</tbody>
</table>

The constant wave conditions used in these simple tests are specified in the table below.

Table 3.2 Wave condition used for the UnaLinea model convergence studies

<table>
<thead>
<tr>
<th>Wave conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave height, $H_s$</td>
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<tr>
<td>Wave period, $T_z$</td>
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<tr>
<td>Wave direction, $\alpha_0$</td>
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</tbody>
</table>
In this section, the simple case of inserting an infinitely long impermeable groyne in the middle of the model domain is examined. The analytical solution is presented in further detail in Appendix.

A combination of runs varying the time-step, the grid-size and the numerical scheme were carried out. Though not all results are shown here, the sensitivity of the solution to each of the parameters is explained below to allow an appreciation of the different issues.

(a) Sensitivity to grid-size “AS1”

The sensitivity of the model solution to the grid-size was assessed by running the simple case “AS1” for different grid-sizes keeping all the other parameters constant. The result comparison is shown in Figure 3.3 below. The grid-sizes used in these tests were: 75m, 100m, 150m, 200m, 250m, 300m, and 400m.

Normally for a deterministic detailed design study, discretisation of the order of 10m to 25m for the model grid would be utilised to allow resolution of groyne fields and so on. However, in order to achieve a rapid probabilistic 1-line model able to cover regional scales, where detailed scheme design is not an issue, different grid-sizes needed to be analysed to be able to achieve rapidity whilst maintaining solutions close to those achieved using finer resolution. In this example all grid-sizes provided reasonable results, although grid-sizes larger than 250m showed a more significant departure from the solution. So, at a regional-scale, grid-sizes of up to 200-250m appear to allow a reasonable solution to be achieved.
Figure 3.3  Sensitivity of solution for case “AS1” to increasing grid-size
(b) Sensitivity to time-step “AS1”

In order to gauge sensitivity of the solution to the time-step, the simple case was run for different time-steps keeping all the other parameters constant and the results compared with the analytical solution. The result comparison is shown in Figure 3.4.

The time-steps used in these tests were: daily, weekly, fortnightly and monthly. Normally for a deterministic detailed design study, hourly or 3-hourly wave conditions would be used. However, the potential of using large time-steps in furthering the aim of achieving a rapid probabilistic 1-line model at regional scale, where scheme appraisal is not as critical, makes such an investigation worthwhile. Different time-steps were analysed to identify an appropriate time-step that provided rapidity while still maintaining solutions close to those achieved from finer resolution.

The results indicate that weekly time-step results are very close to those obtained from a daily time-step. For longer time-steps than a week, the results start to depart from the solution significantly.
Figure 3.4  Sensitivity of solution for case “AS1” to increasing time-step
(c) **Sensitivity to numerical scheme “AS1”**

Several solvers for the continuity equation in the one-line model have been examined, two of them explicit and one of them implicit. The performance of the Euler explicit solver and the 3-level fully-implicit solver was analysed in this study.

A number of runs with a different combination of grid spacing and time-step were carried out using both numerical schemes. Table 3.3 shows the runs carried out, as well as which of them were unstable, and whether the results varied from one solver to the other. In only one occasion (dx = 150m, dt = week), the implicit scheme was stable when the explicit scheme had been unstable. In all the other cases, the model was either stable or unstable seemingly independent of which numerical scheme was used. The causes of the instabilities have not been examined in great detail here, but the instability of the Euler (explicit) scheme can be explained by the stability criteria discussed above. With regard the implicit scheme, which is considered to be unconditionally stable (Fletcher, 1990), the emergence of unstable model runs was unexpected.

In terms of accuracy, out of the 20 stable tests carried out, three were more accurate with the implicit scheme when compared with the explicit scheme.

**Table 3.3 Stability and accuracy comparison for implicit and explicit numerical solvers – test case “AS1”**

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<td>√</td>
<td>√</td>
</tr>
<tr>
<td>month</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
</tbody>
</table>

### 3.4.7 Grid convergence study – constant point source “AS2”

A systematic grid convergence study in the spirit of Roache (1998) has been carried out with the aim of choosing an appropriate time-step and grid spacing to aim for in a rapid 1-line model such that it would still provide acceptably accurate answers.

The study methodology is described in the previous section. In this section, the idealised case “AS2” with an initially straight shoreline and constant waves extended to include a constant source at a single point (to represent a river, beach recharge or series of cliff-falls) is described. The analytical solution is presented in further detail in Appendix 2).

The set up to allow the 1-line model UnaLinea to examine these test cases is presented in Table 3.1 above. The constant wave conditions used in these simple tests are specified in Table 3.2 above.
This study was done in a similar fashion to that reported above for “AS1”. In this simple case a constant point source to represent, for example, a series of continuous regular cliff-falls, was specified in the middle of the domain.

A combination of runs varying the time-step, the grid-size and the numerical scheme were carried out. Though not all results are shown here, as for case “AS1”, the sensitivity of the solution to each of the parameters is explained below to allow an appreciation of the different issues.

(a) Sensitivity to grid-size “AS2”
Sensitivity of the solution to the grid-size has also been performed for AS2. The results are shown in Figure 3.5. The grid-sizes used in these tests were: 75m, 100m, 150m, 200m, 250m, 300m, and 400m. The results suggest that grid-sizes of up to 300m give reasonable results when compared to the baseline solution obtained with a grid-size of 75m.

![Figure 3.5 Sensitivity of solution for case “AS2” to increasing grid-size](image)

(b) Sensitivity to time-step “AS2”
A similar set of time-step sensitivity tests to those carried out for case “AS1” has also been carried out for case “AS2”, the results being shown in Figure 3.6 below. The conclusions are similar; in as much as a weekly time-step seems to be appropriate in this case. Fortnightly, and longer, time-steps induce results which vary significantly from the solution.
Figure 3.6  Sensitivity of solution for case “AS2” to increasing time-step
(c) Sensitivity to numerical scheme “AS2”
Several solvers for the continuity equation in the one-line model have been examined, two of them explicit and one of them implicit. The performance of the Euler explicit solver and the 3-level fully-implicit solver was analysed in this study.

A number of runs with a different combination of grid-spacing and time-step were carried out with both numerical schemes. Table 3.4 below shows the runs carried out, as well as which of them were unstable, and whether the results were different from one solver to the other. In only three test (dx = 150m, dt = week and dx = 200m, dt = fortnight and dx = 250, dt = month), the implicit scheme was stable when the explicit scheme had been unstable. In the tests relating to case “AS1”, this had only happened in one occasion. In all the other cases, the model was either stable or unstable independently of which numerical scheme was used.

In terms of accuracy, out of the 19 stable tests carried out, two of them were more accurate with the implicit scheme in comparison with the explicit scheme and one of them was better with the explicit scheme; the one with the biggest dt and dx tested.

Table 3.4 Stability and accuracy comparison for implicit and explicit numerical solvers – test case “AS2”

<table>
<thead>
<tr>
<th>dx</th>
<th>75m</th>
<th>100m</th>
<th>150m</th>
<th>200m</th>
<th>250m</th>
<th>300m</th>
<th>400m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Numerical scheme</td>
<td>E</td>
<td>I</td>
<td>E</td>
<td>I</td>
<td>E</td>
<td>I</td>
<td>E</td>
</tr>
<tr>
<td>day</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>week</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>fortnight</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>month</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

From the convergence study described above for the idealised cases “AS1” and “AS2”, we can conclude that a suitable time-step would be weekly and a suitable grid-size would be 100-200m if we are to accommodate point sources and barriers to drift at regional scale. It is not expected that such a model should be utilised for detailed scheme appraisal at this time- and space- discretisation, but having established acceptable levels of resolution which still provide acceptably accurate solution, it should be feasible to maintain the rapid solution sought. The numerical scheme does not appear to have a significant influence in the accuracy or performance of the model, so either could be used. Additionally, though not mentioned above, elapsed processing time is very similar for both the explicit and implicit schemes coded.

Interestingly, each scenario carries with it different degrees of stability as time- and space-discretisation vary. Such a comparison indicates the value of examining more than one test case. Table 3.5 shows a comparison of stability between the
introduction of a groyne and the input of a continuous point source for the explicit scheme examined.

### Table 3.5 Comparison of range of stability for varying time and space discretisation – groyne v point source with explicit numerical scheme utilized

<table>
<thead>
<tr>
<th>AS 1 - Infinite groyne analytical solution</th>
<th>AS 2 - Constant discharge from a source at a point</th>
</tr>
</thead>
<tbody>
<tr>
<td>dx</td>
<td>dt</td>
</tr>
<tr>
<td>--------------------------------------------</td>
<td>-------------------------------------------------</td>
</tr>
<tr>
<td>day</td>
<td>✓</td>
</tr>
<tr>
<td>week</td>
<td>✓</td>
</tr>
<tr>
<td>fortnight</td>
<td>✓</td>
</tr>
<tr>
<td>month</td>
<td>✓</td>
</tr>
</tbody>
</table>

#### 3.4.8 Filtering wave input

The need for probabilistic modelling dictates a requirement for a robust, reliable, accurate and rapid deterministic model of shoreline evolution, and some effort has already been expended in arriving at such. The repeated running of a deterministic model could potentially consume large amounts of time. It is not uncommon, in probabilistic modelling, for outcomes to be realised after several weeks of processing.

To minimise the time required processing the solution, it is suggested above that time-steps of a day or a week in combination with grid-sizes of 200-250m should be, and can be, aimed for. To be able to time-step weekly as oppose to hourly or 3-hourly, for example, results in an approximate reduction in the run time by a factor of 100. It is therefore highly beneficial to arrive at appropriate model input (wave conditions, for example) so that the model time can be discretised more coarsely without losing significant detail. This filtering, together with the optimisation of the grid-spacing, should allow probabilistic outcomes to be examined within, say, minutes.

A wave-filtering model has been derived by HR Wallingford which reduces a wave climate time-series to a series of sequential morphologically-averaged conditions. In effect, these conditions, which may be daily or weekly for example, (still seen by the model in terms of wave height, period and direction) are those which induce the equivalent amount of longshore drift to the same length of hourly or 3-hourly records. A typical application would be to reduce a 20years-worth of 3-hourly wave time-series to 20years-worth of weekly morphologically averaged conditions (see Figure 3.7 for an example comparison).

The theory was derived during the 1990s, but is yet to be published. Given a wave climate, represented by a scatter diagram of wave height against direction, this theory reduces this wave climate to a single wave condition. For single weekly conditions, one week of wave records is represented as a scatter diagram.

Given a scatter diagram, so that for each wave height bin (H_i) and each wave direction bin (θ_j) has a certain number of occurrences (n_ij), the total number of occurrences in the scatter diagram is given by N so that \( \sum n_{ij} = N \).
The potential longshore sediment transport for each wave condition \((H_i, \theta_i)\) can be defined by the CERC formula as:

\[
q_{ij} = \frac{n_j H_i^{2.5} \sin 2(\theta_j - \Phi)}{N}
\]  

where \(\phi\) is the angle of the beach normal.

The sum of all of the potential longshore drifts is then given by the summation, so that \(Q = \sum q_{ij}\). We wish to find a condition which represents the wave climate in terms of longshore drift. There is a wave condition which will work for all values of the beach normal. This representative condition is the canonical \((H_s, \theta)\) pair.

The canonical pair \(\bar{H}, \bar{\theta}\) is found by solving the following equations:

\[
\begin{align*}
\sum n_j H_i^{2.5} \sin 2(\theta_j - \Phi) &= Q \\
\sum n_j H_i^{2.5} \cos 2\theta_j &= 0
\end{align*}
\]  

which resolve as:

\[
\bar{H}^{2.5} = \frac{\sum n_j H_i^{2.5} \cos 2\theta_j}{N \cos 2\bar{\theta}}
\]  

\[
\tan 2\bar{\theta} = \frac{\sum n_j H_i^{2.5} \sin 2\theta_j}{\sum n_j H_i^{2.5} \cos 2\theta_j}
\]

Due to the fact that the inverse of the tangent is multi-variant, there are four possible mathematical values for \(\bar{\theta}\). Two of these values lead to \(\bar{H}^{2.5}\) being negative (and \(\bar{H}\) being complex) and these are rejected. Two possibilities for \(\bar{H}\) and \(\bar{\theta}\) remain, differing only in \(\bar{\theta}\) by 180º. In almost all cases, only one of these is physically sensible.

The time-series data should also contain the wave period associated with \((H_i, \theta_i)\) at each time-step, so that the representative wave period is calculated as the average period.

When there is data in the time series with zeroes for values of the wave height and wave period, this data is treated as calm. The method does not take into account calm data for the derivation of the morphologically averaged wave conditions within that time period over which the representative condition is being sought. To overcome this, the calm periods within the representative time period are added up and the proportion over which there is no calm data is calculated. This proportion is then used by UnaLinea, in this case, as a multiplier to the time-step thus accounting for the calm periods. For the last time-period of the initial time-series, if there are not enough wave conditions to calculate the averaged wave conditions, these averaged conditions are not calculated.
Further, since for this application the aim is to obtain a time-series of wave data with larger time-step in order to drive a shoreline evolution model with less computing effort, the representative conditions are required at the same depth at which the wave time-series have been generated. The representative conditions, therefore, are derived from those driving the longshore transport calculations (i.e., at wave breaking point) by refracting them back into deeper water.

![Figure 3.7](image)

**Figure 3.7** Comparison of 20 years of 3-hourly wave records with the same 20 years represented as morphological events

### 3.5 Longshore sediment transport formulae

UnaLinea has two options for the formulation used for the longshore sediment transport. These are:

- CERC formula
- Damgaard and Soulsby (1997) formula.

The user has the option to select which transport formula is preferred, and the actual choice will depend on the intended application.

#### 3.5.1 CERC Formula

For waves of approximately constant height along a beach with nearly straight contours, $Q$ can be approximated by:

$$Q = K_1(y_s)^{-1}E_b(nC)_b(\sin 2 \alpha_b)$$

(18)
where

\[ K_1 \] is non-dimensional coefficient
\[ E \] is the wave energy density = 0.125 \( \rho g H^2 \)
\[ H \] is the significant wave height
\[ g \] is the acceleration due to gravity
\[ \rho \] is the water density
\[ \gamma_s \] is the submerged weight of beach material in place
\[ nC \] is the group velocity of the waves
\[ \alpha \] is the angle between their crests and the local depth contours
\[ \tan \beta \] is the mean slope of the beach face, and
\[ b \] denotes breaking wave conditions (where used as a subscript).

This equation is the well known CERC (Scripps) formula and describes the alongshore sediment transport due to obliquely breaking waves. Other well-known formulae can be readily substituted for this in the UnaLinea model.

\[ K_1 \text{ dependency with } D_{50} \]

![Graph showing K1 dependency with D50](image)

**Figure 3.8  Relationship of \( K_1 \) (CERC formula) with \( d_{50} \)**

Several studies have been carried out on the dependency of the \( K_1 \) non-dimensional coefficient to the beach parameters, such as the sediment size (median grain diameter, \( d_{50} \)) or slope. The most accepted correlation is with sediment size. UnaLinea adopts a logarithmic variation between the coefficient and the sediment size, as introduced by Swart (1976) and shown in Figure 3.8. In this Figure, the formulations by Valle et al (1993) are also shown for comparison.

**3.5.2 Damgaard and Soulsby (1997) formula**

This physics-based formula is only for bed-load longshore sediment transport and therefore intended primarily for use in shingle beaches, although it can also be applied to the bed-load component on sand beaches.

The formula is:
\[ Q = \max\{Q_1, Q_2\} \]

where:

\[ Q_1 = 0.19 (g \tan \beta)^{1/2} (\sin 2\alpha_b)^{3/2} H_b^{5/2} (1 - \hat{\theta}_{cr}) \]

for \( \hat{\theta}_{cr} < 1 \)

\[ 12(s - 1) \]

\[ Q_2 = Q_1 \]

\[ 2/12(s - 1)T^{1/4} \]

\[ \frac{0.24 f(\alpha_b) g^{1/8} d_{50}^{1/4} H_b^{19/8}}{12(s - 1)T^{1/4}} \]

for \( \theta_{wr} \geq \theta_{wof} \), or

\[ (19) \]

\[ Q_2 = \frac{0.046 f(\alpha_b) g^{2/5} H_b^{13/5}}{12(s - 1)^{6/5}(\pi T)^{5/5}} \]

for \( \theta_{wr} < \theta_{wof} \)

\[ (20) \]

subject to \( Q_2 = 0 \) for \( \theta_{max} \leq \theta_{cr} \)

where:

\[ \hat{\theta}_{cr} = \frac{16.7\theta_{cr} (s - 1)d_{50}}{H_b (\sin 2\alpha_b) \tan \beta} \]

\[ f(\alpha_b) = (0.95 - 0.19 \cos 2\alpha_b)(\sin 2\alpha_b) \]

\[ \theta_{w} = \frac{0.15H_b^{3/4}}{g^{1/4} (s - 1)(T d_{50})^{1/2}} \]

\[ \theta_{wof} = \frac{0.004H_b^{6/5}}{g^{1/5} (s - 1)^{7/5} d_{50} T^{2/5}} \]

\[ \theta_{w} = \max\{\theta_{w}, \theta_{wof}\} \]

\[ \theta_{m} = \frac{0.1H_b (\sin 2\alpha_b) \tan \beta}{(s - 1)d_{50}} \]

\[ \theta_{max} = \left[ (\theta_{m} + \theta_{w} \sin \alpha_b)^2 + (\theta_{w} \cos \alpha_b)^2 \right]^{1/2} \]

\[ \theta_{cr} = \frac{0.3}{1 + 1.2D_s} + 0.055[1 - \exp(-0.020D_s)] \]

\[ D_s = \left[ \frac{g(s - 1)}{\nu^2} \right]^{1/3} \]

\[ H_b \]

wave height at breaker line (rms wave height)

\[ T \]

wave period

\[ d_{50} \]

median grain diameter

\[ \tan \beta \]

beach slope

\[ \nu \]

kinematic viscosity of the water

\[ s \]

ratio of sediment density to water density
The dependency of the sediment transport with sediment size can be inferred by calculating the transport for different sizes, leaving all the other parameters constant. In Figure 3.9 above, the calculated longshore transport for a beach of a slope of 1/10 under constant waves of $H_b = 1\text{m}$, $T_p = 6\text{s}$, $\alpha_b = 10^\circ$ is shown for different gravel grain sizes.

### 3.5.3 Formula comparison

According to Soulsby (1997), the Damgaard and Soulsby (1997) formula should have a wide applicability because it has a stronger basis in physics, and it includes dependencies on grain size, beach slope and wave period (which the standard CERC formula does not include per se, but is inherent within the calibration parameters). However, the CERC formula includes suspended transport and has the virtues of simplicity and ease of calibration.

The longshore transport calculated for a beach of a slope of 1/10 under constant waves of $H_b = 1\text{m}$, $T_p = 6\text{s}$, $\alpha_b = 10^\circ$ is $40,000\text{m}^3/\text{yr}$ for Damgaard and Soulsby (1997) formula and $800,000\text{m}^3/\text{yr}$ for the CERC formula. This value is about 20 times larger, and according to Soulsby (1997) is probably an overestimate of that factor because the standard CERC formula is calibrated for suspended transport of fine sands rather than bed-load transport of shingle. Whichever transport formula is opted for, modellers should be aware of the potential variation in results.

### 3.6 Accommodating seasonal beach profile changes

As has been discussed above 1-line models track a single beach contour, such as the Mean High Water mark, and assume that the beach profile is a constant slope. However, it is conceivable that some beaches across the globe adopt a very seasonal character.

For example, the beach slope may flatten during the winter, effectively pivoting around a point on the profile, perhaps just below Mean Sea Level, resulting in a landward transition of the plan-view position of the Mean High Water mark being...
tracked. Should this be the case, then the reduction in width of the beach, and consequent reduction in its performance as a defence, could result in over-topping and cliff-erosion, for example, being exaggerated during the winter period relative to the summer period when the beach width may increase as its slope alters to reflect the summer climate. It is also notable that winter climates are more likely to be more energetic, and this, coupled with the possible seasonal changes in the beach as a defence, could increase the likelihood of cliff-failure or over-topping of seawalls.

To capture some of this seasonal beach performance, the UnaLinea model can be operated with a varying beach slope; a typical slope during the summer, and a typical slope during the winter. Figure 3.10 shows this schematically where “ypos” is the position of the tracked contour relative to the baseline of the model. Here, the summer and winter swash limits (“Yswash_summer” and “Yswash_winter”) are shown to vary, potentially reducing the defence standard of the beach; in this example fronting a cliff with cliff-top position (“cpos”) and slope (“cslope”).

Figure 3.10 Schematic view of seasonal profile changes effectively altering tracked contour location “ypos”

The following sub-sections describe an investigation into seasonal beach slope changes at Hornsea, on the Holderness coastline. It is notable that the analysis failed to identify the anticipated summer/winter representative slopes as well as a zone, or point, of pivot. Nevertheless, the exercise was valuable since it revealed a seasonal trend in landward/seaward translation of the shoreline. The assessment is reported below for completeness and information. Further investigations into seasonal beach behaviour would help refine this approach in the future.
3.6.1 Beach profile analysis, Hornsea

This sub-section presents the results of an analysis of beach profiles, which has utilised Halcrow’s Shoreline and Nearshore Data System (SANDS) software. SANDS provides the ability to store beach profile surveys, to view them graphically and to analyse them to identify trends in beach levels at a location over time.

Beach profiles at Hornsea were provided by East Riding of North Yorkshire Council were imported into SANDS, and then defined as either “winter” (March/April) or “summer” (September) profiles, depending upon the time of survey. Hornsea was selected for this analysis because it is relevant to the pilot-study area described later in this report. Summer and winter beach profile graphs were then created for each profile location. The range of profile variations were then used to create beach profile envelopes for each location.

Beach gradients were also calculated, to assess whether the net slope of the beach changes between winter and summer profiles. This information was used to determine whether it is possible to identify a ‘pivot point’ around which the beach rotates, when it changes from a summer to a winter profile (see Figure 3.1 for an illustration of this).

(a) Beach profiles

Beach profiles change in response to the level of wave energy experienced, with the tendency for low to moderate wave conditions to result in a steep gradient beach, whilst under rougher storm conditions, beaches tend to develop a gentler gradient. As higher energy waves tend to occur during autumn and winter in the UK, these flatter profiles are known as a “winter profile”, the steeper beach tendency to be associated with a “summer profile” (Shepard, 1950) (see Figure 3.1).

As well as the prevailing wave conditions, the beach slope also depends upon other factors such as beach composition and sediment size, which in turn affect water percolation, and is also affected by man-made interventions such as groynes and offshore structures.

Whilst the surveying of beach profiles is an invaluable tool in appraising coastal change, it should be remembered that they only provide a snap-shot in time, whilst beaches are undergoing constant change. Depending on the timing of a survey, any one profile may be representative of either a very short-term event, such as a storm, or alternatively may represent a longer period of wave activity; without linking profiles to real-time wave energy data, it is therefore difficult to determine what the profile actually shows. For this reason it is important to obtain as long a time series of data as possible so that an envelope of change can be produced.

A beach profile also only represents a two-dimensional cross-shore component of a beach system, whilst on some coasts it is the longshore movement of material that is a more significant process than the cross-shore transfer. Therefore careful analysis of beach profiles is required to ensure that they are not misinterpreted.

The purpose of this task is to assess whether the beach along the Hornsea section of coast exhibits seasonal variations, and if so, whether a typical summer and winter profile can be defined.
(b) **Import of beach profiles**

Beach profile data for 11 locations along a section of coast in East Riding that is being used in the software development; these locations were named P038 to P049. The dataset spanned a total of 10 years, and for each location there were up to 19 surveys available, with surveys having been undertaken biannually; in March/April and then in September. The March/April surveys were taken to represent a “winter” beach profile, whilst the September surveys were taken to represent the “summer” beach profile. All profiles were manipulated into the required format and uploaded to SANDS.

Using the processed data, seasonal beach profile graphs were created for each location (these are included in Appendix A). The range of profile variations were then used to create beach profile envelopes for each location (these are included in Appendix B). Beach profiles and envelopes have been plotted on an exaggerated elevation scale to highlight differences between profiles. Some data had to be edited during quality control as shown in Figure 3.12.

![Figure 3.12 Comparison of raw data (left) against corrected data (right)](image)

*Figure 3.11 Typical “winter” and “summer” beach profiles (after Komar, 1998)*
(c) **Beach slope assessment**

As well as looking at the cross-shore variations that occur over time, simple calculations of beach slope have been undertaken. Using SANDS it is possible to determine beach slopes between two set reference points. So that different locations along the coast could be directly compared it was decided that it was most appropriate to use reference levels common to all profiles.

Ideally, calculation of beach gradient would be conducted between the swash height (i.e. the upper limit of where sediment transport may be expected to occur - possibly defined by a most-landward berm/beach crest) and the depth of closure (i.e. the depth below which drift is considered to be negligible – in beach profiles this would be defined as where the envelope of change thins out towards the offshore).

Initial analysis of the beach profiles showed, however, that this approach would not be viable for two reasons:

- firstly, although the beach profiles do reach the “swash height”, there is not a distinguishable feature that defines this point (see Figure 3.13); and
- secondly, many of the profiles do not extend far enough offshore for a closure depth to be consistently reached – this is particularly true for the winter profiles.

![Figure 3.13 Typical beach profiles, at Location P042](image)

It was decided, therefore, that tide levels would be used as reference beach levels in the calculation of beach gradient; this removed any subjectivity in the analysis.
procedure. Standard tidal levels for the stretch of coast being appraised were taken from the 2011 Admiralty Tidal Tables (see Table 3.6).

Table 3.6  Tidal levels at Spurn Head (from Admiralty Charts)

<table>
<thead>
<tr>
<th>Tidal Level</th>
<th>Water Level (mOD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Low Water Spring (MLWS)</td>
<td>-2.7</td>
</tr>
<tr>
<td>Mean Low Water Neap (MLWN)</td>
<td>-1.2</td>
</tr>
<tr>
<td>Mean Sea Level (MSL)</td>
<td>0.2</td>
</tr>
<tr>
<td>Mean High Water Neap (MHWN)</td>
<td>1.6</td>
</tr>
<tr>
<td>Mean High Water Spring (MHWS)</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Figure 3.14 shows the various tide levels at Spurn Head superimposed on the beach profiles for location P042. The beach profiles measured here are representative of those measured at other profile locations.

Figure 3.14 Tide levels at Location P042

In order to undertake a very simple appraisal of beach slope it was decided that only two reference levels would be used.

As discussed above, it was not possible to use the closure depth as a lower limit as many of the profiles do not extend this distance offshore, similarly many profiles also finished above the MLWS level. It is, however, important to capture the lower beach as much as possible; therefore, a lower level of -2m OD was chosen as it was determined to capture the majority of profile data.
Using the same approach the higher levels were appraised. Figure 3.15 demonstrates that the majority of profiles do not reach the MHWS level at profile P042, and this is true at a number of the beach profile locations. The MHWN level (+1.6m OD) encompasses a greater number of profiles; therefore this level was used to give the most comprehensive analysis at each location.

The gradient of each beach profile was therefore calculated within SANDS between +1.6m OD and -2m OD.

It was not possible to analyse as many winter profiles as summer profiles, using this approach, because sea conditions during winter surveys generally tend to be rougher and therefore the surveys did not extend as far offshore.

(d) Definition of a beach “Pivot Point”

Investigations were also carried out to establish whether it is possible to identify a beach “pivot point”, around which a beach might rotate between its summer and winter form (see Figure 3.10 and 3.11).

In order to do this, a trial methodology to plot crossing points between consecutive winter/summer profiles was derived.

(e) Beach profile plots

Beach profile graphs are included in Appendix A. Two graphs have been produced for each location: one illustrating summer profiles and one illustrating winter profiles.

Envelopes of winter and summer profile extents have been produced from the variations in beach profile, and are directly compared for each location; these are included in Appendix B. A “midpoint” profile has also been calculated for the two seasons at each location, which may be taken as an approximation of the “average” beach profile for that season.

Comparison of the beach profiles shows that it is difficult to discern a representative summer and winter beach profile at each location. This may be for a number of reasons:

- The beach profiles were surveyed in March/April and then again in September – at these stages in the year the profiles may be in transition between their winter/summer states, thereby not representing their true winter/summer states.
- Beach surveys only represent a snap-shot in time and may therefore be reflective of very recent energy conditions, rather than representing a longer term winter or summer profile.

Comparison of the beach profile envelopes, however, reveals a noticeable pattern of landwards – seawards translation in the beach profile between the seasons. The midpoint profile, though only an approximation of an “average” profile highlights this effect. The translation is particularly noticeable in the beach envelopes of locations P040 to P044, although all locations show signs of seasonal variation in position of the “average” profiles. In comparison with the winter profiles, the summer profiles are generally located further seawards and show higher elevations at any one point.
(f) Identification of seasonal slope

Beach profile gradients calculated for each profile are presented in Appendix C. Where the beach profile did not extend to the analysis levels, the gradient has not been calculated – this is reflected by a blank space in the table.

At each location, and within each season, there is a large variation in beach profile gradients. This makes it difficult to discern any clear difference between the summer and winter beach profile gradients.

An average of all gradients derived for each location has been calculated – this shows that the average gradient does not change greatly between seasons at the majority of locations. This agrees well through observation of the profile plots, again suggesting that translation of beach position is a more important factor in seasonal change at East Riding than change in beach slope.

(g) Identification of beach “Pivot Point”

It was not possible to define a “pivot point” with any degree of confidence. In most cases the consecutive profiles either crossed in a large number of places throughout the length of the beach or did not cross at all.

As discussed in Sections 3.1 and 3.2 beach profiles for winter and summer seasons at East Riding do not appear to pivot around a defined point. Instead the profile seems to show a landwards – seawards translation between seasons.

3.7 The cliff-recession module

The 1-line cliff-recession model incorporated within UnaLinea is necessarily simple. This is necessary to ensure that the rapidity of the modelling application is maintained. Such simplicity requires, therefore, that the numerical representation of the physical processes involved in the recession of soft-cliffs is minimised. To ensure that the methodology still bears a semblance to reality, the model has been developed with expert engineering judgement as a primary input parameter.

In effect, this means that the user would have to seek expert advice to ensure that the cliff-recession model operates within accepted bounds. In the development and proof-of-concept presented here, default values of cliff behaviour are assumed.

This is not an uncommon approach in systems modelling techniques (Burgess et al., 2006) where the user effectively guides the models to match expectations. In this instance, it is expected that the regional stretch of shoreline has been divided into what are known as Cliff Behavioural Units (CBUs), and the general process of the cliff steepening/ failing/ re-stabilising is therefore known (HR Wallingford, 2005).

Figure 3.15 shows a schematic view of the landward migration of the cliff-top resulting from beach recession. Whilst there is adequate beach width in front of the cliff to protect from erosion, the cliff is considered to be stable (Figure 3.15, top). If the beach-width in front of the cliff reduces, such that beach berm is eroded, any further recession of the beach will result in a steepening of the cliff-slope – increasing its propensity to fail (Figure 3.15, middle). During this process, a proportion of “volume1” is added to the beach.
Within a CBU, the cliff can be expected to fail when it reaches an average angle $\alpha_f$ and will, after failure, adopt an angle $\alpha_s$. Since neither $\alpha_f$ nor $\alpha_s$ can be predicted precisely, the model compares its cliff slope within a range of slopes where the cliff is known to become unstable. This range is CBU-dependent, and a linear distribution of the probability of cliff failure assigned between 0 at the lower slope and 1 at the higher slope. A random number is generated by the cliff module, and if this is less than the probability of cliff failure, the cliff fails. If the cliff is deemed to fail (Figure 3.15, bottom), a stable post-failure slope $\alpha_s$ is selected randomly from within an established range observed within the CBU. The cliff top retreats, and sediment is released on to the beach – a proportion of “volume2”.
Figure 3.15 Schematic representation of the cliff-recession model
This simple model therefore requires the geometry of the cliff to start with – its height, toe position and cliff-top position, and a geomorphological assessment of the pre- and post- landslide angles. The shoreline evolution model determines the time-evolution of the toe-position; and this accommodates the possibility that there may be seasonal variation in the beach slope – and hence in protection afforded to the base of the cliff by the beach.

It is not strictly correct to examine the output of a single deterministic run of the UnaLinea shoreline evolution model due to the variation of angles $\alpha_f$ and $\alpha_s$ that could be possible, and because the beach width itself (which is dependent on the order of morphological events) is such a controlling factor in determining the recession of the cliff-toe. As a result, the deterministic UnaLinea model, when run with the probabilistic cliff-recession module engaged, must also be run in a probabilistic fashion.

### 3.8 Probabilistic application of UnaLinea - UnaLineaProb

It was necessary to establish a probabilistic application of the very rapid 1-line model UnaLinea in order to accommodate the event-based timings of probabilistically defined sediment-loading, and to construct a view of the statistics of the long-term behaviour of the shoreline. Loadings might include fluvial and cliff-fall inputs of sediment to the beach, for example, and a statistical representation might allow the likely narrowest beach widths to be established.

The aim, therefore, was to re-run the deterministic UnaLinea shoreline evolution model repeatedly with randomly sampled morphologically-averaged events and cliff-fall loads to produce a probabilistic summary of the beach position. Ultimately, this probabilistic behaviour of the shoreline will be used to examine the flood-risk.

UnaLineaProb, as the UnaLinea model run in probabilistic model is named, requires one or more time-series of morphologically-averaged (effectively, “filtered” wave conditions as described above) conditions, and a description of the event-based loading (as is provided here by the cliff-recession model). UnaLineaProb also requires an UnaLinea model to be already set up, calibrated, and validated, as well as a description of the parameters controlling its convergence.

At each UnaLinea model grid point, the mean and standard deviation of:

- The final beach position over the time spanned by the model ($Y_{\text{final}}$)
- The average beach position over the time span ($Y_{\text{ave}}$)
- The minimum beach position over the time span ($Y_{\text{min}}$)
- The maximum beach position over the time span ($Y_{\text{max}}$).

can be established. In addition, further statistics of beach and cliff positions can be determined, and these include (but are not limited to):

- Histogram of toe levels at seawalls
- Histogram and percentage exceedence positions of cliff-top retreat.
A flowchart describing the UnaLineaProb algorithm is given in Figure 3.16. UnaLinea, with the cliff-module engaged, is called over a number of realisations and each is given a randomly sampled year of morphologically averaged conditions up to the number of years of interest – perhaps covering several epochs. This allows long time periods to be examined, and ensures that the seasonality of the time series is preserved. Years are sampled with replacement and the same years are selected for every time series when there are more than one of them so that dependence between series is not lost. After an initial number of realisations, convergence is checked periodically by monitoring the variance of the total sum of $Y_{\text{ave}}$ over all grid points (see Figure 3.17).

After running UnaLinea, the final ($Y_{\text{final}}$), average ($Y_{\text{ave}}$), minimum ($Y_{\text{min}}$) and maximum ($Y_{\text{max}}$) beach positions over the $n$ years are extracted for each grid point. These are used to update the running means and standard deviations of each of these quantities. Statistics for other beach parameters, such as toe levels at seawalls and cliff-top position are also established. The variance of the sum of $Y_{\text{ave}}$ over all grid points is also updated as this is used for convergence.

![Flowchart](image-url)

**Figure 3.16 Basic flowchart of UnaLineaProb**

The above procedure is repeated for a minimum number of realisations before the current variance of the total $Y_{\text{ave}}$ is stored. After a further user-selected series of realisations the new variance is compared with the old and if the absolute change in
variances is less than a predefined percentage, the algorithm is said to have converged. If this is not the case, the new variance is stored to be compared with the variance after another batch of realisations. This is repeated until either the algorithm has converged or a maximum number of realisations has been reached.

Figure 3.17 Convergence of UnaLineaProb
3.9 Under-lining erosion-risk and flood-risk models

3.9.1 UnaLineaProb output

Section 3.8 above describes the probabilistic method used to enable the very rapid shoreline evolution model UnaLinea to be applied when event-based sediment loading is added as beach volume. This section describes the type of information which can be extracted from the running of UnaLineaProb.

Figure 3.18 shows a plan-view of a 10km portion of a schematic model shoreline (yellow line) which is approximately 55km long providing an overview of the type of output available from the beach/cliff recession model through one deterministic realisation. The model has an assumed starting cliff position 50m landwards of the shoreline (dark green line). Between 45500m and 48500m alongshore can be seen recession of the shoreline, and the subsequent erosion of the cliff-line. Elsewhere in the model domain, the beach width remains sufficient throughout the run period to protect the cliff from erosion, though between about 44250m and 45500m the cliff is close to eroding.

Figure 3.18 Portion of output from rapid deterministic UnaLinea model incorporating cliff-recession and shoreline erosion modules. “Y” refers to shoreline position, “C” refers to cliff-top position

It is clear, though, that such a cliff module has limited use when the UnaLinea model is run in deterministic (ie single-realisation) mode. To appreciate further how the event-based sediment loading of the beach, and the statistics of the behaviour of the system can be of value, Figure 3.19 shows results of a probabilistic run for the same 55km schematic model setup over the entire domain.
Figure 3.19 shows the type of output that can be extracted from the application. For clarity, the shoreline contour displayed is some way down the beach, and therefore a reasonable distance seaward of the cliff line. A histogram of cliff-top positions at a single x-point from the Monte-Carlo simulations is presented. Note that this information is also available for the toe level at a seawall – a key parameter in establishing over-topping volumes in the modified RASP model – and the position of the shoreline. The data used to generate such histograms are stored at every model node. The Figure presents the mean, minimum and maximum positions of the shoreline (black) and cliff-top (red) after just 5 years of simulation, with the sea being towards the top the page.

This schematic domain has been used to establish the model functionality (intentionally, to examine stability issues and so on) and very high erosion rates are consequently seen within the model domain, which itself has several additional features of note:

- The domain boundaries are closed.
- The wave conditions are assumed to be uniform along the entire domain.
- There is an infinitely long groyne at chainage 32000m.
- There is an additional event-based point source at chainage 10000m.
- There is a seawall between 18000m and 28000m.
- There is a seawall between 36000m and 37000m.

Figure 3.19 Minimum, mean (solid) and maximum of the shoreline (black) and cliff-top positions (red) after 5 years throughout a schematic regional-scale model. A density estimate of the cliff top is also given for a selected beach position.

Where the assessment of flood risk and coastal erosion management is made, the application of this probabilistic development has obvious advantages and connotations over and above the standard practice of deterministic testing alone. During the development reported here, UnaLineaProb was also developed and applied on the coast of Calabria, Italy on behalf of Autorità di Bacino Regione Calabria.
Briefly, the coastline in the vicinity of the mouth of the River Savuto on the west coast of Calabria has receded in recent decades. It is thought that this erosion is due to a combination of factors which essentially relate to the interruption of the supply of sediments both from the updrift coastline and the river itself which has been, and still is, subject to aggregate extraction (Plate 3.1).

Plate 3.1 Aggregate extraction plant (foreground) in the River Savuto, Italy. The river bed is dry in this image, but evidence of flood flows can be seen from the damage to the bridge at the centre of the photograph (Photo courtesy of Stripling, 2010).

A numerical model of fluvial-load was established, and a histogram of beach-forming sediment volumes for a range of return-periods established. This histogram was sampled at each time-step by UnaLineaProb, and the nature of the histogram was that the majority of time-steps saw no loading. The beach-forming sediments were then used to increase the beach volume at the mouth of the river.

In conjunction with the event-based loading of beach-building sediments from the river model, a facility to nourish the beach artificially was also included. The model allows the user to modify the river-loading histogram, and to control the artificial beach nourishment. As a result, the effectiveness of various management intervention programmes in redressing the erosive tendency of the shoreline could be ascertained.

Figure 3.20 shows the output from a 20-year probabilistic simulation of the shoreline behaviour in the vicinity of the River Savuto assuming that there is no active intervention planned (dots), and in the event that intervention induces a factor of five
increase in the loading from the river (solid). In this research application, it was not possible to consider the presence of coastal defence structures other than groynes, and so significant erosive potential is observed. It is also shown that intervention to increase the sediment loading of the river appears to have very little impact – perhaps an indication of the extent to which the river has been worked. Presented in the image are the mean (of the shoreline position at the end of each 20-year realisation), and the minimum and maximum positions of the shoreline reached during all of the 20-year realisations. The model suggests that this degree of intervention has minimal beneficial influence on the surrounding shoreline, with most of the impact being seen close to the river mouth.

Figure 3.20 Minimum, mean and maximum shoreline positions reached under probabilistic simulation of the shoreline evolution given present-day and enhanced fluvial sediment loading.
Figure 3.21 shows another simulation where the current fluvial sediment loading is augmented by several artificial nourishment schemes at the coastline. In this instance, nourishment was varied in volume and placed at the shoreline between the mouth of the river and “Villagio del Golfo”. Clearly the nourishment helps to reduce the identified erosion potential, and the model development is shown to be a useful tool in helping to refine possible intervention strategies. But, over and above traditional deterministic applications, in addition to these coarse statistical data there exists the option to examine the statistics of the possible future shoreline behaviour in more detail. For example, percentiles of shoreline position can examined, and risk (a product of probability and consequence) determined. Indeed, the progression of this application would readily lead itself towards the implementation of a flood risk assessment for the Villaggio del Golfo. The Section 3.9.3 below describes how the RASP-SU (structured uncertainty) methodology has been enhanced to accommodate UnaLineaProb.
Figure 3.21 Minimum, mean and maximum shoreline positions reached under probabilistic simulation of the shoreline evolution given present-day fluvial sediment loading augmented by several different artificial nourishment programmes.

3.9.2 Rapidity of UnaLineaProb

Of continual concern throughout this initial development of UnaLineaProb was the amount of time required to provide convergence when operating in probabilistic mode in order to maintain its rapid nature. The writing and reading of files during model execution is unavoidable at present, and is responsible for much of the processing time required. To give some idea of the rapidity of the model, the 5-year deterministic simulation shown in Figure 3.18 took approximately 1s to complete.
The probabilistic simulation required 300 iterations to reach a 2% convergence level on the variance of the mean beach position after 5 years. These 300 deterministic realisations required 18 minutes of processor time. It is noteworthy that the storage of the histogram information adds significantly to the overall run-time for convergence (a single deterministic run, for example, requires less than 1s), and a more selective process for histogram generation may reduce this processing time further.

For comparison, this probabilistic model was recently applied (January 2011) to a geomorphological model study for the EA at Pagham East Beach. The model was only 2km in length, and information about the likely short-medium term changes in shoreline position was key – so a 5 year epoch selected. There were no cliffs involved, and the model examined the impact of variations in drift rates, onshore feed and boundary conditions. In this case (ie no requirement for histograms), the probabilistic model required less than 15s to converge using an Intel Pentium Duo Core 1.8GHz laptop processor.

3.9.3 Enhancement of RASP-SU

Beach Toe level is considered to be a static feature in RASP, with most of the RASP principles developed for fluvial applications where embankments etc. are considered to be static in FRA. Beach levels at the toe of a seawall, however, can be constantly varying due to morphological changes both in the short term and the long-term. The research presented above is an efficient and effective means, exploiting both deterministic and stochastic methods, for describing the behaviour of the beach at the toe of a seawall at broad-scale.

The Environment Agency (EA) relies heavily upon their National Flood Risk Assessment (NaFRA) to support flood risk and investment decisions at all levels. However, it is important to understand the uncertainty associated with model results in order to confidently make decisions which rely upon them. This was recognised by the NaFRA programme managers in 2007, who approved funding for the development of a new version of the RASP model to specifically quantify uncertainty in the RASP results. The model, known as RASP-Structured Uncertainty (RASP-SU) (formerly known as RASP-MC) performs a staged Monte-Carlo analysis using the RASP HLM+ model to propagate uncertainty in model input parameters and model structure functions through to the uncertainty in the final risk results.

In addition to the forward propagation of uncertainty, the model is based upon a variance-based sensitivity approach that allows for the backward propagation of the uncertainty to individual parameters. This enables the quantification of sensitivity to each individual variable of structure function considered in the uncertainty analysis. The RASP-SU software provides an insightful tool to support the decision making process within flood risk management.

RASP-SU allows for the uncertainty to be expressed in all of the key input parameters to RASP, however it was not previously possible to explore the uncertainty due to the toe level of coastal defences (ie the beach level at the toe of the defences). Under the current project, the RASP-SU software was extended to include the consideration of uncertainty in defence toe levels, alongside all of the previously available uncertainty.
parameters. This allows the RASP-SU model to be directly compatible with the results from the previously described UnaLineaProb model.

For the case study, all uncertainty parameters and model structure functions were fixed at their typical NaFRA values with the exception of defence toe levels which were obtained from UnaLineaProb. Figure 3.22 shows a flow chart of the processing workflow. This is described in further detail below.

![Flow chart of the processing workflow](image)

**Figure 3.22 Flow chart of the processing workflow**

The RASP-SU model run is performed in series of stages in order to optimise the computational burden of running a full variance based sensitivity analysis on many dozens of possible input parameters within a full flood risk model. The SEAMaT GIS framework manages the operation of each stage after the UnaLineaProb model run has been completed.

The first stage of the RASP-SU model run, is a probabilistic overtopping calculation. This is the component of RASP-SU that has been extended for accommodating the
defence toe-level distributions. The UnaLineaProb model yields a distribution of beach levels for each model node for every year of its simulation. After the UnaLineaProb model run completion, SEAMaT writes these results into the RASP-SU model database and then commences the RASP-SU Stage1a model.

The RASP-SU Stage1a model uses a look-up table to match the UnaLinea model nodes with their corresponding RASP defence lengths. RASP-SU samples a toe level value and then the Protop model samples from the variables used in the overtopping calculations to produce a probabilistic distribution of overtopping volumes for the failed and non-failed conditions and a distribution of expected volume.

RASP-SU Stage 1b is a pre-processing stage run using the RASP Economic Pre-processing tool. This produces distributions of damage given depth for each Impact Zone. Within the case study at Holderness none of the parameters within stage 1b were given as distributions and therefore no detail is provided here for this stage of the RASP-SU model.

Stage 2 performs the sampling of system state, sampling of volume, spreading of flood water and calculation of the damage. The Stage runs this analysis for all return periods and calculates EAD. It then repeats this process many thousands of times until the mean EAD converges on a stable value.

After the RASP-SU model run has concluded, SEAMaT imports the principal statistics for the key model results to the SEAMaT database and loads them into the map. These are:

- Defence toe level (per year)
- Defence overtopping volume (per return period)
- Impact Zone depth (per return period)
- Impact Zone damage (per return period)
- Impact Zone risk (EAD).

Previously, running the RASP-SU model was a complicated process that could take the experienced user many weeks to build a model, run the analysis and map the results. A significant part of the analysis has now been automated within SEAMaT making this task a much quicker and more reliable.
4 Pilot study site: Holderness

It is acknowledged that the nature of the Holderness coastline (Figure 4.1) is far more complex than that accounted for in this proof-of-concept study. Indeed, the uncertainty surrounding even the longshore drift rates renders an accurate model of the site improbable at this stage. Instead of aiming to represent the actual processes governing the evolution of the Holderness coastline, therefore, the model application reported is one which demonstrates the functionality of the modelling methods derived only. Any numeric or currency values quoted are not considered to be anything other than demonstrative. It is thought, however, that not only is the site a potentially interesting one from the point of view of demonstrating the concept of underlining erosion- and flood-risk models, but that it is also pertinent to include a description of the processes that are thought to be occurring along this stretch of coastline. This description has been extracted from Appendix 11 HR Wallingford (2002).

Figure 4.1 Location map of the Holderness coastline showing relief, backshore character and longshore extent of the regional-scale under-lined modelling system

4.1 Description of the coastline

The indented coastline of Flamborough Head is replaced to the south by the smooth curving coastline of Holderness (Figure 4.1). A significant amount of work has been done on describing and quantifying the development of this coastline, conversely, relatively little has been done on determining drift rates. The Holderness coastline
from Bridlington to Kilnsea has very high rates of erosion, due to the boulder clay outcropping at sea level. 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. Both cliffs and shore-face are eroding, while the shore-face has a relatively thin layer of sediment overlying till (which can erode by abrasion). This till is often exposed.

The Holderness beach profile can be classified as an example of Sunamura’s (1992) Type-A, where the rock resisting force is less than the assailing force and the shore platform extends below low water without a break. Wingfield and Evans (1998) point out that Holderness is different from a typical type-A:

- The coast is cut into soft rock, so the erosion rates are very high.
- Cliff erosion takes place by destabilization.
- The shoreface only acquires a sparse and varying supply of sediment to form a beach (except for the extensive South Smithic Bank). Wingfield and Evans (1998) attribute this to the following three reasons. Flamborough Head acts as a barrier to sediment transport from the north. The northern third of the coastline (around Bridlington) has only 70% of the retreat rates shown further south. The sediment supply produced by erosion is transported rapidly south. The youth of the eroded rock means it is unlikely that the surfaces are antecedent from older cycles of sea level changes.

Wingfield and Evans (1998) also give figures for the average gradients for the shoreface ramp and the seabed seaward of the shoreface ramp along four profiles. The shoreface ramp extends out to between about 11m and 14m below MHWS and the seabed seaward of the shoreface ramp out to 10km offshore was included, where the depth was between 24m and 28m. These gradients are given in Table 4.1.

| Table 4.1 Gradients of the shoreface ramp and seabed seaward of it for Holderness |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| Barmston                        | Hornsea         | Tunstall        | Dimlington      |
| Gradient of shoreface ramp      | 1:133           | 1:118           | 1:179           | 1:78            |
| Gradient of seaward seabed      | 1:708           | 1:833           | 1:476           | 1:708           |

Estimates of erosion from several studies are given in Balson, Tragheim and Newsham (1998). They conclude that about 1/3 was from cliffs and about 2/3 was from the shore-face. The average rate of erosion from a number of studies yields 3.2_{10^6}m^3/year. Wingfield and Evans (1998) estimate average erosion rates of 18m^3/m/year for the cliff, 26m^3/m/year from the shoreface ramp and provide estimates of rates for deeper water than that as well. One of the most comprehensive studies of the rate of recession of the Holderness cliffs was made by Valentin (1954, 1971) using Ordnance Survey maps. Valentin suggested that the average recession rate was 1.2m per year but that the rate increases southwards in response to energy input from wave action from the north, as shown by the following averaged rates:

- Sewerby (Bridlington) to Earle’s Dyke: 0.29m/year
- Earl’s Dyke to Hornsea: 1.10m/year
Hornsea to Withernsea: 1.12m/year
Withernsea to Kilnsea Warren: 1.75m/year

The behaviour, transport pathways and sinks depend on particle size and composition. However, the composition varies along coast, as well as the cliff height and recession rates. Balson et al. (1998) reported that the average composition is 74% to 84% silt/clay, 10% to 15% very fine sand, 5% to 10% coarse sand and 1% boulders. Wingfield and Evans (1998) note that about 80% of the sediment released is mud (silt and clay) transported in suspension and distributed throughout the North Sea (with some entering estuarial budgets). Approximately 1% is large gravel and cobbles that help form the ribs or ords along the Holderness coastline. Therefore approximately $6.4 \times 10^5$ m$^3$/year of fine sand or coarser is released between cliff top and base of wave action (about 15m depth). The sand is transported by waves and tides to form mobile beaches or sand banks (notably South Smithic) or is transported south towards Spurn Point.

Maddrell, Home, Thurston and Rennie (1999) have analysed bathymetry at Holderness. The offshore part of their analysis (about 20m contour) always showed erosion. They suggest that recession rates may be governed by on/off-shore sediment transport as much as longshore transport at the beach.

The lithology of the cliffs makes them highly susceptible to erosion. The weakly consolidated boulder clay consists of a clay matrix containing a mixture of coarse sediments and pebbles. Erosion takes place intermittently and at variable rates by mass movement as a result of sub-aerial weathering processes. Alternative wetting and drying of the clay leads to cracking, rotational slips and slides. Surface cracks and potential slips are seen at the cliff top. Dislodged material is quickly removed from the base of the cliff by wave attack, so steepening and destabilising the cliff face. The result is that the cliff top recedes intermittently and irregularly as a series of bights.

Most of the cliff line is unprotected by coastal defences. Where these have been built (e.g. at Withernsea and Hornsea) rates of erosion are locally reduced and groyne systems have been successful in capturing sand and maintaining beach levels. This is also clearly visible in Valentin’s recession rates (as shown by Balson et al 1998). However, as a direct result, erosion is severe immediately to the south or 'downdrift' of these frontages.

The rate of cliff erosion not only relates to the wave exposure. The configuration of the beach also plays an important role. Erosion is accelerated with the passage of pronounced runnels (locally known as ords) parallel to the cliff base. These features are a marked characteristic of the sandy beaches along the east coast of Holderness and Lincolnshire. Between Barmston and Spurn Head as many as ten ords may exist. Once developed, they migrate southwards as a continuous system under north and north-easterly wave conditions. The fact that ords are not found north of Barmston may be due to the sheltering effect of Flamborough Head. The precise mechanism for the development of ords is not known. Studies have shown that the 'normal' beach profile is modified by the presence of an ord. The lower beach widens and, as a ridge
of sand gradually moves landwards, it encloses a water-filled runnel at the foot of the cliff, often exposing the boulder clay platform to erosion.

The beaches fringing the Holderness coastline are narrow and consist of a thin veneer of material only 1-2 m thick over the shore platform. If longshore transport models do not take into account the limited volume of sediment that is available to be transported, they can overestimate the longshore transport rates by modelling the longshore transport of sand where there is actually solid shore platform. Such transport rates are referred to as potential sand transport rates.

Exchange between the beach and nearshore zones takes place as a result of beach drawdown under storm wave conditions and onshore movement in calmer conditions. Such exchanges may be important in the development of ords but there appears to be no long-term source of beach material from offshore, rather the opposite may occur. The beaches between Barmston and Hornsea are relatively low and narrow with the clay substratum being frequently exposed. The open exposure of this stretch of coast means that there is high potential for alongshore movement of sediment both northwards and southwards. The net effect of wave action is a southward transport of sand along the whole of the Holderness coast.

The rapidly eroding boulder clay cliffs of the Holderness coast terminate near Kilnsea. At Kilnsea Warren the boulder clay surface drops below sea level and is overlain by wind blown sand. The sand deposits extend southwards as a result of the pronounced southward net littoral transport. They terminate at the distal end of the spit feature of Spurn Head.

The continued existence of the Spurn peninsula depends heavily on the supply of material from the erosion of the Holderness cliffs. Much of the cliff material is clay; the sand content and hence the southward sand transport is limited in volume. The neck of the spit is quite narrow and the dunes are only a few metres high. There was a severe breach of the dunes (but not the underlying clay till) in 1996 that was quickly filled with concrete rubble. Other wash-over events have taken place recently in this area which can disrupt the road, despite the reinforcement of the backshore with imported “earth”. IECS (1992) reports that Spurn is eroding at the root and has rotated by 17º between 1824 and 1990. Further south the spit widens to form a spatulate shape and there the sand dunes are healthier and considerably higher. Breaches of the underlying clay till to form channels are very rare with the last significant breach of this type occurring half way down the length of Spurn in 1849 (de Boer, 1964). A description of the development of Spurn Point over the Holocene is provided in Binnie, Black and Veatch (2000).

4.2 Estimates of longshore drift rates
No study has systematically modelled the variation in wave conditions or drift rates from Flamborough Head to Spurn Point. However, a number of studies have estimated drift rates at particular stretches of the coastline. The studies and their estimates of drift rate are given in Table 4.2.
Table 4.2  Longshore drift rates at Holderness

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<th>mE</th>
<th>mN</th>
<th>Name</th>
<th>Dir</th>
<th>Q [m$^3$/yr]</th>
<th>Type</th>
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<td>45000</td>
<td>Tidal</td>
<td>IECS (1991)</td>
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NS = transport rate not specified – only average direction due to tides specified.
* = average of two numbers
** = average of four numbers

4.3 Discussion of longshore drift

The models with sediment transport driven by waves only (Table 4.2) all show drift rates to the south, although there are no estimates of wave-driven transport between Bridlington and Flamborough Head. The HECAG SMP (Posford Duvivier, 1998) states that the sheltering effect of Flamborough Head allows a longshore drift from south to north, causing changes in the beach level and shape to the north of Fraisthorpe (between Barmston and Bridlington). Posford Duvivier’s (2000) modelling at Bridlington gave a strong north to south drift at the town, so northwards drift towards Flamborough Head is likely to be limited to the section between Bridlington and Flamborough Head. Northwards drift that gets close to Flamborough Head may be transported offshore into Smithic Bank by the tidal re-circulation to the south of the headland.

The sediment transport studies that used tides and no waves indicate that the nett tidal residual transport is to the north between Bridlington and Hornsea, but to the south from Tunstall southwards. These studies did not claim that this was the nett direction of motion – rather they provided an estimate of the tidal influence in a region dominated by wave-driven transport. The reason for this change in direction is the influence of Flamborough Head, which creates a circulation pattern behind it during the southwards flowing tide. This result was also obtained during the PISCES coastal area modelling for the Southern North Sea Sediment Transport Study (HR Wallingford, 2002).

There are two estimates of sediment transport rates from observations of morphology. These are considered to provide unreliable magnitudes of sediment transport, but their directions are considered reasonable, as they are consistent with other transport directions. HR Wallingford has produced three results for the longshore transport rate
of sand for the same cross-shore profile at Hornsea. The three estimates (from lowest to highest) are given for sediment transport out to 150m from the top of the beach, down to the 10m contour and down to the 15m contour (approximately the base of wave action). They differ by an order of magnitude and illustrate the difficulty in determining a longshore transport rate. In this case, BGS facies data indicates that there is no sand further than about 1500m from the coastline. This corresponds to approximately the middle option ($58,000m^3/\text{year}$).

This degree of uncertainty, or lack of corroboration, regarding the likely longshore drift rates along Holderness has caused the calibration of the integrated Pilot Study model to be only marginal. A general nett southerly drift of sediment is induced in the model, though a nett northerly element also occurs where the orientation of the shoreline induces it. This is not considered to be an issue in the context of this proof-of-concept application, and further calibration would be required if it were desirable to consider the output as predictive.


4.4.1 Derivation of wave climate

As with the representation of longshore drift in the shoreline evolution model, only cursory attention has been paid to the derivation of the wave climate and this is considered appropriate to drive the proof-of-concept application presented in this study at this stage. A back-tracking ray model was used to hindcast 13 years of 3-hourly wave climate data from using wind data from Gorleston: 1978 to 1991 (Figure 4.2).

This data was processed as described in Section 3.4.8 above to provide a 13-year time-series of daily morphological events with which to drive the UnaLineaProb probabilistic shoreline evolution model. To achieve better representation of local conditions in this regional-scale modelling procedure, UnaLinea provides the capability to consider multiple wave points such that interpolation of wave conditions along the coastline of interest is feasible. For this proof-of-concept application, however the resulting morphological events are assumed to be constant in space (though variable in time), and this may lead to some unexpected behaviour of the shoreline.
4.4.2 Construction of model domain
A reasonably accurate representation of the model domain was required, and this included the incorporation of data pertaining to:

- Sediment size (estimated from Sutherland et al. 2002)
- Water levels (Admiralty)
- Extreme overtopping rates (Environment Agency’s MDSF2 National Coastal Extremes Database)
- Beach gradients (analysis of East Riding of Yorkshire beach data)
- Berm levels (analysis of East Riding of Yorkshire beach data)
- Initial shoreline position (OS Map, MHWS)
- Initial cliff-top position (digitised from ortho-rectified aerial photography)
- Cliff elevation (Environment Agency’s Composite DTM data (based on LiDAR))
- Groyne locations (ortho-rectified aerial photography)
- Seawall locations and properties (Environment Agency, National Flood and Coastal Defence Database)
- Flood-spread model impact zones, cells and neighbourhood volumes (Created using HR Wallingford’s RFSM pre-processing software)
- Property data (Environment Agency’s National Receptor Database)
- Depth Damage Tables (Flood Hazard Research Centre Multi-Coloured Manual).

Figure 4.1 shows the model domain, and summarises the backshore character along the coast. Figure 4.3 presents an example of locating some of the existing groyne positions within the regional model, while Figure 4.4 shows an example of differentiation between the backshore character. This “flagging” has a bearing on the
process modules utilised in the modelling procedure. Once these data are registered within the GIS database, the model control files are automatically built.

Figure 4.3 Locating existing groyne fields within the GIS for inclusion in the modelling task
4.4.3 Model operation

A flow-chart of the underlined erosion- and flood-risk modelling procedure is given in Figure 3.22. The model runs are initiated from forms accessed within the GIS. Probabilistic shoreline evolution modelling together with RASP-SU is one of the run options, albeit the most advanced and essentially represents the underlined erosion- and flood-risk modelling process.

To run a model, the user must first create and import the input data necessary to for the model to operate. Since the modelling sequence described here includes a coastal model with cliff erosion and backshore toe level analysis coupled with a flood risk model it is necessary to perform a significant amount of model pre-processing. Much of the pre-processing was undertaken using ArcGIS standard tools although for efficiency, some of the RASP pre-processing suite of tools were used to build the RASP-SU models (eg the Accdata program was used to construct the rapid flood spreading model (RFSM) and the Economic pre-processing tool used to create the depth versus damage input tables.)

The model input data were organised in two databases; an ESRI Personal Geodatabase implementation of the SEAMaT datamodel, described in Section 3.2, was used to store the coastal model, the model configuration variables and default parameters, while a SQL server database was used to store the RASP-SU data.
To run the model, the user first specifies the SEAMaT database to use and then opens the SEAMaT graphical User Interface (GUI) which guides the user through entering all of the specification for the particular model run. Some example screenshots of the GUI are shown in Figures 4.5 and 4.6.

![Figure 4.5 Example screenshot of software](image1)

![Figure 4.6 Example screenshots of user-friendly GUI used to configure and initiate a model run](image2)

Once the model run has been initiated, the SEAMaT software controls all of the model operation and manages the results while keeping a detailed record of the input variables entered by the user and configuration variables used for the model run. After the model run has been completed, the results are added to the GIS map enabling the modeller to quickly visualise the shoreline and cliff positions, the defence toe levels and overtopping volumes, and the Impact Zone depth, damage and risk. The statistics and percentile results for these outputs are held in the SEAMaT database enabling the uncertainty in these to be explored.
4.5 Results from underlined erosion- and flood-risk

As has been previously suggested, the model application presented here is a proof-of-concept only, and the results should therefore not be taken literally. Nevertheless, it is important to demonstrate the range of model capability that has emerged from this research. Model findings are all based on a single-scenario test, and relate to the statistical behaviour of a groyned shoreline as a first-line of defence. This defence is then backed by a mixture of seawall and soft-cliffs, and the cliffs interact with the beach through event-based failures. The statistical performance of the seawall as a defence is then examined, and the results from the Risk analysis are mapped for dissemination.

4.5.1 Probabilistic shoreline evolution

For clarity, Figure 4.7 shows a portion of the probabilistic shoreline model results at the southern end of the Hornsea defences, though the standalone GIS application provides these detail throughout the entire model domain facilitating examination of model output. The mean shoreline position at the end of each 10-year realisation is shown together with the minimum and maximum shoreline positions occurring during the convergence of the model. It is important to realise that the maximum and minimum lines are not necessarily indicative of concurrence, but may have happened at any time throughout the probabilistic simulation. Note that where the shoreline is seen to pass landwards of a seawall, this shoreline is considered to be virtual, and indicates a lowering of the beach level at the seawall itself rather than a recession of the tracked contour.
The terminal groyne at the southern end of Hornsea is shown to induce localised recession of the shoreline, and in effect, a potential lowering of the beach where there is insufficient beach volume as well as the potential to allow cliff recession. The modelled littoral drift regime provides sufficient continuity of beach volume to afford natural protection to the cliff further south where the beach volume is seen to increase.

4.5.2 Cliff recession
Figure 4.8 shows how the shoreline response presented above exposes the cliff to the possibility of failure, and there is localised recession of the soft-cliff in this vicinity. The volume of material lost from the cliff is added to the beach, and this, together with the modelled littoral drift regime, is sufficient to sustain an adequate beach volume further south such that the cliffs there are not likely to undergo significant recession.
Figure 4.8  Representation of the modelled probabilistic behaviour of the cliff at the southern end of the Hornsea defences throughout a ten-year period

4.5.3  Rapid flood-spread modelling

Figure 4.9 shows the extent of the Rapid Flood-Spread Model (RFSM) adopted for this research and development. The model was developed for the NaFRA ’08 study (Lhomme et al) and has been enhanced using Environment Agency data relating to properties and the terrain obtained during this research programme. Also apparent in Figure 4.9 is a more extensive view of the shoreline behaviour at Hornsea, and where the shoreline is seen to travel landwards of the seawall, this is indicative of a long-term tendency for a lowering of the beach levels at its toe.
Figure 4.9  Extent of the Rapid Flood Spread Model (RFSM) utilised in the process of underlining

The RFSM domain extends through Hornsea, and is bounded to the north south and west with higher ground. The domain is divided into impact zones and is bounded in the east by a seawall. Figure 4.10 shows a clearer view of the impact zones in an area selected for further presentation of modelling results. Impact Zone 471 is highlighted for continuity of result presentation throughout this report.

Figure 4.11 shows the properties in the model database, and defines defence lengths. In this instance, each coastal model node is assigned its own defence length, and each defence length therefore carried its own dedicated description of the statistical behaviour of the beach. Figure 4.12 shows a summary of the statistics of the beach toe level for defence lengths which are likely to affect the flooding of Impact Zone 471. This particular example suggests that the health of the beach (ie it’s volume) is likely to increase with time. The RFSM model has details regarding each defence length in its database, and these details include crest levels, extreme forcing conditions and histogram of toe level behaviour – elements which are all required to complete the flood modelling. Figure 4.13 presents a plot of the mean flood depth in a range of Impact Zones for the underlined model simulation.

In terms of the RASP-SU (structured uncertainty) aspect of the model, this scenario represents certainty in all parameters except the level of the beach at the toe of the wall, where the uncertainty of this parameter is contained within the histogram of toe-
levels obtained from the probabilistic simulation of the shoreline behaviour discussed in Section 4.5.1 above. Values of flood depth for other return periods as well as minimum, maximum and standard deviation values are also shown for Impact Zone 471 in Figure 4.13. The GIS database, however, contains this information for all Impact Zones that have flooded and these values can also be plotted.

The RFSM also derives information regarding the volumes of water spreading throughout the model domain, for example, and on the expected damage (EAD) throughout the domain. Figure 4.14 shows the expected damage plotted for the locality of Impact Zone 471, and tabulates the cost of damage expected for Impact Zone 471 for a range of return period events.

Figure 4.10 Detail of Rapid Flood Spread Model impact zones at the coast, highlighting Impact Zone 471
Figure 4.11 Detail of property within Impact Zone 471, and definition of defence lengths
Figure 4.12 Statistical summary of toe level behaviour for defence lengths likely to influence the flooding of Impact Zone 471. The table pertains to defence length 19.
Figure 4.13 Detail of flood depth within and surrounding Impact Zone 471(highlighted) for a 1000yr return period event
Figure 4.14 Detail of expected damage (£) surrounding Impact Zone 471 (highlighted) for a 1000yr event
5 Conclusions and Recommendations

This report documents the research undertaken in developing methods to link the broad-scale behaviour of the beach to the reliability and performance of shoreline defences, cliff erosion and flooding of the coastal plain with associated impacts. The research provides improved support to the management of open and defended coastlines taking account of both erosion- and flood-risks and the interactions between the two. Looking forward there is a clear uptake pathway for the research through the on-going development and rollout of the RASP family of tools (in particular it is expected to underpin the development of an integrated coastal- and flood-risk asset management tool.)

The research has resulted in:

1) An overview of the current methods used to assess broad-scale coastal erosion- and flood-risks.

2) Development of a GIS database system capable of managing the complex tasks of model set-up, model execution and associated data management.

3) Descriptions of the numerical scheme-based experiments employed to develop a very rapid and robust deterministic shoreline evolution model.

4) Monte Carlo simulation engaging the very rapid shoreline evolution model as a tool capable of describing the expected future shoreline behaviour in a stochastic manner.

5) Further investigations into maintaining rapidity of model execution through the filtering wave input to provide morphologically-averaged conditions.

6) Investigations into the seasonal behaviour of beaches with a view to incorporate the influence of short-term beach response in the assessment of long-term erosion- and flood-risk.

7) Exploitation of the probabilistic shoreline evolution model capability within the RASP-SU (structured uncertainty) suite of models.

8) Prototype proof-of-concept software demonstrating the underlining of erosion- and flood-risk models along the Holderness coastline.

The research has demonstrated a practical and credible approach to integrating regional coastal erosion- and flood-risk assessment within the structured uncertainty framework of the RASP methodology. This is a significant advance on current approaches, enabling the effectiveness of a beach as a defence (both as a flood defence and protection to an eroding cliff) to be incorporated, replacing the current approach that simply uses a user defined toe level within the assessment of flood-risk and ignores the erosion risk. The ability to consider the beach as a dynamic rather than static defence system, and thereby assigning coastal erosion-risk, is a significant step forward on the path of asset management.
In the process of generating the proof-of-concept presented in this research report, a series of elements requiring further investigation have become apparent. These elements are varied in their nature, ranging from process-based investigations through practical issues to philosophical questions relating to the future applicability of the integrated modelling capability. It is beyond the scope of this research to prioritise and describe these elements in any great detail, though it is important that any future developments consider the full range in their planning. Nevertheless, these issues lead to the specific recommendations made below:

- To improve upon the representation of seawalls within UnaLinea whilst maintaining rapidity of model execution.

- To broaden the base from which model data can be gleaned. At present, for example, the wave conditions are hindcast through application of a back-tracking ray model. The rapidity of this method is appropriate, but the public availability of this model is restricted.

- To extend the capability of the GIS system to manage the models so that the influence of climate change expectations can be accommodated.

- To increase the capability of UnaLineaProb such that it can account for the influence of a more complete range of coastal structures in its description of the probabilistic behaviour of the shoreline. This should include, but not be limited to, detached breakwaters. Ensuring model rapidity should be a priority in this process.

- To increase the modularity of UnaLineaProb so that it can accommodate a wider range of back-shore types such as dunes and barrier beaches. Ensuring model rapidity should be a priority in this process.

- To further streamline the model operability and data management either within the GIS, as developed to date, or through some other user-orientated interface. Ensuring model rapidity should be a priority in this process.

- To investigate the possibility of the process-based models “self-calibrating”. The advantage of the GIS database development would become more apparent if models were to execute their own calibration. The management and quality control of measured data within the GIS is a skill that is reasonably well-advanced, indeed the GIS was developed for this purpose. The operation of models and management of model-origin data within GIS is a relatively new art, but with this data sitting side-by-side with quality measured data there exists the opportunity to readily exploit the existence of both. Once calibration had been achieved, the models would even be able to inform the user how “skillful” it had been and an objective measure of confidence assigned.

- To investigate the value of the underlined risk models as a tool for consultants and practitioners in the field of coastal asset management. This should incorporate a consultation exercise, a programme of development aimed at
scenario testing with a view to optimisation of coastal management practice in the light of flood-risk assessment, and a detailed dissemination plan.

- To pilot the integrated flood and erosion risk model at a national scale - replacing the existing spate process of NaFRA and NCERM with a single integrated model (enabling better data sharing between models and importantly enabling the interactions between coastal flood and erosion risks to be captured).

## 6 Route to uptake

The pilot software for Holderness was critically reviewed by Halcrow Group Limited to assess the applicability of the tool from an industry perspective. The review is presented in Appendix D. Unfortunately the reviewers focussed very heavily on the user friendliness of the prototype tool rather than on the concept that it demonstrates. In addition to a number of conclusions addressing the installation procedure, lack of user-manual and reliance upon the software developers to build and configure the prototype, the following conclusions were made:

- “Run time was long (several hours) on the default setting” The default setting is normally optimised prior to installation of the modelling tool to gain accurate results with minimal run time. This procedure was not undertaken for the prototype that Halcrow tested. However, when starting a model run, the user is offered the simulation settings and is able change them prior to commencing the simulation. By changing these settings, good results can be achieved with a five to ten minute run-time. Fixing these simulation settings as the new defaults is made by editing a table in the GIS.

- “In the trial…”, “…a uniform grain size”, “…a single wave data point”, “…two sediment transport formulae were used” These were all simplistic aspects used for the prototype site for demonstration. They are flexible aspects that can and would be specified differently for each model site as validation is undertaken.

- “Allow defence deterioration over time”. The model currently calculates the flood risk for present day defence condition. The authors agree that incorporating defence deterioration would be a useful addition to the functionality.

- “It would be useful to include other hard defence types in the future”. The authors agree that further development to include more coastal defence types would beneficial.

- “Calculation of erosion rates...” and “overview of the sediment budget would be useful” These are calculated at run-time but not captured in the database and presented to the user in the GIS. It would be straightforward to capture these data while the model is running to provide the user with more useful information about the model simulation.

- “The software currently allows the joint consideration of coastal erosion risk and flood risk. This is useful in instances where management policies are being developed for eroding cliff areas which may impact on beach levels down drift,
thus impacting on flood risk. The potential exists for the economic costs and benefits of different options to be assessed”

- “The software has the potential to assist in the prediction of coastal response, under different management regimes, over timescales of 10 to 20 years; therefore if the tool were set up and accurately calibrated then it would be potentially useful to Shoreline Management Plans and Strategy Plans to support baseline scenario assessments and options development.”

The research has demonstrated a practical and credible approach to integrating regional coastal erosion and flood-risk assessment within the structured uncertainty framework of the RASP methodology. It is clearly of great benefit to the practitioner to be able to capture the function and performance of the beach and cliff system within coastal flood risk models.

The MDSF2 tools, as used for National Flood Risk Assessment and soon to be used for scheme appraisal, long term strategies and local flood risk studies presently incorporates RASP methods to perform probabilistic flood risk modelling and tools to assess the losses to property and agriculture associated with shoreline erosion. The adoption of the modelling approach developed within the present research into the MDSF2 tools would address two shortfalls in the current tools.

1. There is presently no modelling facility for creating cliff erosion contours. Users must generate these outside of the MDSF2 tools and import them in order to calculate economic losses due to coastal erosion. Inclusion of the UnaLineaProb shoreline evolution and cliff recession model would allow the user to undertake cliff erosion modelling within the MDSF2 software, providing for better integration of the modelling tools and therefore better reliability and consistency in the modelling approach used for SMPs and coastal strategies.

2. The coastal defences are considered in MDSF2 as fixed structures without consideration of the mobile nature of the beach environment and implications that this has on coastal defence performance. A single value is presently used (often crudely estimated) for the defence toe level and this value is used to determine overtopping rate and hence inflow volumes. Inclusion of the UnaLineaProb and RASP-SU modelling approach would enable a probability distribution of defence toe levels to be modelled from which the flood risk model can sample values. This would represent a significant improvement in the MDSF2 tool. Rather than using a single value for defence toe level, the flood risk model could take into consideration the uncertainty associated with this potentially highly variable property of the coastal defences via consideration of a range of overtopping rates depending upon the potential variations in beach levels fronting the defences.

As described, there would be clear benefits in the uptake of the modelling approach into the MDSF2 tools, which would allow the tools to be used to support a wider and more complete range of integrated modelling studies at the coast. With the EA currently in the process of developing a new defence asset database system, flood modelling tools and investing in better underlying datasets, the timely uptake of the
current research into the new generation of Environment Agency models could be of significant benefit.

7 References


Stripling, S. Panzeri, M., Kemp, J., & Brampton, A. "Broad-scale morphodynamic shoreline modelling within a standalone GIS coastal management tool: GTI-SEAMaT" *Proceedings of Institute of Civil Engineers International Conference on Coastal Management*, 31 October to 1 November 2007 pp119-129.


Appendices
Appendix A

Beach profile graphs
Beach profiles

**Summer**

**Winter**
Super Work Package 4: Infrastructure Management
FRMRC Research Report SWP4.3

Work Package 4.3: Broad Scale Integration of Coastal Flood and Erosion Risk Models 23/05/2011

P041
Summer

P041
Winter
Appendix B

Beach profile envelopes
Beach envelopes

Beach Envelopes

P038

P039

Winter High
Winter Low
Winter Midpoint
Summer High
Summer Low
Summer Midpoint
Beach Envelopes

P040

P041
Beach Envelopes

P042

P043
Beach Envelopes

P044

P045
Beach Envelopes

P046

P047

Elevation (mOD)

Chainage

Elevation (mOD)

Chainage

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Beach Envelopes

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Each line represents different elevation stages over chainage for summer and winter conditions.
Appendix C

Beach profile gradients
### Beach profile gradients

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Work Package 4.3: Broad Scale Integration of Coastal Flood and Erosion Risk Models 23/05/2011
Appendix D

Critical Review of the Integrated Modelling System for the Pilot Site at Holderness