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Development of an Integrated Soft Cliff Model to Determine the Impacts of Environmental and Climatic Change on Coastal Recession

by

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ABSTRACT

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DEVELOPMENT OF AN INTEGRATED SOFT CLIFF MODEL TO DETERMINE THE IMPACTS OF ENVIRONMENTAL AND CLIMATIC CHANGE ON COASTAL RECESSION

Natasha Elizabeth Carpenter

Understanding soft cliff systems is a significant challenge owing to the complex recession process and the need to quantify future responses to climate change. Process-based geomorphic modelling provides a key method for developing our understanding. However, existing models are frequently criticised for their simplified treatment of the cliff. Therefore, the overriding aim of this research was to contribute towards the development of a more integrated model. To facilitate this, this research has applied, evaluated and refined the SCAPE (Soft Cliff and Platform Erosion) model to a study frontage of variable lithology and coastal planshape on the south west coast of the Isle of Wight (UK). The initial model appraisal highlighted the need to further understand and quantify the role of variable material strength on shore platform geomorphology and rates of cliff toe retreat. The model was subsequently refined and demonstrated that outcropping layers of variable material resistance about mean sea level are a key control on the rates of cliff erosion, particularly for low sediment frontages. Weaker layers were found to result in an asymmetric increase in retreat in comparison to a more resistant layer of the same characteristics owing to the contrasting effects on the shore platform slope. This emphasises the importance of not extrapolating historic rates of retreat across frontages of variable lithology. Coastal management studies must consider relative changes in material resistance up the cliff face, the thickness of variable layers and the rate of sea-level rise to determine the magnitude of impact and duration of exposure.

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List of accompanying materials

- CD of associated publications:
    - Carpenter, N. E., Stuiver, C., Nicholls, R.J., Powrie, W., Walkden, M (2012). Investigating the recession process of complex soft cliff coasts: An Isle of Wight case study. Proceedings of the 33rd Conference on Coastal Engineering. P. Lynett and J. Mckee Smith. Santander, Spain, ICCE.
    - Carpenter, N. E., Nicholls, R.J., Powrie, W., Dickson. M.E (2013). Development of a process-based model to understand the effects of variable lithology: An Isle of Wight case Study. Coasts, Marine Structures and Breakwaters. Edinburgh, UK, ICE.
    - Carpenter, N. E., Dickson, M.E., Nicholls, R.J., Powrie, W (In Review). Investigating the effects of varied lithology on soft cliff geomorphology and recession rates. Marine Geology (Submitted December 2013).
    - Carpenter, N. E., Dickson, M.E., Nicholls, R.J., (In Review). Understanding the Role of Varied Lithology on Soft cliff planshape evolution under high and low sediment availability. Earth Surface Processes and Landforms (Submitted January 2014).

DECLARATION OF AUTHORSHIP

I, Natasha Elizabeth Carpenter declare that the thesis entitled *Development of an Integrated Soft Cliff Model to Determine the Impacts of Environmental and Climatic Change on Coastal Recession* and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research. I confirm that:

- this work was done wholly or mainly while in candidature for a research degree at this University;
- where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
- where I have consulted the published work of others, this is always clearly attributed;
- where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
- I have acknowledged all main sources of help;
- where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
- Parts of this work have been published as:
    - Carpenter, N. E., Stuiver, C., Nicholls, R.J., Powrie, W., Walkden, M (2012). Investigating the recession process of complex soft cliff coasts: An Isle of Wight case study. Proceedings of the 33rd Conference on Coastal Engineering. P. Lynett and J. Mckee Smith. Santander, Spain, ICCE.
    - Carpenter, N. E., Dickson, M.E., Nicholls, R.J., Powrie, W (In Review). Investigating the effects of varied lithology on soft cliff geomorphology and recession rates. Marine Geology.

- Carpenter, N. E., Nicholls, R.J., Powrie, W., Dickson. M.E (2013). Development of a process-based model to understand the effects of variable lithology: An Isle of Wight case Study. Coasts, Marine Structures and Breakwaters. Edinburgh, UK, ICE.
- Carpenter, N. E., Dickson, M.E., Nicholls, R.J., (In Review). Understanding the Role of Varied Lithology on Soft cliff planshape evolution under high and low sediment availability. Earth Surface Processes and Landforms.

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Nomenclature

Standard Alphabet

a	Beach slope constant coefficient
B	Height of the retreating cliff
BL	Beach level factor
C_g	Wave group celerity at the breaker line
C_i	Random variable representing the magnitude of the ith recession event
CT	Cliff toe protection factor
c	Cohesion
D	Depth of the shoreface
D_1	Sediment grain size
d	Depth below the berm level
$_d$	Decay constant
E	Erosion rate
E_a	Abrasion
E_{ss}	Erosion by excess shear stress
F	Erosive forces
f_1	Dimensionless distribution of erosion under a breaking wave field
f_2	Tidal variation of the water level
f_3	Slope of rock elements
h_*	Depth of closure, the boundary of the profile, beyond which there is little loss of sediment

h_b	Maximum wave height for a five year return period
H_{bs}	Breaking wave height
H_s	Significant wave height
I	Imposed removal rate
i	Inundation
K_1	CERC Coefficient
K_a	Coefficient to convert sediment thickness ratio to abrasional units
K_{ss}	Calibration coefficient to convert excess shear stress into erosional units
L_*	Length of the active (eroding) profile
M	Material resistance and some other hydrodynamic constants
N	Random variable representing the number of cliff falls that occur during duration (*t*)
N_o	Number of waves of a particular type
n	Number of historic observations of cliff position
P	Sediment overfill function
P_z	Depth
p	Probability
Q_p	Potential sediment transport rate
Q_s	Longshore sediment flux
R	Shoreline retreat rate
R_1	Historic profile retreat
R_2	Future profile retreat

S	Storminess factor
S-L	Sea-level rise factor
S_c	Change in the rate of sea-level rise
S_1	Historic sea-level rise
S_2	Future sea-level rise
s	Normal stress
T	Wave period
t	Time
u	Pore water pressure
v	Variance
W	Weathering rate
W_0	Weathering coefficient
w	Winter rainfall factor
X	Distance seaward of the berm edge
X_t	Recession distance at time (*t*)
x	Longshore coordinate
y	Horizontal dimensions
z	Vertical dimensions/elevation

Greek Alphabet

α	Average slope across the surf zone
α_f	Falling slope angle
α_i	Initial slope angle

$\boldsymbol{\alpha}_s$	Stable slope angle
$\boldsymbol{\beta}_0$ *and* $\boldsymbol{\beta}_1$	Maximum likelihood estimators for linear extrapolation
$\boldsymbol{\varepsilon}$	Random variable that has a Gaussian distribution with zero mean and variance (*v*)
$\boldsymbol{\varepsilon}_1$	Historic equilibrium rate of recession
$\boldsymbol{\varepsilon}_2$	Future equilibrium rate of recession
η	Changes in cross-shore position of the shoreline
θ	Angle between the wave crests and the shoreline at the breaker line
ξ	Sediment thickness
ξ_{tmax}	Maximum thickness of the moving layer
ρ	Calibration coefficient to convert excess shear stress into erosional units
σ	Total Applied normal stress
σ'	Effective stress
τ	Shear strength
τ_c	Critical shear stress
Φ	Coefficient of friction
x	Seaward distance of berm edge

Definitions and Abbreviations

AONB	Area of Outstanding Natural Beauty
BGM	Beach Grade Material
BWA	Beach Wedge Area
CBU	Cliff Behavioural Unit
CCO	Channel Coastal Observatory
CD	Chart Datum
CERC	Coastal Engineering Research Centre
dGPS	Digital Geographical Positioning System
FEM	Finite Element Analysis
FLAC	Fast Lagrangian Analysis of Continuum
FoS	Factor of Safety
IPCC	Intergovernmental Panel on Climate Change
IoW	Isle of Wight
LiDAR	Light Detection And Ranging
NAI	No Active Intervention
OD	Ordnance Datum
OMS	Ordinary Method of Slices
Q3D	Quasi-3D
RMSE	Root Mean Square Error
SAC	Special Area of Conservation
SCAPE	Soft Cliff And Platform Erosion

SLR	Sea-level rise
SMP	Shoreline Management Plan
SSSI	Site of Special Scientific Interest
TLS	Terrestrial Laser Scanner
UCS	Uniaxial Compressive Strength
UKCIP	United Kingdom Climate Impacts Programme
WUN	World Universities Network

Glossary of Terms

Beach Grade Material	The proportion of sediment that is sufficiently coarse to be retained on the beach.
Beach Wedge Area	Refers to the triangle that defines the width and maximum elevation of the beach above MHWS.
Cliff Behavioural Unit	Categorises a section of cliffline based on the causes of coastal instability and subsequent mass movement mechanisms.
Coastal Offset	The cross-shore distance between the shoreline position of an embayment in comparison to adjacent sections.
Complex Cliffs	Strongly linked sequences of scarp and bench sediment sub-systems, therefore inducing complex feedback mechanisms.
Composite Cliffs	Consist of a variable lithology and/or coupled sequences of contrasting sediment sub-systems e.g. material from the upper cliff does not necessarily fall directly onto the foreshore.
Equilibrium erosion rate	Regarding numerical modelling this refers to the point at which the initial starting conditions have no effect on the shore profile state and the retreat rate becomes constant.
Factor of Safety	The ratio between resistive forces and destabilising stresses acting on the slope.
Mode A (Rock Strength Limited Erosion)	Recession is regulated by the adjustment of foreshore slopes, which are controlled by the material resistance properties.

Mode B (Transport Limited Erosion)	Where the beach volume is sufficiently large, waves are unable to attack the foreshore unless denuded by a local gradient in longshore sediment transport.
Simple Cliffs	Characterised by a near vertical cliff face of a single lithology with limited storage of debris material at the cliff toe. Such cliffs typically have a rapid response to basal marine erosion.
Threshold Beach Volume	The volume below which the beach is not believed to provide sufficient protection and cliff erosion continues with prevailing coastal conditions.
Water Content Ratio	The quantity of water contained in a material expressed as a ratio, where; 0 is completely dry through to the value of the materials porosity at saturation.

1. Introduction

1.1 Global perspective and problem statement

Coastal cliffs are estimated to account for 80% of the world's coast (Emery and Kuhn, 1982). Within this category soft rock cliffs represent a significant resource; comprising approximately 12% and 18% of the European and UK coastline, respectively (Eurosion, 2004). Their composition results in susceptibility to recession, the process of which is highly episodic and stochastic, related to the prevailing meteorological conditions combined with basal marine erosion at the cliff toe (Hobbs et al., 2002, Schwartz, 2005).

An understanding of future soft cliff retreat rates is required to inform a range of coastal management activities including; a) economic appraisal of coastal strategies (e.g. hold the line versus no active intervention); b) calculation of sediment budgets; and, c) estimation of the life of existing and future cliff-top infrastructure such as building and shore parallel roads (Hall et al., 2002). One of the fundamental challenges coastal specialists are faced with is to understand how the impacts of climate change will influence retreat (Brown et al., 2006). This is supported by worldwide problems associated with the sustainability of coastal settlements and maintaining land-use under high rates of soft cliff retreat (in excess of 1m/yr) in the USA, Canada, Japan, Russia, Denmark, Germany and the UK (Sunamura, 1992). Furthermore, there is a need for more sustainable and adaptive strategies considering the substantial financial commitments associated with the provision of coastal defences and slope stabilisation works (Dickson et al., 2007, Linham and Nicholls, 2010), which will face increasing pressure with climate change.

A UK Government review in 2002 stressed the importance of cliff management and the need to develop further analytical prediction methods (Lee, 2002). Traditionally, prediction has been undertaken through extrapolation of historical data into the future. However, this method is being increasingly recognised as unreliable considering the impacts of climate change, which present a change in future conditions, and the complexity of the cliff system which includes a range of interactions and feedback mechanisms.

One method which can respond to these needs is process-based geomorphic numerical modelling. This enables cliff system interactions (including the shore face, cliff face and fronting beach) and system changes to be simulated provided they can be described in numerical terms (Hall et al., 2002, Quinn et al., 2010). A range of models are available, one example being the SCAPE (Soft Cliff and Platform Erosion) model, developed by Walkden and Hall (2005), which simulates the emergence of soft rock shore profiles in the mesoscale (a period of 10-100 years). However, modelling inherently involves simplification of the system under question and consequently existing models are criticised for the generalised manner in which they treat cliff behaviour (Trenhaile, 2009). For example, many models assume coastal and marine processes are the key drivers of soft cliff recession, while more complex sub-aerial processes are frequently omitted (Hall et al., 2002). The cliff system must be treated in a more integrated manner if future rates of retreat are to be accurately understood (Trenhaile, 2004). In response it is important to enhance our understanding of the cliff system and identify key areas where model development should be focused.

1.2 Context of study

1.2.1 Definition of soft rock cliffs

Coastal cliffs are defined as a geomorphic feature in the form of a denuded coastal escarpment which is shaped by two key processes; a) coastal/marine action (operating on material at and under the water depth); and, b) Terrestrial (acting on material above the water level (Castedo et al., 2012, Masselink and Hughes, 2003)). Soft rock cliffs are defined by Pye and French (1993) as including “lithologies of any geological age which are poorly consolidated or poorly cemented, including; glacial till, outwash deposits, friable sands and weakly consolidated clays and shales.” Areas of variable lithology, for example limestones or sandstones overlying clays are also included where failure of soft lithology at the base of the cliff leads to failure. More quantitatively, they are defined by Hawkins (2000) as material with an Unconfined Compressive Strength (UCS) of less than 2.5MPa.

Soft cliffs are an important resource for their physical, biological and earth science conservation value. As they erode, they release sediment to the coastal and marine system which can contribute to downdrift beach volumes (Lee and Clark, 2002). They commonly exhibit shallower gradients than hard rock cliffs, which enables greater colonisation of vegetation (Lee, 2002) and development of a wide range of habitats (Whitehouse, 2007). They also create geomorphically diverse coastlines owing to the complex interactions between rock character, geological structure and inland relief, combined with the applied forces of marine and sub-aerial processes (Lee and Clark, 2002).

Figure 1-1 provides a schematic profile through an eroding cliff, from which the key features and their interactions are apparent:

- **Cliff face** – The erosive feature which marks the interface between marine and sub-aerial processes.
- **Talus** – Debris material which is delivered to the cliff toe by upper cliff failures. This material can provide some temporary protection to the cliff toe from basal wave erosion and, upon disaggregation, can contribute to the beach volume.
- **Beach** – A wave-lain deposit of sediment in the upper shoreface. When of sufficient volume it may afford protection to the cliff toe and underlying shore platform through dissipation of wave energy and protection from abrasion (Walkden and Hall, 2005).
- **Shore Platform** - An erosional surface feature which is intrinsically linked to past cliff recession (Masselink and Hughes, 2003). It can also provide protection to the cliff toe by attenuation of wave energy (Stephenson and Kirk, 2000).

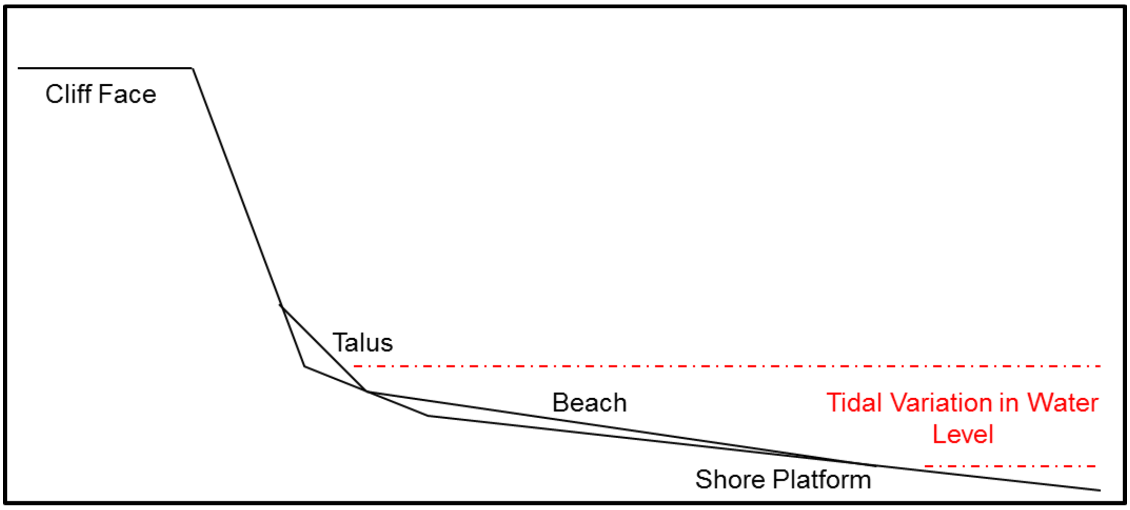

Figure 1-1: Schematic profiles through an eroding soft rock cliff (after Walkden & Hall, 2005)

1.2.2 Classification of the cliff system

The dynamic nature of the soft cliff system leads to contrasting modes of behaviour (Lee, 2002). It is important that this is understood to provide an appropriate foundation for predicting future behaviour. To facilitate this understanding, cliffs may be considered as cascading sediment transport systems, consisting of inputs, throughputs and outputs of material. Under this principle a range of Cliff Behavioural Units (CBUs) can be identified which span the cliffline and may be coupled to adjacent units within any defined sediment cell (Lee and Clark, 2002, Rendel Geotechnics, 1998):

- **Simple Cliffs** – Typically consist of a predominant lithology, a near vertical cliff face and a single sequence of inputs and outputs. Debris material from falls and slides is characterised by restricted storage and provides limited protection to the cliff toe. Therefore such cliffs have a rapid response to cliff toe erosion.
- **Composite Cliffs** – Consist of variable lithology and therefore coupled sequences of contrasting simple sub-systems. The outputs from one system do not necessarily form the input to the next (e.g. material from the upper unit may not necessarily fall directly onto the foreshore and may require a sequence of events).

- **Complex Cliffs** - Strongly linked sequences of scarp and bench sub-systems, each comprising of their own inputs, storage and outputs of sediment with complex feedback mechanisms.
- **Relict Cliffs** - Sequences of pre-existing landslides susceptible to reactivation by progressive marine erosion at the toe and/or elevated groundwater levels.

CBUs provide an important basis for understanding the coastal cliff system, emphasising the link between sub-aerial and marine sub-systems (Lee, 2002). This will be particularly important when considering composite or more complex cliffs systems exhibiting a variable lithology, as their geomorphology yields towards interacting sub-systems and feedback mechanisms.

1.3 Research aims and objectives

Based on the issues presented above, the overriding aim of this study is to contribute towards the development of an integrated, process-based model of coastal cliff recession. Such a model can ultimately be used as a prediction tool for composite cliff systems (as introduced in Section 1.2.2) considering the impacts of variable lithology on cliff geomorphology and retreat rates. A coupled model (simulating both the coastal and terrestrial cliff system) will also enable further insight into the impacts of climate change on the cliff system. This will contribute towards sustainable coastal management. To achieve this aim, four objectives are proposed:

1. Take a systems view of the coastal cliff system;
2. Assess the limitations of existing cliff recession models;
3. Improve the capability of a cliff recession model drawing on real-world observations, including a study frontage on the south west coast of the Isle of Wight (UK);
4. Understand how the impacts of environmental and climatic change will influence shore profile geomorphology and rates of cliff toe retreat.

Along with the research aims and objectives outlined above, a further benefit will be to understand recession rates at the study frontage in more detail. It is envisaged that the results can be used to inform future land-use planning by considering the impacts of a range of climate change scenarios over the next 100 years. Hence they will support the links of shoreline management and land-use planning, which is seen as an increasingly important objective (Brown et al., 2006). Moreover, the final, extended model will be generalised (not site specific). Therefore it will be suitable for application at other soft cliff sites with modified prevailing and in-situ conditions.

1.3.1 Structure of thesis

The structure of the remainder of the thesis is as follows:

- **Chapter 2** provides a review of soft rock cliff system which is summarised in a systems-based model.
- **Chapter 3** introduces the study frontage of the south west coast of the Isle of Wight, providing justification for its selection and background information.
- **Chapter 4** presents the research methodology. It delivers a critical analysis of the range of cliff retreat prediction methods currently available. This leads to the selection of a preferred model to be improved within this research.
- **Chapter 5** presents the preliminary results considering the application and assessment of the existing 2D and quasi-3D versions of the preferred model. Their current ability to replicate the study frontage is evaluated and leads to identification of a range of model refinements.
- **Chapter 6** applies the refined model to investigate key geomorphic relationships relating to shore profile geomorphology and rates of cliff toe retreat.
- **Chapter 7** applies the refined model to the study frontage for validation and evaluation purposes. The model is then used to consider future predictions of cliff recession at the site under a range of climatic and environmental change scenarios.
- **Chapter 8** presents the conclusions of the research, the subsequent knowledge contributions and recommendations for further work.
- **References**
- **Appendices:**
    - **A** – SCAPE Numerical Description of Erosion

- **B** – Modifications to SCAPE Code
- **C** – Model Predictions of Study Frontage Rates of Retreat
- **D** – Abstracts of Publications to Date

2. Soft Cliff System: Characterisation and Processes

The first objective of this research is: *to take a systems view of the coastal cliff system*. Therefore, the structure of the chapter is as follows:

- Section 2.1 introduces the cliff system and associated sub-systems;
- Section 2.2 reviews the sub-systems and associated factors;
- Section 2.3 develops a systems model based on the above findings;
- Section 2.4 concludes the chapter.

2.1 Introduction to understanding the cliff system

In the past, behaviour of the coastal soft rock cliff system has been likened to beaches owing to their rapid responses to prevailing conditions. However, they share fundamental behaviour characteristics with hard rock cliff systems (Trenhaile, 2009), for example, the processes of erosion on both are irreversible (Sunamura, 1992). Cliff erosion can be defined as an external, cyclical process which ultimately results in the weakening and removal of material on the cliff face, as outlined in Figure 2-1. Behind this simple flow diagram there is significant complexity, with a variety of mechanisms driving the detachment of material (as earlier demonstrated by the cliff features highlighted in Figure 1-1 and the concept of CBUs). This highlights the need to appreciate the broad range of factors which control cliff behaviour (Bromhead, 1979, Del Rio and Gracia, 2009, Quinn et al., 2010).

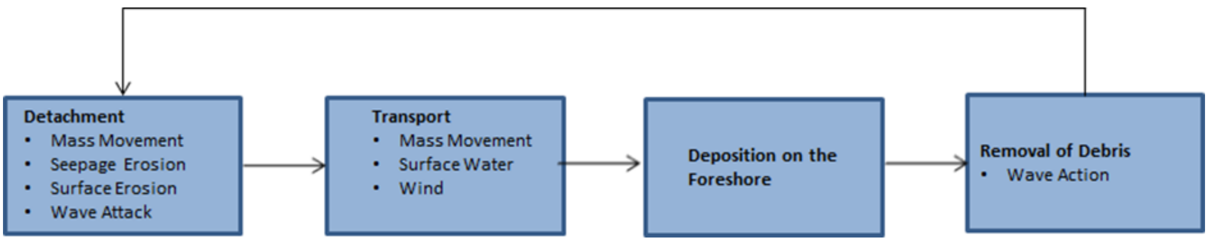

Figure 2-1: Four-stage Cliff erosion process (Lee and Clark, 2002)

Table 2-1 outlines the key sub-systems within the cliff system, their associated factors and the features they influence. This has been developed considering a review of literature which will be disseminated in the following sub-sections.

Table 2-1: Summary of the key sub-systems influencing the coastal cliff system

Sub-System	Role /Description	Cliff Features Under Influence	Associated Factors
Geotechnical, Geological & Hydro-geological	The internal controls of the cliff system which ultimately determine its shear strength.	Cliff face and talus.	• Geology, lithology & structure • Groundwater, pore water pressure and seepage erosion • Cliff geometry (height and slope) • Strain softening & progressive failure
Sub-Aerial	Processes acting under the atmosphere on the earth's surface.	Cliff face and talus.	• Slope vegetation • Weathering
Coastal and Marine	Exposure of the cliff system to driving coastal forces.	Shore platform, beach and talus.	• Wave exposure • Shore platform protective capacity • Beach protective capacity and longshore sediment transport
Meteorological and Climatic	Atmospheric drivers and potential changes to the system as a result of climate change.	Indirect influence through other sub-systems.	• Rainfall • Tidal levels & sea-level rise • Storms and storm surges
Human	Anthropogenic intervention of the cliff system	Cliff face and beach.	• Engineering structure at cliff toe • Slope stabilisation & Artificial drainage

2.2 Review of factors influencing coastal cliff system

In an attempt to enhance our understanding of the cliff system, numerous studies have tried to define the relative importance of the factors presented in Table 2-1. The relationships identified are documented in the following sub-sections to provide a holistic understanding of the cliff system. This review will assist in the development of a systems model in the following Section (2.3).

2.2.1 Geotechnical, geological and hydro-geological sub-system

This section presents a review of the factors within the geotechnical, geological and hydro-geological sub-system.

2.2.1.1 Geology, lithology and structure

These factors influence the shear and resistive strength of the cliff. Firstly, shear strength is an important determinant of cliff stability considering the ratio between resistive forces and destabilising stresses acting on the slope, otherwise known as the Factor of Safety, FoS (Bromhead, 1986). It is defined as the maximum shear stress that a material can withstand before failure, therefore a slope will only be as strong as its weakest horizon (Isle of Wight Council, 2000). As outlined in

Equation **2-1**, it is dependent on the nature of material and the presence of water and is defined by the coefficient of friction ($tan\phi$) multiplied by the stress applied at right angles to a plane (*s*, normal stress), plus cohesion (*c*). Cohesion is independent of inter-particle friction and is derived from inter-particle bonds. It is a significant factor in clays (which are a common lithology of soft rock cliffs) and zero in pure sands. Shear strength also determines the scale and frequency of the detachment process (introduced in Figure 2-1). For example, soft rock cliffs with lower shear strength (e.g. Glacial Till) are likely to recede via mass movements, followed by extended periods of inactivity, whilst harder cliffs (e.g. Granite) may recede via small but more frequent falls (Lee et al., 2001).

$$\text{Shear Strength} = c + s(\tan\phi)$$

Equation 2-1

Resistive strength describes the resistive properties of the rock to erosion and is a function of grain size (with finer material being held together by cohesion), unit weight and water content (Gelinas and Quigley, 1973). Davidson-Arnot and Langham (2000) found that the resistive strength of clay rapidly increased with depth, corresponding to a decrease in water content. It was found that softening of the cohesive material by the addition of water enabled direct erosion by wave induced shear stress. This emphasises the need to consider the geological properties of the cliff and how they may influence the recession process.

Jenkins et al. (2011) highlighted lithology as a major control on the style and extent of landslides on the Isle of Wight, UK. On a section of the south west coast the character of failure was demonstrated to be determined by the presence and thickness of sandstone units. Figure 2-2 identifies three types of failure zone (A - C):

- **Zone A** represents whole cliff activity with thinner sandstones being incorporated into landslides as rotated blocks, the sandstones only act to limit failure when outcropping at beach level and where the cliff above is relatively low.
- **Zone B** represents cliffs where a thick layer of sandstone acts as a natural revetment behind the beach or as reinforcement to the cliff when above beach level
- **Zone C** represents cliffs where no significant sandstone reinforcement is present and subsequently the whole cliff is active even when low in height.

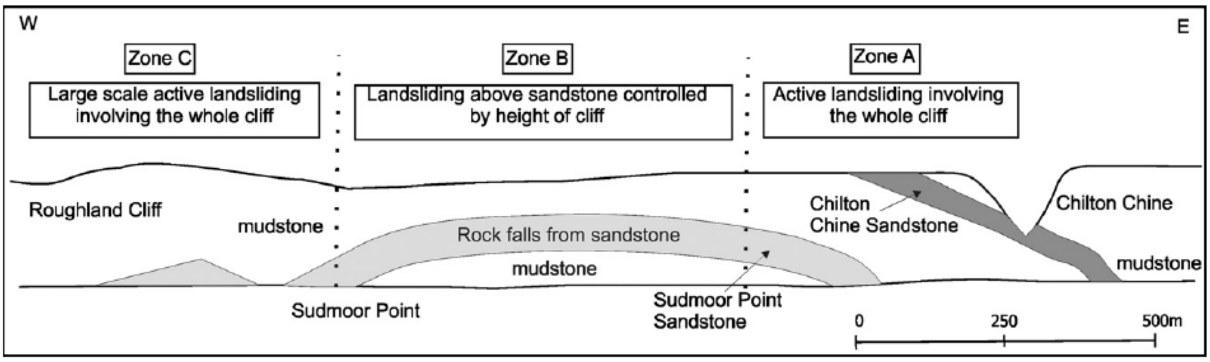

Figure 2-2: Location of sandstones and their influence on landslides at Sudmoor Point, Isle of Wight (Jenkins et al., 2011)

A range of numerical modelling studies (including Valvo et al, 2006, Walkden and Hall, 2011, Limber and Murray, In Review-ab) have also considered the effect of cliff lithology. These findings are discussed later in Section 2.2.3.3 owing to the interactions with the process of longshore sediment transport identified.

Structural weaknesses (faults and joints in the rock) are also influential as they lead to a reduction in shear strength (Skempton and Hutchinson, 1969). When they are exposed in the cliff face they can be exploited by waves and lead to accelerated rates of erosion (Moore and Griggs, 2002). Tension cracks may also develop owing to an increase in tensile stresses as the cliff face becomes steeper. Wolters and Muller (2008) studied the effect of cliff shape on internal stresses and rock slope stability using a finite element analysis (FEM) of a middle Cretaceous chalk cliff of 30m to 200m. They found that the development of tension cracks on the cliff top results in a connective line of shear stresses between these cracks and the base of the cliff. This increases the probability of shear failure along this slip line. However, the investigated cases did not result in large enough forces to produce such failures.

2.2.1.2 Groundwater, pore water pressure and seepage erosion

Equation 2-1 highlighted that frictional resistance varies with the level of applied normal stress (i.e. the load), whilst cohesion exists independently of compressive forces. It assumes that shear strength is the result of interactions between mineral particles. However, water is also a major influence as it exerts its own pressure, subsequently reducing the amount of particle to particle contact and hence the frictional component of shear strength (Waltham, 2002). Fluids can support compressive forces but not resist shearing forces; therefore friction depends on the difference between the applied total normal stress and the pore water pressure. The difference (or part of the normal stress which is effective in generating resistance) is known as the effective stress (σ’) and is given by:

$$\sigma' = \sigma - u$$

Equation 2-2

where σ is the total applied normal stress and *u* is the pore water pressure. Therefore, shear strength is correctly defined in terms of effectives stress so:

$$\tau = c' + \sigma' \tan \phi$$

Equation 2-3

As a result, the hydrogeology (pore pressure regime) is considered to be a major governing factor for slope stability (Dijkstra and Dixon, 2007, Wyllie and Mah, 2004). Variations in pore pressure are determined by a number of climate dependent variables such as rainfall, evaporation and temperature. Periods of heavy rainfall can increase the groundwater level through infiltration which can result in the generation of positive pore water pressures that increase soil weight, while decreasing its shear strength. This cycle makes the slope significantly more susceptible to failure (Timpong et al., 2007). This relationship was further supported by the process-based model results of Castedo et al (2012) for responses of idealised cliffs to a range of groundwater conditions (from drained to fully saturated with different water ratios). In all simulations the number of recession events caused by circular failures increased with the water content ratio (the quantity of water contained in the cliff material, see Glossary of Terms) and where groundwater content was high the total recession distance of the cliff was greater.

Moore and Brunsden (1996) examined the relationship between pore water pressure and ground movement using real time, continuous data for the Dorset coast, UK. The results generally supported the expectation that a rise in ground water level resulted in the onset of movement. However, further detailed analyses found that there were often discrepancies and poor correlations between the two. For example, movement often ceased while pore water pressure continued to rise and, after a standstill, higher pressure was required to restart movements. The progression in these relationships infers an apparent strength-gain with movement. Considering interactions between pore water pressure and rainfall, further studies are discussed in Section 2.2.4 (Meteorological and Climatic Sub-System).

Finally, seepage erosion is another important factor within the detachment process (Figure 2-1). The process relates to water movement through the cliff face which results in undermining of material and rock falls. On the south west coast of the Isle of Wight at Chale Bay Jenkins et al (2011) describe the formation of a bench feature midway up the cliffs owing to seepage erosion from the presence of clay aquitards. The undermined material is deposited on the bench and moves seaward through a series of compound slides. This process produces a cliff top retreat rate which is more rapid than that of the cliff base and highlights the importance of sub-system interactions.

2.2.1.3 Cliff geometry (height and slope)

Cliff height influences the magnitude of shear stress, with stresses increasing linearly with height. Therefore, high cliffs are found to have a greater inherent instability owing to the loading caused by the weight of the overlying strata (Wolters and Muller, 2008). Quinn et al (2010) found cliff height to be a key determinant of the dominant processes governing slope instability at Holderness, UK. Cliffs below 7 m OD (Ordnance Datum) were determined to be predominantly controlled by processes of marine erosion and abrasion (the scouring action of beach material against the cliff slope/shore platform). Cliffs between 7 m OD and 15 m OD were found to be more influenced by structural failures (as the minimum angle under which the slope failed was greater than the average angle of sub-vertical fissures). Finally, cliffs in excess of 15 m OD were receding primarily as a result of mass failures. These higher cliffs are still influenced by marine processes but their susceptibility to mass movements at lower slope angles causes geotechnical mechanisms to be dominant. Results using the Process-based model of Castedo et al. (2012) for the same stretch of coastline were in agreement with these findings.

As cliffs will naturally degrade to a stable slope; the steeper the cliff the greater the risk of instability. The FEM investigation by Wolters and Muller (2008) found that steeper cliff angles result in a concentration of stress trajectories at the base of the cliff (as outlined in Figure 2-3). These give rise to high shear stresses at the cliff base, which can reduce shear strength and induce local failure of material (Wolters and Muller, 2008). Overall, cliff steepening was found to be a critical factor for cliff instability; generating a situation where small external influences (e.g. wave impact) can trigger a failure. The consideration of cliff slope has been included in a number of studies including Dawson et al (2009) - as will be further discussed in Section 4.3.1, which highlights the importance of this factor.

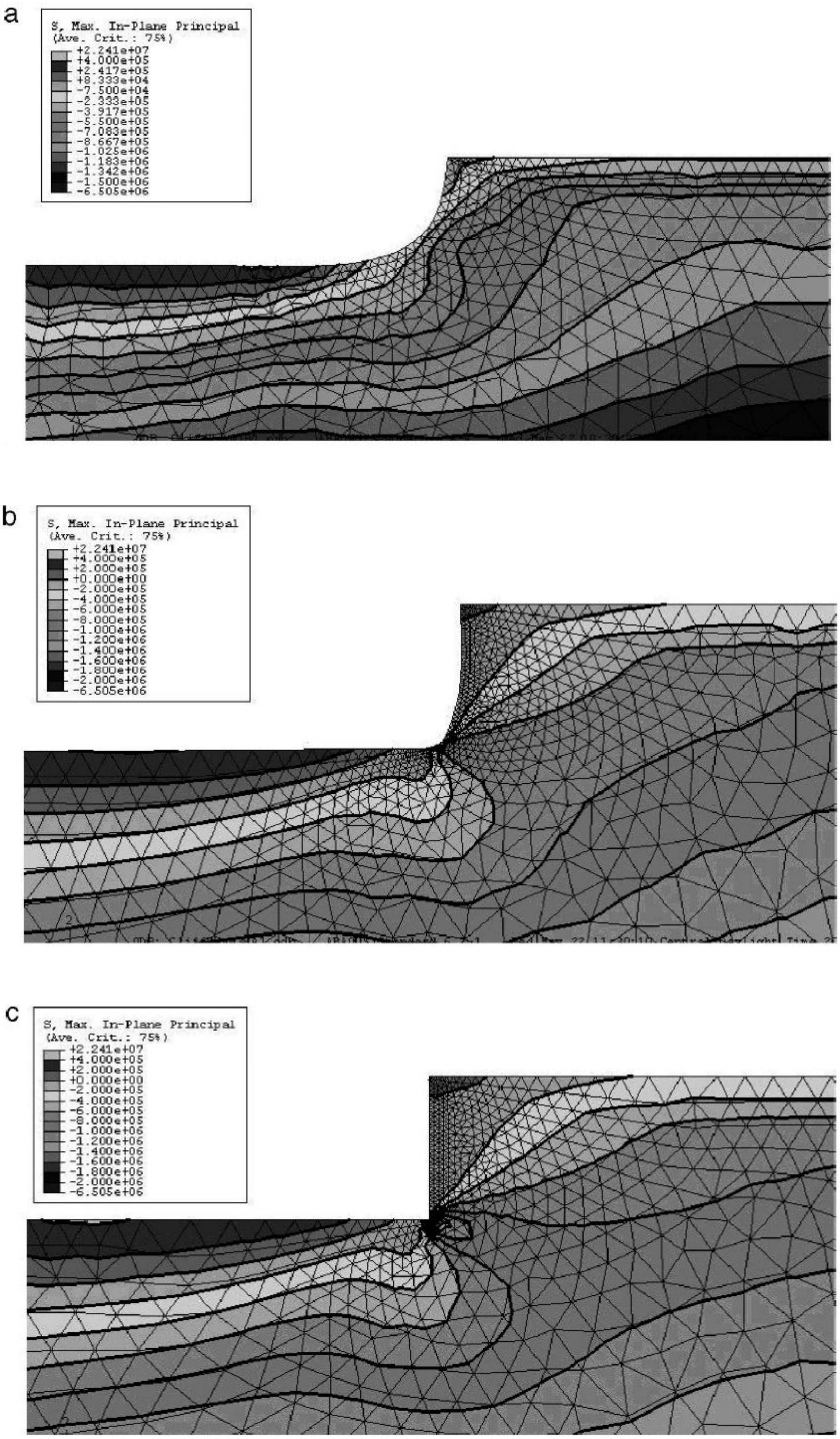

Figure 2-3: Stress distribution for varying cliff slopes; 50º, 85º, 90º respectively (Wolters and Muller, 2008)

2.2.1.4 Strain softening and progressive failure

Strain softening is defined as a reduction in shear strength with shear strain. If an area is subjected to extra strain it will fail and its strength will fall towards critical value. The area will shed load to adjacent areas which will then also become overstressed. In this way a progressive failure can occur so that further landsliding extends the area of instability (Powrie, 2004, Jones, 1993). The progressive failure of jointed rock slopes is also related to the number of discontinuities along the potential failure surface and the gradual reduction in shear resistance as these increase through the intact rock mass (Terzaghi, 1960).

2.2.2 Sub-aerial sub-system

This section reviews the factors situated within the sub-aerial sub-system (Table 2-1).

2.2.2.1 Slope vegetation

Vegetation can influence slope stability in a range of ways. Positive effects include; root reinforcement, generation of pore water suctions, protection of the cliff face from weathering processes and surface run-off, buttressing and arching (Bracegirdle et al., 2007, Smethurst et al., 2006). Negative effects include; loading of the upper portion of the slope, uprooting and overturning.

A study of a London clay embankment by Smethurst et al. (2006) found that rough grass cover does not necessarily generate sufficient soil drying in the summer months for soil suctions to be retained into the winter/early spring when low evapotranspiration and high rainfall make slope stability most critical. However, the drying caused by this vegetation and the prolonged time taken to re-wet the soil does prevent critical water and pore water pressures being reached as often or for as long a period as when vegetation is not present.

2.2.2.2 Weathering (physical, chemical and biological)

Weathering can cause weakening of the cliff face and promote erosion through a range of mechanisms: physical, chemical and biological. Coastal cliffs and the intertidal shore platform are susceptible as they are exposed to both air and water. Therefore, in sheltered environments weathering is considered a major erosive process.

Physical weathering can result from wetting/drying, freeze thaw action, thermal expansion and salt crystallisation (Waltham, 2002). However, these processes are strongly controlled by climatic factors (Masselink and Hughes, 2003). With respect to freeze-thaw weathering, frosts on the coasts of southern England, UK, are infrequent and rarely penetrate deeper than 0.3m (Dornbusch et al., 2008). Therefore the impact of even the most intense frost events is limited to surface spalling and shattering of the cliffs and therefore provides minimal contributions to cliff recession (Robinson and Jerwood, 1987).

Salt weathering is caused through the presence of salts in the capillaries of coastal rocks which undergoes volumetric changes due to their absorption of water, temperature induced expansion or crystal growth from solution (Trenhaile, 1987). These volumetric changes result in widening of cracks and subsequent weakening of the rock. The efficiency of this process increases with rock permeability and porosity (e.g. Sandstone is particularly vulnerable) and is particularly effective under high temperatures and low rainfall.

Chemical weathering results from a number of reactions such as leaching, hydrolysis, oxidation and solution (Waltham, 2002). The efficiency of these processes is mainly determined by the amount of water available for the reaction process and for removal of soluble products. This form of weathering is most significant in hot, humid climates.

Biological weathering refers to the erosion of the cliff and shore platform surface by organisms. This process is typically most important in tropical regions owing to the diversity of flora and fauna and the presence of calcareous substrates (Spencer, 1988). Terrestrial organisms will predominantly affect the cliff face by borrowing whilst marine organisms may attack the shore platform by:

- Chemical erosion underneath dense algal mats;
- Abrasion by surface grazers;
- Chemical or mechanical borers directly removing or weakening rock material (Masselink and Hughes, 2003).

Marine flora and fauna may contrastingly assume a protective role. Some organisms may contribute to the formation of organic crusts that protect the underlying rock from wave erosion and other forms of weathering. Algal mats may also prevent the drying out of the rock surface reducing cycles of wetting and drying (Masselink and Hughes, 2003).

2.2.3 Coastal and marine sub-system

This section reviews the factors situated within the coastal and marine sub-system (Table 2-1).

2.2.3.1 Wave exposure

Exposure to waves is an important control on cliff recession through shore platform lowering, cliff toe undercutting, over-steepening of the cliff face and removal of talus material. (Masselink and Hughes, 2003, Walkden and Dickson, 2008). Mechanical wave erosion is considered the main erosional agent in the majority of swell and storm related environments. This process operates most effectively at, or slightly above, the still water line and highlights the close link with the influence of tidal and storm surge water levels.

Wave erosion is induced by the processes of hydraulic action and abrasion. Hydraulic action refers to the impact of waves, causing pressure variations that weaken the rock by widening any discontinuities present and the removal of dislodged material. Abrasion is the result of particles carried in the water scouring the rock surface. Wolters and Muller (2008) concluded that wave-induced abrasion is the most important process driving soft cliff recession as opposed to hydraulic processes in hard rock cliffs. This was further supported by a review of laboratory studies of cohesive cliffs by Davidson, Arnot and Ollerhead (1995) and their measurements of lakeside glacial till bluffs. However, the latter study highlighted the difficulty in distinguishing between the two.

The removal of material or load by excavation can also lead to a progressive series of internal changes such as lateral expansion of the slope. The opening of fissures and tension cracks and ultimately a reduction in strength (Skempton and Hutchinson, 1969). This leads to a progressive change in the factor of safety and can result in slope failure.

2.2.3.2 Presence and characteristics of shore platform

Shore platforms (as introduced in Figure 1-1) are horizontal or gently sloping rock surfaces found in the intertidal zone. They are an erosional surface feature formed by both marine and sub-aerial processes, as such their formation and geology is intrinsically linked to the cliff face (Masselink and Hughes, 2003). However, owing to their different forms they experience different types of wave attack. Shore platforms are eroded by breaking waves as opposed to the more localised, impulse loads which attack the cliff toe (Walkden and Hall, 2005). The junction between the shore platform and the cliff face is governed by the tide and tends to emerge just above the level of high water spring tides (Walkden and Hall, 2005).

Figure 2-4 defines two contrasting models of platform evolution (de Lange and Moon, 2005). The equilibrium model considers a constant erosion rate across the entire profile and, once at equilibrium, the width remains constant. In this case it is suggested that marine processes are dominant. Contrastingly, the static evolution model describes when the seaward edge of the shore platform remains constant whilst cliff recession continues, resulting in an increase to its width with more dominant sub-aerial processes. However, as noted by Stephenson (2008) there is no agreement over which model is correct or as to whether the seaward edge can mark the original position of the shoreline. Furthermore, there is much debate amongst geomorphologists over the processes responsible for shore platform development (Stephenson and Kirk, 2000).

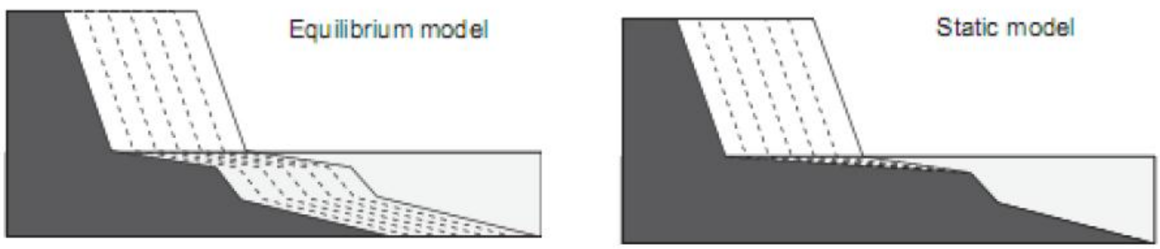

Figure 2-4: Diagram of contrasting models of shore platform evolution

(de Lange and Moon, 2005)

The presence of a shore platform influences the cliff system by its ability to protect the cliff toe through wave attenuation (Trenhaile, 2009). Consequently, rates of cliff recession are directly linked to the shore platform elevation and gradient as supported by a range of studies; Kamphuis (1987), Goudie (1995), Stephenson and Kirk (2000), Walkden and Hall (2005), Dornbusch et al (2008), Walkden and Dickson (2008) and Ogawa (2013).

In the development of the SCAPE model, Walkden and Hall (2005) argued that the shore platform forms the primary determinant of soft cliff erosion. They also recognise the influence of negative feedback between the shore platform and the cliff face, which acts to regulate the erosional processes. For example, high cliff erosion rates create a wider shore platform which provides greater protection against wave energy, subsequently reducing future retreat (Walkden and Hall, 2005). This relationship was similarly supported by the findings of Dornbusch (2008) for a field study of chalk cliff in East Sussex, UK over a 130 year period.

2.2.3.3 Presence and characteristics of a fronting beach and longshore sediment transport

The presence of a beach can either act to enhance erosion through the process of abrasion or provide protection owing to its dissipating effect on incoming wave energy if of sufficient thickness (Davidson-Arnott and Ollerhead, 1995). For example, Dornbusch (2008) found that the erosion rate of the chalk cliffs of East Sussex was reduced with a decreased beach volume. This was attributed to the reduced effects of abrasion by beach material, combined with increases in the shore platform width. In contrast, several studies have identified a correlation between areas experiencing accelerated rates of erosion and decreased beach volume including Moore and Griggs (2002) and Hapke et al (2009).

However, the protective role of the beach can be limited and varies with wave energy. For example, in a study of a shale shore platform overlain by a mixed sand and pebble beach it was found that erosion could occur where the beach was less than 5 cm thick, but was dependent on high wave energy when the beach thickness exceeded approximately 13 cm (Robinson, 1977). Similarly, Ferreira et al (2000) investigated the depth of beach disturbed under breaking waves for a series of sandy beach sites and found that the average depth was 0.23 H_{bs} (where H_{bs} is the breaking wave height).

These limitations have led to a range of studies identifying protective beach volume thresholds, below which the beach is not believed to provide sufficient protection and cliff erosion continues with prevailing coastal conditions. A study of the relationship between beach levels and recession rates along the north Norfolk and Suffolk coasts (UK), identified a non-linear increase in the average recession rate as the beach profile area above high water decreases below 20 m^2 (Lee, 2008). This was further illustrated by the 2D SCAPE model results of Walkden and Dickson

(2008). Their sensitivity testing of a central section of Walkden and Hall's (2005) model of the Naze, Essex, UK identified a threshold beach volume of 30 m^3/m (Figure 2-5). Below this level the shore platform was found to continue to erode, subsequently steepening the profile. This leads to the seaward migration of beach material, increasing the beach width but reducing its thickness, consequently returning equilibrium erosion rates[1] back to their pre-beach levels.

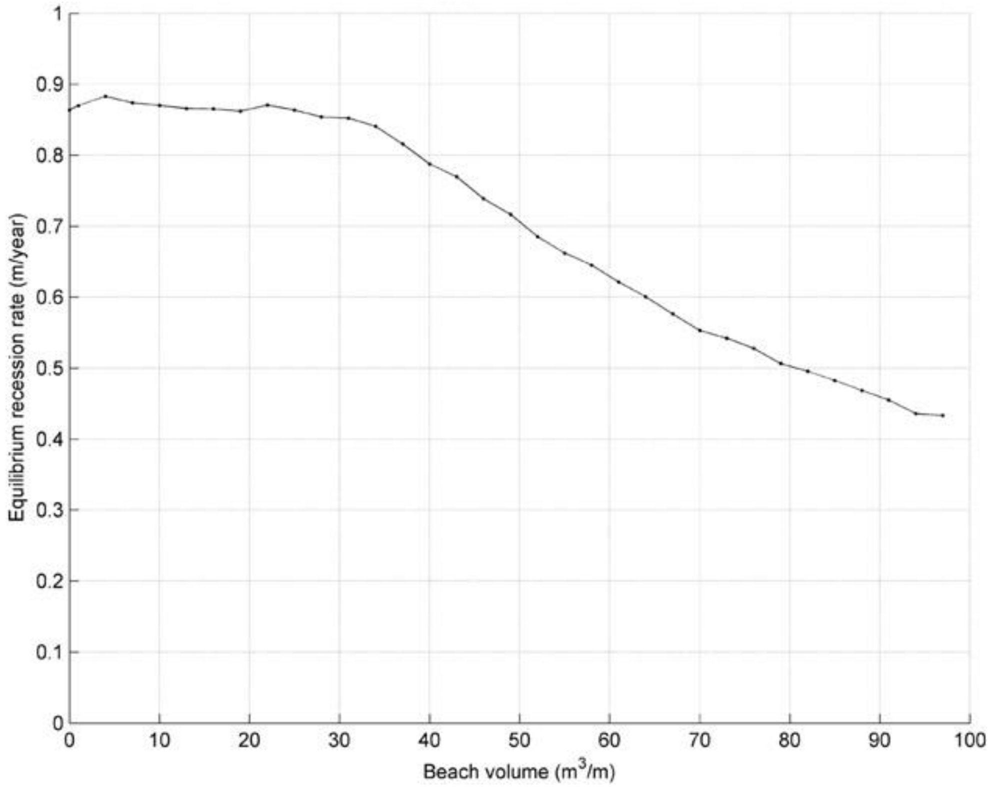

Figure 2-5: Sensitivity of equilibrium shore recession rates to the presence of a beach (Walkden and Dickson, 2008)

The protective nature of fronting beach volumes can also be related to the grain size of the material. This controls the slope of a beaches equilibrium profile and can therefore determine if it is either reflective or dissipative (Dean, 1994). However, Trenhaile (2010) found no correlation between this factor and either profile morphology or contemporary erosion rates when applied to model runs for cohesive clay coasts.

[1] Equilibrium erosion rate refers to the point at which the model starting conditions have no effect on the shore profile state and the retreat rate becomes constant (Walkden and Dickson, 2008)

The above findings provide an understanding of the influence of protective beach volumes against cross-shore erosion. However, owing to the effects of longshore sediment transport, a series of models have been developed to understand the relationship between longshore interactions and fronting beach volumes including; Valvo et al (2006), Limber and Murray (2011), Walkden and Hall (2011) and Limber and Murray (In Review–ab). Valvo et al (2006) developed a numerical model of plan-view coastal evolution (CEM) considering interactions between fronting beach volumes and longshore variations in underlying lithology. The model simulations stressed the importance of longshore sediment transport processes in balancing retreat rates along coastlines with heterogeneous cliff characteristics. For example, considering longshore changes in the availability of Beach Grade Material (BGM) from the eroding cliff, it was found that initially shoreline segments underlain by a low percentage of BGM retreat faster resulting in the development of shoreline indentations. However, longshore transport redistributes sediment from the adjacent sections of high BGM to infill the embayments. Consequently, over time the retreat rate becomes spatially uniform (after approximately 60 years) and the offsets (the cross-shore distance between the shoreline position of the indentation and those in adjacent sections) reach a constant value.

Similar behaviour was observed when considering longshore variations in the weathering rate of the underlying rock, with indentations initially forming in less resistant rock but longshore retreat rates reaching steady state over time due to sediment infilling. The model revealed how subtle indentations reflecting the underlying geologic framework do not necessarily imply spatially heterogeneous retreat rates. However, the results apply to sandy, sediment rich shorelines (such as the south east coast of the USA) in that they are based on a weathering rate that exceeded the overall retreat rate of the frontage. Therefore, results do not specifically relate to soft rock cliffs, in particular considering the development of shore platforms and their effect on wave attenuation.

Limber and Murray (2011) demonstrated how coastlines can reach an equilibrium configuration of persistent headlands and bays, independent of longshore variations in cliff resistance, by means of an exploratory numerical model which described the balance between abrasive and protective processes as a function of beach width. Their cell-based model domain explored large-scale, long-term trends in evolution considering a 20km frontage over millennial timescales. The results showed how, for a rocky coast of an initially random shape (which may arise as a result of a newly flooded, fluvially dissected landscape), embayments will initially experience higher rates of retreat (due to abrasion by beach sediment) than headlands (which are swept clear of sediment). However, as the embayments infill due to longshore sediment transport, rates of retreat will decline as the beach takes on a protective role. At this point the retreat rates of the embayment will become less than that of the headlands. Consequently, headland features will become transient features of the landscape unless they are large in cross shore extent relative to the steady state beach width (Limber and Murray, 2011). This demonstrates how beach volumes can independently control coastal planshape evolution. However, the results apply to abrasion-driven coasts where sediment supply and losses are of similar magnitude. Thus, as noted by Limber and Murray (2011), this theory may not be applicable to where other mechanical erosion processes are more effective.

Walkden and Hall (2011) applied the quasi-3D (Q3D) SCAPE model (which includes longshore sediment transport through coupling with a one-line model) to north Norfolk, UK. This included sensitivity testing of the two model calibration parameters; the CERC coefficient (a scaling factor of the longshore transport rate, Hanson and Kraus, 1989) and the material resistance parameter (a hybrid parameter of cliff resistance combined with other hydrodynamic constants). The results demonstrated how, when cliffs are fronted by protective beach volumes, the CERC coefficient becomes a more dominant parameter than material resistance owing to negative feedback. This was further highlighted by introduction of fixed beach volumes into the model. Walkden and Hall (2011) identified a threshold beach volume of 25 m^3/m (a similar threshold to the proposed by Lee, 2008 and Walkden and Dickson, 2008), above which the long term rate of cliff retreat was found to remain sensitive to the beaches presence. Overall, the results revealed two contrasting modes of shoreline behaviour:

Mode A: Rock Strength Limited Erosion – where recession is regulated by the adjustment of foreshore slopes, which are controlled by the material resistance properties. Such conditions may be induced by high material resistance or high rates of longshore transport.

Mode B: Transport Limited Erosion – where the beach volume is sufficiently large, waves are unable to attack the foreshore unless denuded by a local gradient in longshore sediment transport.

Finally, Limber and Murray (In Review-ab) developed a new, exploratory model of plan-view, millennial-scale coastal evolution to understand the effect of longshore differences in lithology for rocky coasts. The results showed how initial cliff lithology can largely determine coastal planshape evolution in terms of whether headlands will be persistent or transient features. Sediment rich coastlines were shown to evolve more rapidly, and offsets between headlands and embayments were found to be inversely proportional to beach sediment supply. The results provided an important foundation to understanding the influence of lithological controls on coastal planshape evolution under a range of sediment conditions. However, as noted by Limber & Murray (In Press-b) the model greatly oversimplifies the processes occurring on rocky coastlines.

2.2.4 Meteorological and climatic sub-system

This section reviews the factors situated within the Meteorological and Climatic sub-system (Table 2-1).

2.2.4.1 Rainfall

Rainfall can act in a number of ways to promote slope failure either as a preparatory factor that makes the slope increasingly susceptible to failure or as a triggering factor which initiates movement of the cliff (Crozier, 1986). It can reduce the cliffs factor of safety through a number of processes (these are intrinsically linked to the hydrogeological factors described in Section 2.2.1):

- Increased groundwater levels;
- Increased soil weight;
- Increased pore water pressures;
- Developing seepage pressures/erosion;
- Decreased apparent cohesion and weakening of clays by softening;
- Liquefaction;
- Rain splash weathering.

While this demonstrates that rainfall is a major component of cliff recession, it should be noted that it is its influence on the water content of the slope which is of particular significance (Crozier, 1986, Ibsen and Brunsden, 1996, Timpong et al., 2007). Crozier (1986) stated that ‘changes in the water content can quickly affect the stability of slope material and have been responsible for triggering, reinitiating and accelerating more landslides than has any other factor'. On this basis, several studies have claimed to identify correlations between landslide events, effective rainfall (the proportion that can contribute to the groundwater table minus evapotranspiration) and groundwater table rise. For example Maquaire (1994, 1997) related historical landslides to these factors on the Calvados and Normandy coasts, France. Bracegirdle et al (2007) identified that intermediately permeable, partially saturated slopes are highly sensitive to rainfall intensity. This was supported by a notable increase in landslide activity on the south coast of the UK between January and March 2001, characterised by a prolonged wet period with a number of high intensity rainstorms.

Ibsen and Brunsden (1993) and Brunsden and Chandler (1996) have both demonstrated that the recorded pattern of landsliding on the west coast of Dorset, UK, is closely linked with the occurrence of wet year sequences[2]. Similarly, Ibsen and Brunsden (1996) analysed the rainfall series of Ventnor, Isle of Wight, UK, and found a positive correlation between the increase in moisture balance and the number of landslide events. However, the latter highlighted the challenge of relating the landslide series to a single cause owing to the dynamic nature of the cliff recession process.

The response of the cliff system to increased rainfall is far more complex than, for example, the river system where direct relationships between rainfall events and discharges can be found (Isle of Wight Council, 2000). As a result a number of studies have also recognised poor correlations between cliff recession and rainfall, for example:

- Julian and Anthony (1994) noted a weak correlation between landslides and wet years in the maritime Alps (France) with only one third of landslides occurring within wet years between 1893 and 1936.
- Clark et al (1995) concluded that the extensive landslide movements experienced at Blackgang, Isle of Wight, UK in 1994 were linked to near continuous, intense rainfall in the previous months. However, a later analysis of rainfall records indicated that this was in fact the 30th wettest winter since

[2] Wetter than the long term mean annual rainfall.

1839 and that similar landslide events could not be correlated to these periods (Isle of Wight Council, 2000).

- Dornbusch et al (2008) identified only weak correlations between rainfall and cliff retreat. The difficulty in trying to relate the mean annual rate of retreat (measured over several decades) with precipitation data averaged over days, months and years was discussed.

Considering these examples, it is clear that the variable temporal and spatial response to rainfall events ensure that it is not possible to define universal laws to forecasting landslide activity and cliff recession. However, rainfall patterns do have an important influence on slope stability. This is particularly noteworthy when considering the predicted seasonal changes in these patterns as a result of climate change. For example, the UK Climate Impacts Programme (UKCIP) predicts a decrease in summer precipitation (-16% central estimate) but an increase in winter precipitation (+14% central estimate) for eastern England. This enhanced winter season precipitation will result in loss of material strength which is likely to coincide with periods when cliff base erosion is also high (Brooks and Spencer, 2012). Therefore interactions between rainfall and climate change are likely to be key factors when considering future rates of soft cliff recession.

2.2.4.2 Tide levels and sea-level rise

The tidal range controls the water level and the amount of time an area is exposed to wave action (Masselink and Hughes, 2003, Robinson, 1977, Walkden and Hall, 2005). The level of the greatest exposure is at and between the mean tide levels where the water level spends most of its time. As the period that the tide will occupy a certain level decreases with increasing range, the potential for mechanical wave energy is greatest in micro-tidal environments (Trenhaile, 1987). Furthermore, the vertical distribution of wave energy is skewed towards the upper portions of the tidal range. In some instances the cliff toe will only be exposed to waves during high spring tides, subsequently limiting the exposure of the cliff face and contributing to the episodic nature of cliff recession.

Clearly sea-level rise will influence tidal levels and in turn cliff recession rates through a number of mechanisms. Increasing water depths will result in changes in wave height and longshore sediment transport, introducing the potential to remove debris material at the cliff toe more rapidly, inducing more frequent slope instability

(Quinn et al., 2010). This will also be influenced by potential changes in wave directionality (Brooks and Spencer, 2012, Walkden and Hall, 2005). Model results of Trenhaile (2011) using a process-based numerical model of cohesive clay coasts developed by Trenhaile (2009) showed that rising sea-levels will trigger faster cliff recession rates owing to deeper water and in turn reduced wave attenuation. This is similarly supported by the model results of Castedo et al. (2012) for Skipsea on the Holderness coastline, UK, where the calculated recession after one hundred years with a range of sea-level rise scenarios suggests a linear relationship with cliff top retreat.

Under constant sea-levels, wave erosive processes tend to flatten the shore profile. However, the shore response to increasing rates of sea-level rise will be to steepen in a non-equilibrium fashion which also results in reduced protection of the cliff toe (Taylor et al., 2004). The trends in shore steepening are supported by the model tests of Walkden and Dickson (2008), outlined in Figure 2-6. This trend is due to a decrease in the amount of time that each elevation of the cliff is exposed to wave attack with increasing rates of sea-level rise.

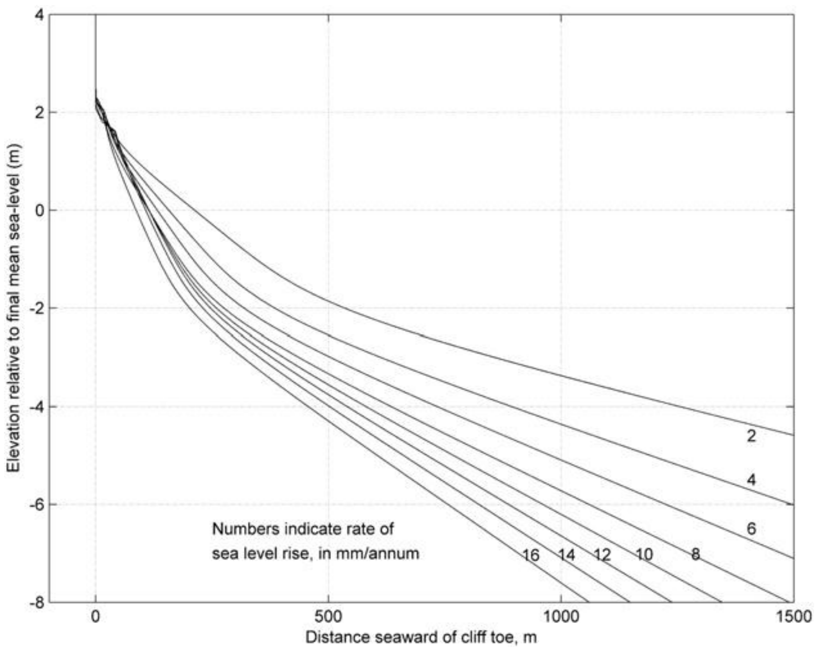

Figure 2-6: Equilibrium Shore Profiles under a Range of Sea level Rise Rates Performed Using the SCAPE Model (Walkden and Dickson, 2008)

In contrast to the above studies, numerical modelling by Lowe et al (2009) using the European Shelf wave model, considering a medium-high emissions scenario suggested only small increases in mean significant wave heights for the East

Anglian coastline (UK) with sea-level rise. Furthermore, only small changes in wave directionality for the southern North Sea were predicted as further supported by Chini et al (2010). Based on these findings, Brooks and Spencer (2012) concluded that the key driving climatic influences on marine processes is sea-level rise, and not associated changes in wave conditions, as supported by Woodworth and Blackman (2004).

2.2.4.3 Storms and storm surges

Along with sea-level rise, the consequences of global environmental change are also likely to include an increasing frequency and magnitude of extreme weather events (Thorne et al., 2007). Wind storm events and storm surges (elevation water levels as a result of low pressure weather systems) will increase the exposure of the cliff toe to wave energy. Brooks and Spencer (2010) identified from a literature review a number of correlations between this factor and short term cliff recession for the Suffolk coast, UK, namely:

- 12-27 m of erosion between 1951 and 1953 associated with the North Sea storm surge of 1953 (Williams, 1956);
- 34.8 m of retreat between 1977 and 1979 attributed to the 11th January 1978 storm surge (Steers et al., 1979); and,
- 15.8 m of recession occurred between winter 1993 and winter 1994 (Lee, 2008).

Contrastingly, Dornbusch et al (2008) reported a decrease in cliff recession rates in east Sussex despite an observed increase in winter storms between 1940 and 1996 provided by Lozano et al (2004). This may be because wave energy is related to the square of wave height, considering that high waves break in deep water and dissipate their energy in the wide, turbulent surf zone; large waves may therefore be less effective erosional mechanisms than waves of moderate height (Trenhaile, 2010). Similarly, Trenhaile (2011) only identified a slight increase in cliff recession as a result of an increase in storminess (represented by a 10% increase in frequency of the three highest waves) considering the results of a process-based cohesive cliff retreat model. However, within the model set-up the initial frequencies of the three large waves were low and therefore an increase would only have a minor effect on overall patterns of erosion.

2.2.5 Human sub-system

The anthropogenic influence of coastal defences and slope stabilisation/artificial drainage was recognised by Del Rio & Gracia (2009). Coastal defences at the cliff toe will directly prevent basal marine erosion. However, they may indirectly encourage downdrift erosion by providing a barrier to sediment downdrift along the littoral system (Brown, 2008). Artificial slope stabilisation methods including drainage will clearly increase the factor of safety of the cliff and reduce the likelihood of processes of mass movement. These parameters will not be discussed in further detail within this thesis which is focussing on natural environmental and climatic changes to the cliff system.

2.3 Integrated systems model of the soft cliff system

Section 2.2 reviewed the range of factors driving the cliff system and demonstrated its diverse nature. A range of positive correlations and interactions between the sub-systems listed in Table 2-1 (and associated factors) have been outlined. For example, rainfall (meteorological and climatic sub-system) affects the pore water pressures and shear strength (geotechnical, geological and hydrogeological sub-system) of the cliff. This combines with basal marine erosion (coastal and marine sub-system) to influence slope stability and in turn cliff recession.

Such interactions highlight the importance of a holistic understanding of the cliff system. To facilitate this, a revised systems-based model of cliff processes is required, which will be presented in stages in this sub-section. The model has been developed considering:

- The key geomorphic features of the cliff system (Figure 1-1);
- The various sub-systems and associated factors influencing the cliff system (Table 2-1 and Section 2.2);
- Examples of previously proposed conceptual models including: Meadowcroft et al (1999), Lee et al (2001), Walkden & Hall (2005), Walkden & Dickson (2008) and Castedo et al. (2012).

Considering the complexity of the cliff system, it is beneficial to break down the model into the two key portions identified in Section 1.2.1; a) Coastal and Marine; and, b) Terrestrial (encompassing both the geotechnical, geological and hydrogeological and the sub-aerial sub-systems). The meteorological, climatic and human sub-systems are external factors which influence both of these portions.

Figure 2-7 presents the model of the coastal and marine portion, identifying the interactions between the key parameters and processes. The key features (identified from Figure 1-1) are the shore platform, the overlying beach, talus material and the cliff toe (highlighted in bold). Between these features an important feedback mechanism can be identified (highlighted in green); namely between the protection afforded to the cliff toe by the shore platform and the overlying fronting beach (which is typically fed by talus material from the cliff and onshore sediment transport). In a system where the shore platform and beach are of significant volume to provide protection to the cliff toe, there will be reduced cliff toe erosion. However, over time the beach will diminish (unless additional sources of beach sediment are available) as less material is provided from the cliff to nourish the beach and existing material is removed by sediment transport. As the beach volume decreases so will its protective capacity, resulting in shore platform lowering and increased exposure of the cliff toe to wave attack. This will lead to increases in cliff erosion until a point where the overlying beach has recovered and regained its protective capacity. This feedback mechanism has been well documented by Walkden & Hall (2005) and Walkden and Dickson (2008).

Figure 2-8 describes the terrestrial portion; this predominantly revolves around the stability of the slope and the onset of mass movements. A key feedback can be recognised between cliff undercutting, which increases the shear stress and in turn reduces the factor of safety of the slope. At the critical point this will induce mass movement from the cliff top, delivering talus material to the cliff toe. This directly links back to the coastal system where talus material provides some limited protection to the cliff toe and contributes to the protective beach volume.

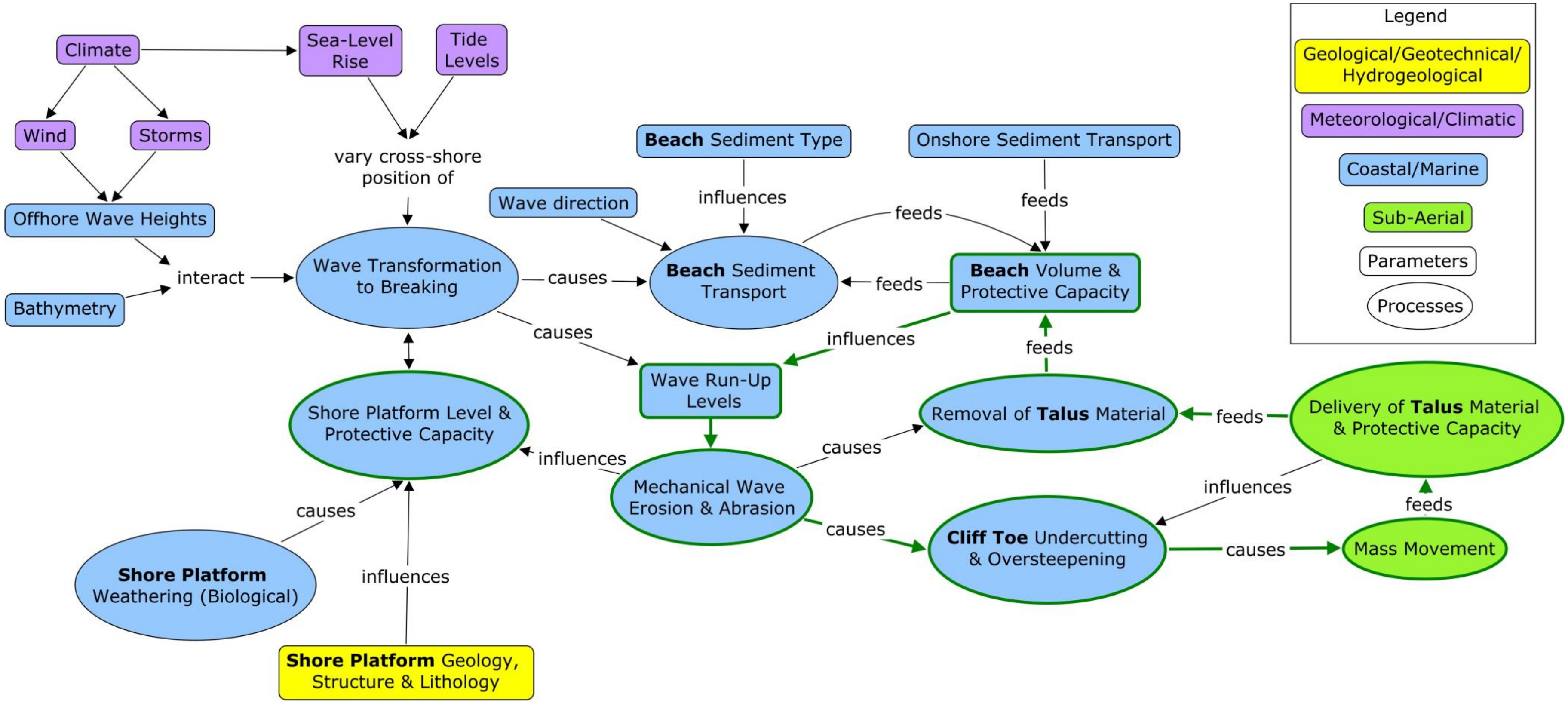

Figure 2-7: Systems model of the coastal and marine portion driving the soft cliff system [34]

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[3] The presence of coastal engineering structure and beach nourishment has not been included within the model

[4] Definition of linking terms:

- Causes – where a parameter or process can directly influence another.
- Influences – where a parameter or process is linked to another.
- Feeds – where a parameter or process drives or provides material to another.

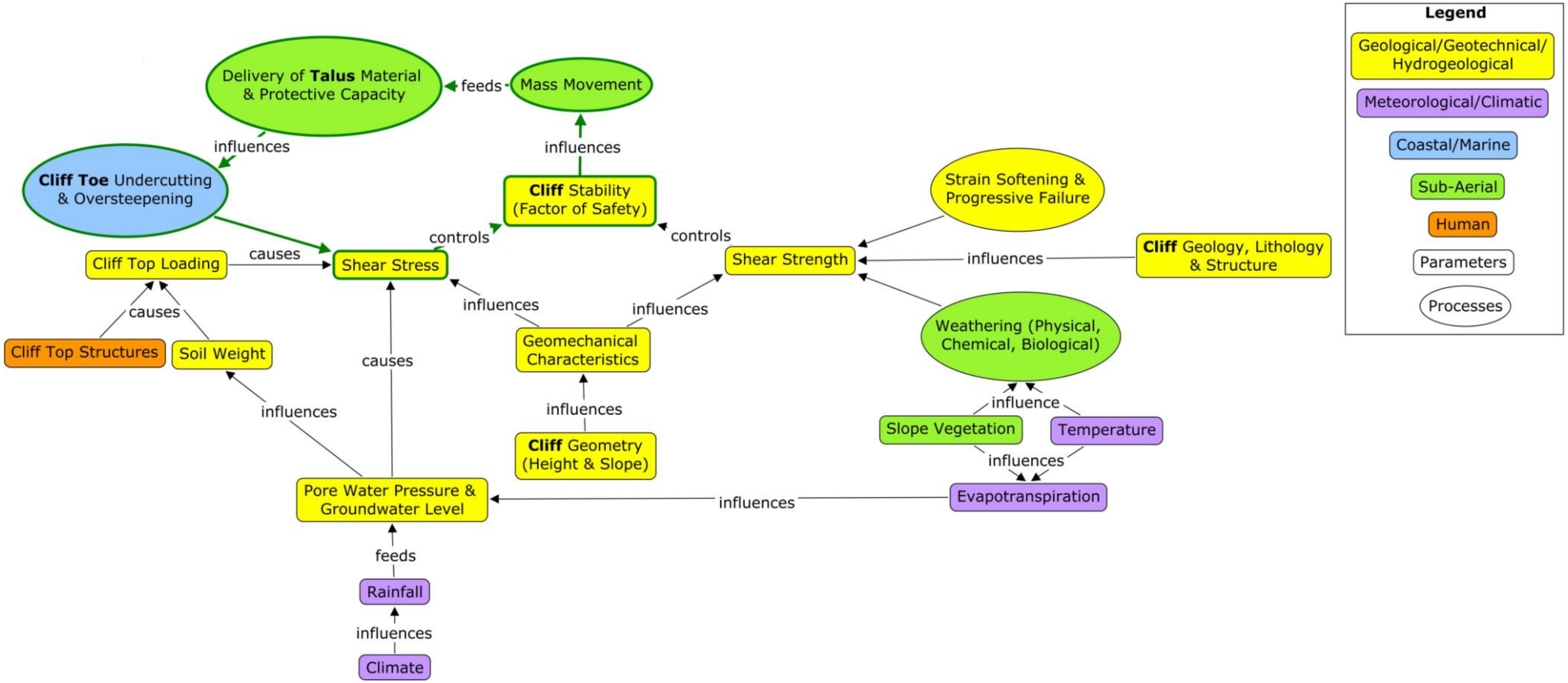

Figure 2-8: Systems model of the terrestrial portion driving the soft cliff system[56]

[5] The anthropogenic impacts of artificial slope stabilisation and drainage are not included within the model.
[6] Definition of additional linking terms:

- Controls - identifies governing parameters

By combining the coastal/marine and terrestrial portions, a final coupled model of the cliff system is presented in Figure 2-9. From this, key linking features between the two portions can be identified:

- The cliff toe, which forms the key interface through wave energy inducing cliff undercutting and over steepening and the subsequent stresses imposed on the cliff slope resulting in instability.
- The delivery of talus material from the cliff top, which can provide temporary protection to the cliff toe from wave energy and contribute towards the protective beach volume.
- The shore platform, which affords protection to the cliff toe through the attenuation of wave energy. The geology of this feature is also typically related to a layer of stratigraphy within the cliff face (although the resistive strength may vary owing to different processes acting on each face).

Based on these linkages, a governing path through the soft cliff system can be recognised, as highlighted in red on Figure 2-9. Within this pathway, the geology, lithology and structure of the cliff face and shore platform can be identified as a key parameter.

The model demonstrates the dynamic, integrated nature of the soft cliff system. It is termed 'generalised' as it attempts to encompass all parameters and processes which have been identified from the review. It is believed that this can form the foundation of an assessment for any CBU, enabling initial consideration of all factors before the key drivers at a specific site are identified. For example, as recognised under the sub-aerial category of Table 2-1, coastal cliffs at climatic extremes may be more influenced by the processes of weathering than those at temperate regions, where they may be considered negligible.

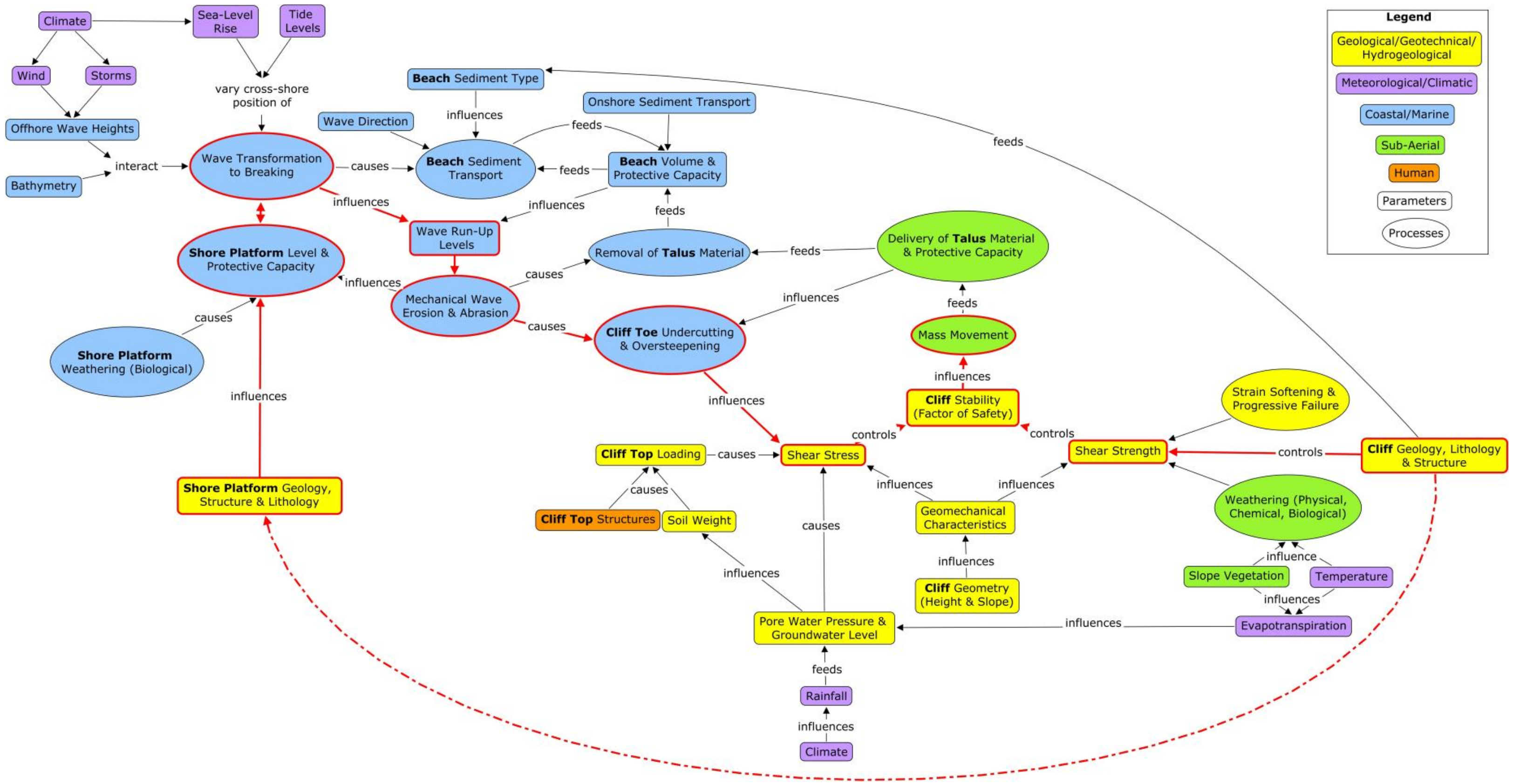

Figure 2-9: Generalised systems-based model of the soft cliff system[7]

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[7] The presence of coastal engineering structures at the cliff toe, beach re-nourishment and artificial slope stabilisation/drainage is not included within the model.

2.4 Soft cliff system: closing comments

The first objective of this research was: *to take a systems view of the soft rock coastal cliff system*. This chapter has subsequently provided a review of the broad range of literature relating to the system, including both field data and numerical model results. The relationships identified have been summarised in a systems-based model (process map).

As introduced in Section 1.1, a major limitation of existing prediction methods is the oversimplification of the cliff system. This is frequently considered to be driven either by coastal/marine or terrestrial processes, while the two are rarely considered in unison. The model demonstrates the importance of cliff toe controls (e.g. geology, lithology and structure) which form a key interface between the coastal/marine and terrestrial portions. Therefore Figure 2-9 provides a foundation for the critical analysis of existing methods and for the development of a new, coupled model.

At this stage of the study, the method was primarily based on findings of the literature review. No attempt was made to verify correlations with additional modelling or field data as the purpose of this objective was to provide a generalised understanding of the soft cliff system that could be applied to any site.

3. Isle of Wight Study Frontage

To confirm key relationships within the cliff system, this research will be supported by observations from real sites. Therefore, as introduced in Chapter 1, insight will be drawn from a study frontage on the south west coast of the Isle of Wight (IoW). This chapter presents details of this frontage:

- Section 3.1 outlines its location and history;
- Section 3.2 provides justification for its selection;
- Section 3.3 describes its physical characteristics;
- Section 3.4 closes this chapter.

3.1 Location and history

The IoW is situated offshore of the south coast of England, UK. The study frontage extends approximately 15 km across the south west coast from Compton Bay to Chale (Figure 3-1). The boundaries have been selected considering the geological constraints to the north (where the cliffs change to a harder chalk geology) and the presence of the Blackgang Chine Landslide to the south (which would be inappropriate to model as it is strongly controlled by geotechnical processes).

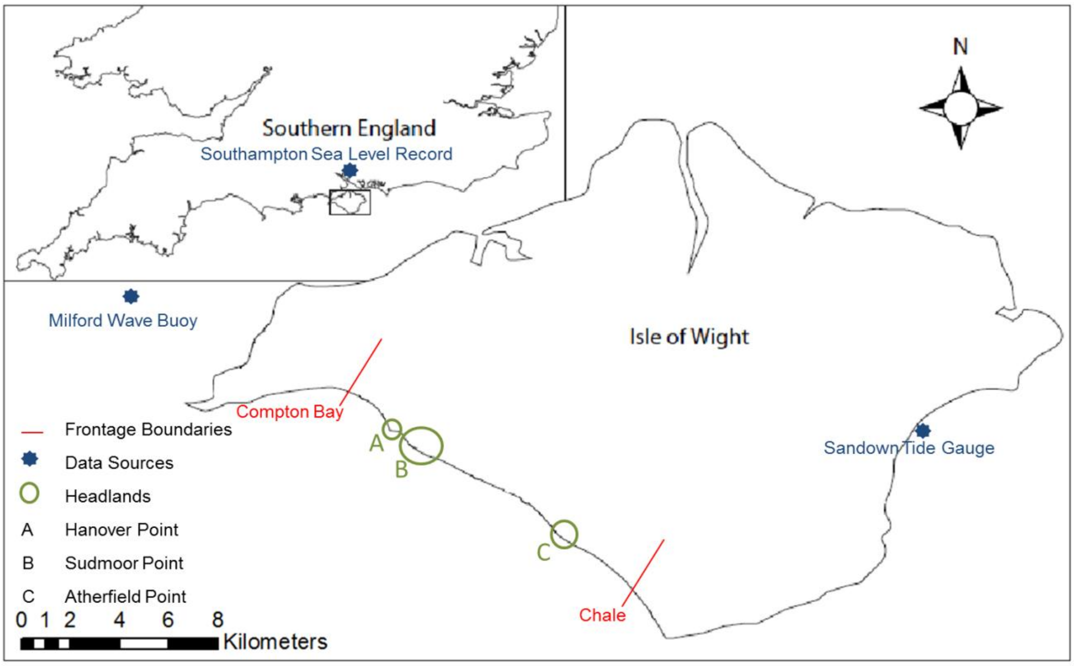


Figure 3-1: Map of the Isle of Wight outlining the Study Frontage, adapted from Leyland (2009)

The shore is unprotected and is covered by a long term policy of 'No Active Intervention' (NAI) within the Island's Shoreline Management Plan (SMP). This is predominantly owing to the areas environmental and landscape importance (as reflected by a number of conservation designations at the site including:

- Compton Chine – Steephill Cove Site of Special Scientific Interest (SSSI);
- World Heritage Coastline;
- Area of Outstanding National Beauty (AONB).

The policy of NAI is further supported by the lack of feasibility and economic justification for localised intervention works (Isle of Wight Council et al., 2010a). However, the cliffs are retreating at a steady rate of 0.2 – 0.5 m/yr as supported by a variety of studies (SCOPAC, 2004), which poses a range of coastal management issues. There are a number of communities and isolated properties which have been lost along the frontage and the A3055 Military Road (which is key infrastructure) had to be realigned in the 1930's at Compton, requiring substantial investment. Two significant stretches of the road are currently recognised as under threat within the study frontage, with one area resulting in a lane closure owing to recent landslide activity (Isle of Wight Council et al., 2010b). This highlights the need for long-term land-use and coastal planning, which is exacerbated by the unknown future impacts of climate change.

3.2 Rationale for frontage selection

The study frontage has been selected considering the areas:

- Varied soft rock lithology, which includes varying strength and composition, and its unique structural geology;
- Diverse geomorphology, which includes a series of headlands and bays and a range of CBU's;
- High long-term rates of retreat combined with coastal management issues;
- Natural character, which has not been interrupted by coastal engineering structures, thus providing a clear picture of natural fluctuations in retreat;
- Data availability.

A particular advantage of the frontage is the opportunity to study more complex cliff systems. For example, it can be noted (as will be further discussed in the following chapter) that the majority of existing soft cliff models have been developed for specific, simple cliff sites. For example, previous applications of the SCAPE model have focussed on the north Norfolk coastline (Dickson et al., 2007). This gently curving, 50 km frontage consists of continuous simple cliffs of relatively homogenous lithology fronted by substantial protective beach volumes. Contrastingly, the shorter, study frontage of the IoW exhibits a varied lithology, a diverse coastal planform, a range of CBUs and low fronting beach volumes as will be further introduced in this chapter.

3.3 Physical characteristics

All of the geological formations of the IoW consist of sedimentary rocks dating from the Cretaceous and early Tertiary Eras, as outlined in Figure 3-2. The study frontage consists of the Wealden and Lower Greensand series of the Lower Cretaceous (approximately 112-120 million years old), the latter of which is overlain by Pleistocene deposits (Stuiver, 2010). The geology has been compressed into an asymmetrical fold known as the Brighstone anticline (Insole et al., 1998).

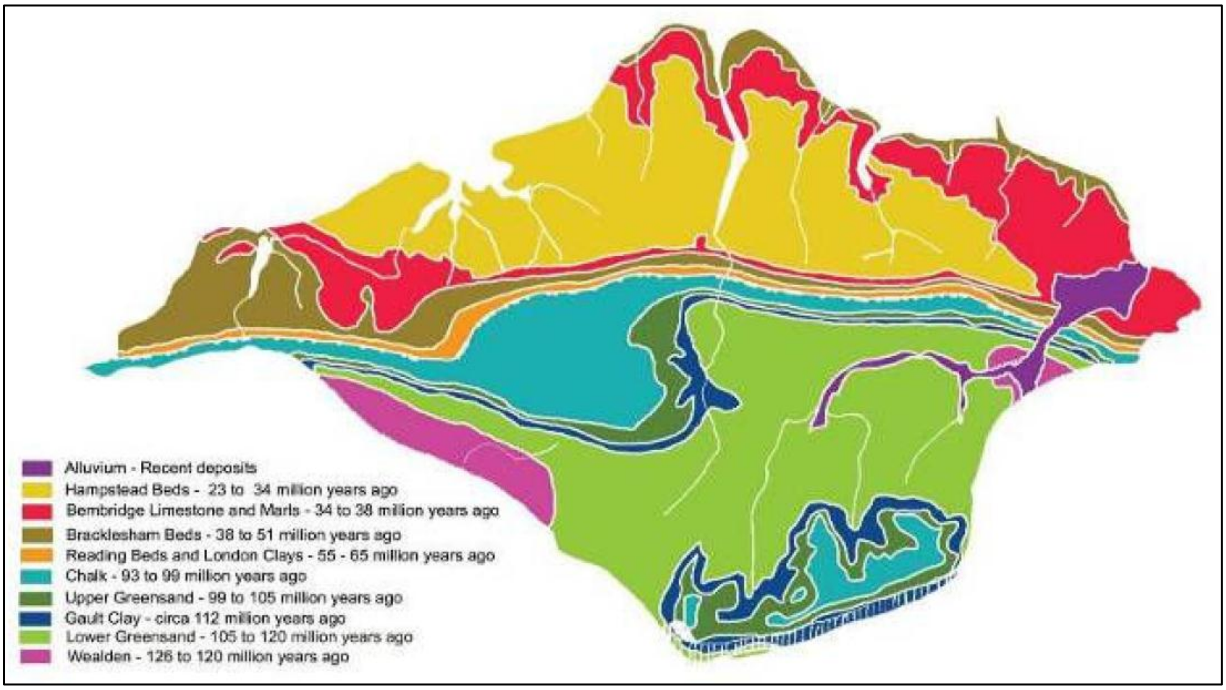


Figure 3-2: Geological map of the Isle of Wight (BGS, 2010)

The coastline of the IoW has been shaped by major sea-level fluctuations. The rising levels of the early Holocene reoccupied the former degraded cliffs, renewing erosion of the soft geology to form the rapidly retreating cliffline seen today (Leyland and Darby, 2008). These cliffs are typically 30 m high with some local variation from approximately 10 m in the north east to in excess of 50 m to the south west. Their morphology varies spatially, reflecting the differing combinations of controlling factors, which highlights the complexity of the frontage. The cliffs typically adopt simple landslide morphology. However, local transitions to complex landslides do exist, particularly towards the south west. This results in periodic high magnitude cliff top events (Isle of Wight Council et al, 2010b).

The frontage is interrupted by a number of coastal gullies (known locally as chines) and is divided into four bays (Compton, Brook, Brighstone and Chale) separated by three discrete headlands (Hanover, Sudmoor and Atherfield respectively, Figure 3-1). Representative images of the study frontage are provided in Figure 3-3.

The headlands are persistent features that can be recognised on maps by the cartographer John Speed dating back to 1611 (University of Cambridge, 2013). Their presence is attributed to the variable lithology of the study frontage in both the longshore and vertical directions, which includes a range of Shales, Marls, Clays and Sandstones. Their geological characteristics are described in Table 3-1, within which the coherence of the rock relates to a visual appraisal for soft rock lithology based on Soares (1993). Coherent rocks are distinguished as those hard to break by hammer impact (compressive strength of approximately 20 MPa) through to non-coherent rocks, described as those which disintegrate easily under finger pressure (<0.5 Mpa). The varying coherence of these materials has been identified as a key control on the development and elevation of dissipative fronting shore platforms and in turn on headland evolution (Stuiver, 2013).

Figure 3-3: Representative images of the study frontage; A) Compton Farm landslide looking north to the chalk cliff frontage boundary; B) Compton Bay looking south showing shore platform; C) looking north from Brook Bay to Hanover Point; D) Sudmoor Point, note the stronger outcropping Barnes High Sandstone and extensive debris material at cliff toe; E) Brighstone Bay looking north; F) Atherfield Point, note the increasing presence of shingle and gravel on beach; and G) looking south from Atherfield Point to Chale Bay, note the outcropping Perna Bed shore platform.

Table 3-1: Geological characteristics along the study frontage, adapted from Insole et al (1998) and Stuiver (2013)

Group	Formation	Member	Lithology	Coherence (Coherent (1) to non-coherent (4))	Additional Comments on Bedding & Structure	Estimated Beach Grade Material[8] (%)
	River Terrace Deposits	Brickearth	Windblown silt	-		35
		Valley Gravel	Coarse angular flint gravel in a sandy matrix	-		76
Lower Cretaceous	Ferruginous Sands	A range of 11 members	Red and Grey Sandstone	1		38
			Whale Chine sandy clays	2		35
	Atherfield Clay	Upper Lobster Beds	Alternating muds and sandy silts	3 – 4		0
		Crackers	Fine sand with concretions	1[9]	Large blocks become detached from the cliff. Massively bedded. Jointing of 10's cm's under the initial weathered surface.	0
		Lower Lobster Beds	Clay	2 (when dry)		0
		Chale Clay	Clay	2		0
		Perna Bed	Calcareous sandstone and sandy	1 (upper) – 2 (lower		0

[8] Beach Grade Material refers to the proportion of sediment that is sufficiently coarse to be retained on the beach (i.e. that which exceeds the littoral cut-off diameter)
[9] Note that tensile strength greatly reduced when saturated

Group	Formation	Member	Lithology	Coherence (Coherent (1) to non-coherent (4))	Additional Comments on Bedding & Structure	Estimated Beach Grade Material[8] (%)
			clay	clay)		
Wealden Beds	Vectis Shale	Shepherd's Chine Barnes High Cowleaze Chine	Inter-bedded Shale and Silt Channel Sandstone Inter-bedded Shale and Silt	2 1[10] 2	Thickly laminated but thinly bedded so more susceptible to weathering and erosion.	1 75 1
	Wessex Marls		Variegated marl inter-bedded with channel sandstones	2(Marl) 1(Sudmoor point sandstone) 3 (Compton Bay sandstone)	Massively bedded. Distinctive pattern of fine fractures.	0 29 3

[10] With the exception of Compton Bay where Member is non-coherent (4)

The cliffs deliver large quantities of sediment to the shoreline. However, most material is believed to be removed offshore in suspension, as indicated by the estimated proportion of beach grade material in Table 3-1. As a result, beaches along the frontage are of low volume, resting as a veneer of sediment on top of the shore platform. Assessment of the Beach Wedge Area, BWA[11] (following Lee, 2008) by Stuiver et al (2013) indicates that the beaches are of insufficient volume to influence rates of cliff toe retreat.

The beaches can be divided into three units based on abrupt changes in median grain size; 1) From the northern boundary of the study frontage to the south of Sudmoor Point the beach displays a dissipative form (i.e. shallow beach slope where wave energy is dissipated over a long distance) and is composed of medium to fine grained sand; 2) From the south of Sudmoor Point there is an increase in the backshore grain size creating a pebble beach which takes on a reflective form until Atherfield Point; and, 3) At Atherfield Point the grain size drops to coarse sand, gradually increasing to the south becoming pebbles again by the southern boundary of the study frontage (Carpenter et al., 2012).

3.3.1 Hydrodynamic climate

The frontage has oceanic fetches in excess of 4,000 km across the Atlantic along with shorter fetches across the English Channel (Isle of Wight Council et al., 2010b). It is exposed to significant swell wave activity as well as to energetic, locally-generated wind waves. Wave data from the Milford Wave Buoy (data from 1996 to present), located to the north west of the study frontage (as indicated on Figure 3-1) shows that the predominant wave direction is from the south south-west with a five year significant wave height of 3.93m (Channel Coastal Observatory, 2010).

The tidal characteristics vary alongshore as the site is close to a degenerate amphidromic point. The tide has been interpolated to represent the study frontage (Table 3-2). The tidal range is small so that wave energy is concentrated over a limited vertical range. However, the shallow nearshore and shore platform causes some dissipation and breaking of large waves some distance offshore.

[11] Beach Wedge Area refers to the triangle that defines the width and maximum elevation of the beach above MHWS

Net wave driven sediment motion in the area is from the north west to the south east. The offshore to onshore supply of sediment by wave-induced or tidal current may account for a proportion of the fronting beaches along the frontage. However, knowledge of nearshore sediments and possible pathways of transfer to littoral transport is very limited (Brampton et al., 1998) and the field characteristics of the cliff/beach system is being further investigated. Just outside the boundaries of the study frontage, the Needles and St Catherine's Point are current-swept bedrock surfaces which imply limited supply potential (Isle of Wight Council et al., 2010b).

Table 3-2: Tidal characteristics at the study frontage

Tide	**Level (m OD)**
Mean High Water Spring (MHWS)	1.12
Mean High Water Neap (MHWN)	0.62
Mean Sea Level (MSL)	0.04
Mean Low Water Neap (MLWN)	-0.54
Mean Low Water Spring (MLWS)	-1.24

Sea levels have been rising at a rate of approximately 1.4mm/yr ±0.54 considering the results of Haigh (2009) for Southampton. The rate of relative sea-level rise is projected to increase at the study frontage. The SMP currently considers the projections of Defra (2006) as indicated by Table 3-3.

Table 3-3: Sea-level rise projections at the study frontage (Defra, 2006)

	Epoch			
	2009 to 2025	**2025 to 2055**	**2055 to 2085**	**2085 to 2105**
Rate of Sea Level Rise (mm/yr)	4.0	8.5	12.0	15.0

3.4 Isle of Wight study frontage: closing comments

This chapter has introduced the study frontage of the south west coast of the IoW. Reference has been made to its unique nature which includes a variable soft cliff lithology and diverse geomorphological composition. Considering the importance of real world observations, the site will be used to provide insight into cliff systems in the evaluation and development of cliff models (objectives 2 and 3 of this research).

4. Research Methodology

Based on objective two; *to assess the limitations of existing cliff models*, this chapter presents the research methodology of this study. The chapter structure is as follows:

- Section 4.1 reviews the range of currently available prediction approaches;
- Section 4.2 provides an evaluation of each approach leading to the selection of an appropriate model for application within this study;
- Section 4.3 provides a detailed critical appraisal of the selected model;
- Section 4.4 concludes this chapter.

4.1 Review of soft cliff prediction methods

This Section presents a review of the range of soft cliff prediction methods currently available in contribution towards objective two of this research.

4.1.1 Introduction

An increased understanding of geomorphological relationships within the cliff system is important to understand future rates of retreat and inform sustainable coastal management activities (Lee et al., 2001). It is a key component of the decision-making process when assessing the level of risk to coastal assets and identifying preferred options for strategic defence - informing the economic viability and cost effectiveness of capital schemes (Hall et al., 2000). It also supports the formulation of land-use planning policies, which avoid locating developments in areas where erosion is likely to occur during the lifetime of a building or for determining appropriate set-backs for managed realignment. Finally, measurement of recession rates is of value for monitoring the performance and effectiveness of coastal defence schemes and their impact on the recession of neighbouring cliffs.

In response to this need, a range of prediction approaches have been developed which fall into five main approaches, outlined in Table 4-1. These approaches involve an increasing degree of analysis and rigour. However, this does not necessarily correspond to an increasing degree of accuracy.

Table 4-1: Summary of available prediction techniques

Prediction Approach	Techniques	Example Application
Extrapolation from Historic Data: Based on the assumption that past cliff recession data can be used to inform future rates.	• Simple Extrapolation • Linear Regression Analysis • Non-Linear Methods	• Lee & Clark (2002)
Structured Use of Expert Judgement: Relies on the individual(s) experience, expertise and understanding.	• Direct Approach • Stability Analysis • Historical Frequency • Development of Process-Response Relationships • Event Trees	• Lee & Clark (2002) • Lee (2005)
Empirical Prediction Methods: Determined based on observations as opposed to theory.	• Geometric Models • Sediment Budget Methods • Data-Based	• Bruun (1962) • Sunamura (1988) • Dean (1991) • Bray and Hooke (1997) • Kamphuis (1987) • Walkden & Dickson (2008) • Quinn et al (2010)
Probabilistic Simulation Modelling: Accounts for the potential variability in	• Single Distribution • Two-Distribution	• Lee et al (2001) • Hall et al (2002)

Prediction Approach	Techniques	Example Application
predictions by utilising the Monte-Carlo analysis technique.		
Process-Response Simulation Modelling: Enables the simulation of changing future conditions and how they may interact with the cliff mass.	• Deterministic or Probabilistic Numerical Modelling	• Meadowcroft et al (1999) • Walkden & Hall (2005) • Valvo et al (2006) • Trenhaile (2009, 2010) • Castedo et al (2012, 2013)

The remainder of this section provides an overview and evaluation of each of the prediction approaches and associated applications presented in Table 4-1.

4.1.2 Extrapolation from historic data

This section outlines key applications under the approach of extrapolating retreat rates from historic data.

4.1.2.1 Simple extrapolation

This technique involves the adoption of the average rate of recession for either a full period (earliest and latest measurements) or for each measurement period (including intermediate measurements) and projecting this rate into the future.

*Recession by year N = Mean Recession Rate * t*

Equation 4-1

where the future cliff position is a function of the mean recession rate and the time period (*t*) in years. The change in cliff position may also be expressed probabilistically by taking account of the variability within the historic record by adding the standard deviation to the mean recession rate.

4.1.2.2 Linear extrapolation

This technique applies a continuous linear model to historical data (Amin and Davidson-Arnott, 1997, Crowell et al., 1997, Hall et al., 2002). Considering the likely lack of data and potentially large sampling intervals, linear regression is most appropriate where cliff recession is dominated by an on-going removal of debris material and frequent landslides (Hall et al., 2002).

$$X_t = \beta_0 + \beta_1 t + \varepsilon$$

Equation 4-2

where X_t is the recession distance at time t, ε is a random variable that has a Gaussian distribution with zero mean and variance v. Hence, the distribution of X_t will be Gaussian with mean $\beta_0+\beta_1 t$. If there are n historic observations of cliff position X_i, at time X_t, then the maximum likelihood estimators for β_0 and β_1 can be found from linear regression theory (Lee and Clark, 2002).

Linear regression analysis incorporating random sampling of recession rates can also be used to build up a probabilistic description of cliff position at a particular time. This approach also accounts for the potential variability in the recession rate, as defined by the probability distribution of the historic records. At each timestep the recession rate can be sampled from this probability distribution using a Monte-Carlo (random) sampling procedure and a time series of cliff positions derived representing one possible sequence of recession events. Repeating this procedure for a range of alternative sequences makes it possible to establish a probability distribution for the cliff position at any year in the future.

4.1.2.3 Non-linear extrapolation

This method may be considered at sites where changes in conditions (e.g. failure of defences or changes in prevailing conditions) have occurred. These variations may be detected by a change in the cliff recession rate at a certain point in time or as a continuous fluctuation in cliff recession (Lee, 2002). However, it is unlikely that sufficient measuring data will be available to predict these trends accurately and this method will not be considered in any further detail.

4.1.2.4 Summary of extrapolation from historic data

Historic cliff recession data typically consists of a limited series of measurements. Consequently the data is insufficient to identify individual recession events but can be used to produce an aggregated rate of erosion. This approach presents a simple approach to projecting historical recession measurements into the future. The uncertainty of the results can also be captured by using a probabilistic framework. However, there are a range of limitations:

- Historical records generally consist of limited measurements of questionable quality. Thus they can be insufficient to explain the pattern of recession events which led to the cumulative loss of land between the measurement dates.
- The historical record needs to cover a wide range (at least one cliff recession cycle) to ensure that infrequent, episodic events are adequately represented. This will limit potential under- or over-estimation of recession.
- Predictions will only be valid so long as the geological, environmental and climatic controls on the recession process remain unchanged. Exposures of a

different geology or changes in prevailing conditions will have a significant effect on future rates.

4.1.3 Structured use of expert judgement

The expert judgement method relies on an individual's geomorphological expertise to develop future scenarios based upon the available historic record and past behaviour. A number of different techniques may be utilised:

- **Direct Approach:** The assessment of recession scenarios based on professional judgement without reference to a detailed breakdown of the specific components of the system.
- **Stability Analysis:** Supplementing expert judgement with computer-based analyses of slope stability.
- **Historical Frequency:** Utilising historical information on the past occurrences of landslides at a given site.
- **Development of Process-Response Relationships:** Establishing initiating thresholds between various parameters and recession.
- **Event Trees:** Tracing the progression of the various combinations of scenario components using logic tree techniques to identify a range of possible outcomes.

Owing to the site specific nature of this approach, only one example of the development of an event tree is presented below as it describes the development of a more generic, structured methodology.

4.1.3.1 Event trees

Recognising the need to make judgements about the effects of changing environmental conditions and shoreline management practices on cliff recession rates, Lee (2005) presented a simple, systematic model for adjusting the historical recession rate to reflect the future. The model can be used either:

1. Deterministically – The effects logically follow particular causes in a non-random manner. The historical recession rate is modified with appropriate adjustment factors to generate a single modified rate, from which a 'best case', 'worst case' and 'best estimate' value can be derived; or

2. Probabilistically – To generate a probability distribution of the rate considering the uncertainty associated with predicting future conditions. An event tree is developed with an estimated probability assigned to each of the possible future conditions at each branch. Each fork in the branching network must represent a mutually exclusive alternative with a cumulative probability of 1.0.

The predicted recession rate for a particular case is described as equal to:

$$Predicted\ Recession\ Rate = Historical\ Recession\ Rate\ \times (S - L) \times w \times BL \times S \times CT$$

Equation 4-3: Deterministic Model

Or

$$P(Case\ n) = P(S - L) \times P(w) \times P(BL) \times P(S) \times P(CT)$$

Equation 4-4: Probabilistic Model

where, *S-L* is the sea level rise factor, accounting for changes in the recession rate owing to variations in sea-level (Box B, Figure 4-1); *w* is the winter rainfall factor accounting for expected changes in slope stability associated with changes in rainfall intensity (Box C); *BL* is the beach level factor, representing changes in the degree of cliff protection provided by the cliff (Box D); *S* is the storminess factor, accounting for changes in wave energy arriving at the shoreline (Box E); and, *CT* is the cliff toe protection factor that represents changes in toe protection including future shoreline management practice at the site (Box F).

The model was applied to the Covehithe cliffs, Suffolk, UK, using both approaches. The results provided a deterministic 'best estimate' of 7.4 m/yr, which was consistent with the predicted mean rate provided by the probabilistic model (7m/yr) and recent monitoring values at the site. The maximum probabilistic predicted value of 15.34 m/yr was noted to be significantly higher than the deterministic 'worst case' estimate (9.4 m/yr). However, this was attributed to the fact that the latter ignores the more extreme combinations of future conditions and past recession rates (Lee, 2005).

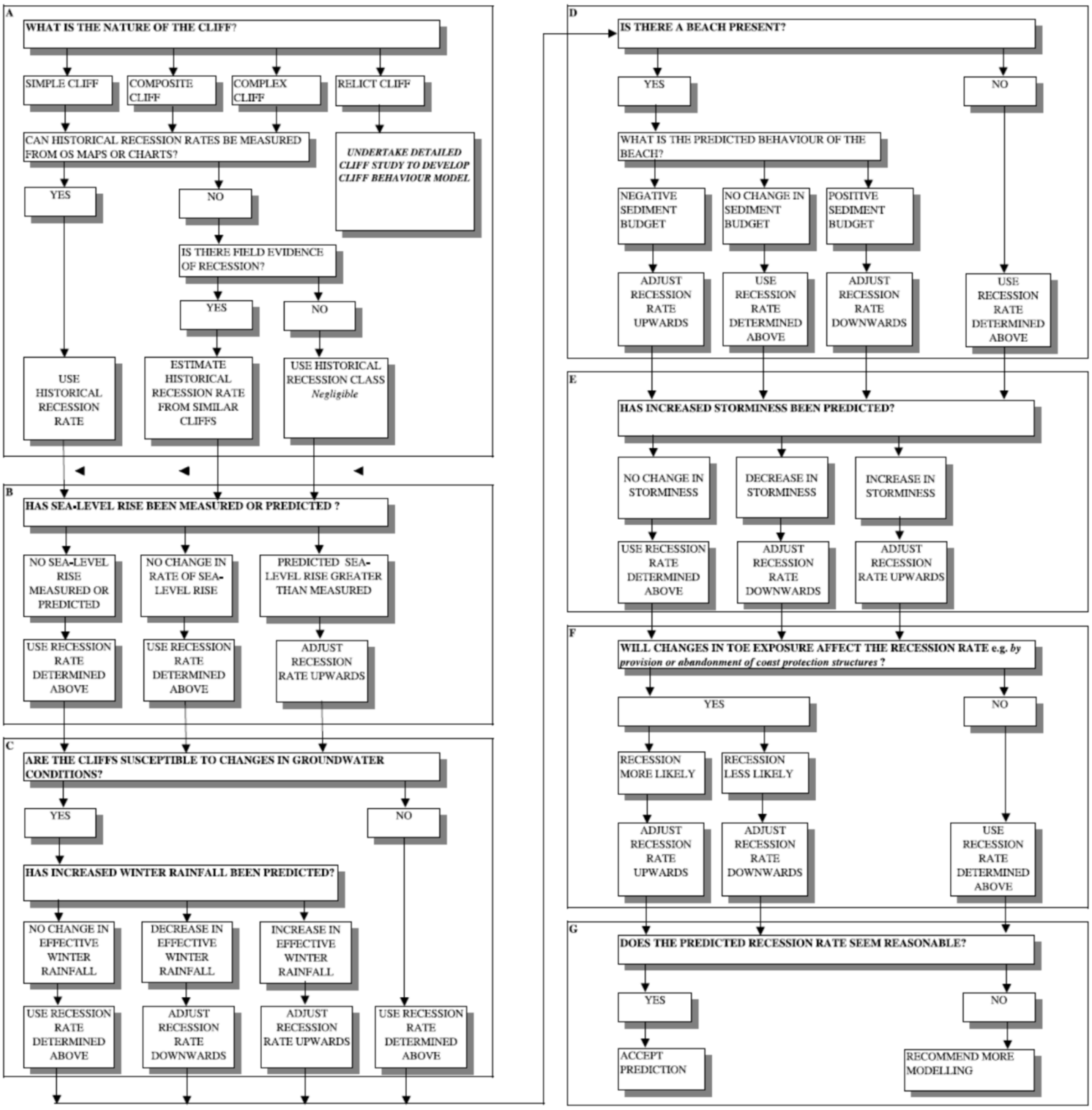


Figure 4-1: Framework of the simple prediction model (Lee, 2005)

4.1.3.2 Summary of structured use of expert judgement

Judgement based methods provide an alternative for when the application of historical records is considered unacceptable due to changing conditions or controls. One advantage is it can be applied with a limited range of data. However, judgements may be subjective. Therefore it is important that several possible scenarios are considered and systematically tested to develop reliable estimates (Lee, 2002). To improve the reliability of results it is also important that a broad range of experts are involved in the process to facilitate the collection of knowledge as well as limiting bias (Lee, 2005). The application of judgement based methods by individuals should be avoided unless more rigorous individual assessments, group consensus or sensitivity testing is used.

4.1.4 Empirical prediction

This section outlines key applications under the empirical prediction approach.

4.1.4.1 Geometric models

Bruun (1962) proposed that under rising sea-levels the beach equilibrium profile (i.e. its average long term form) would be maintained whilst rising with the average water level. To sustain this responsive increase in elevation, a volume of sediment is mined from the upper beach profile (A) and deposited on the foreshore (B). Consequently the beach profile translates landwards as it builds, as outlined in Figure 4-2.

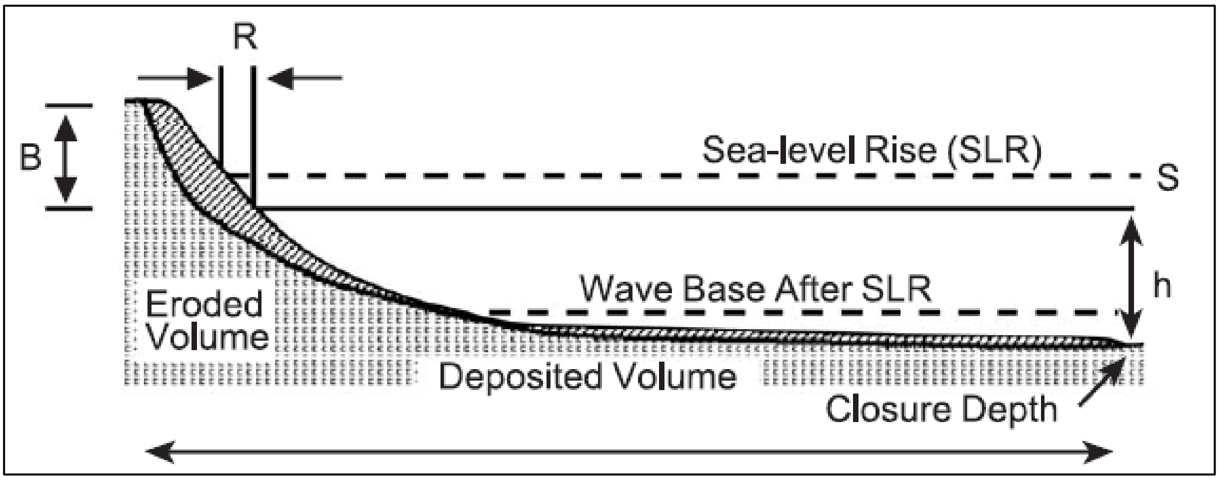


Figure 4-2: Diagrammatic representation of Bruun's sandy shore response to sea-level rise (Cooper and Pilkey, 2004)

This geometric model is defined by:

$$R = \frac{L_* S}{(B + h_*)}$$

Equation 4-5

Where, R is landward retreat, S is sea-level rise, L* is the length of the active (eroding) profile, B is the height of the retreating shore and h* is the depth of closure. The latter is the water depth on cross-shore profiles beyond which successive measurements show negligible vertical change and can be calculated using the formula of Hallermeier (1981b):

$$h_* = 2.28H_s - 68.5\left(\frac{H_s^2}{gT^2}\right)$$

Equation 4-6

Where, H_s is the effective wave height just seaward of the breaker zone that is exceeded for 12 hours per year (i.e. the significant wave height with a probability of exceedance of 0.0137%), g is acceleration due to gravity and T is the wave period associated with H_s.

The method provides a simple approach to understanding shore response under sea-level rise (SLR). However, this generalised replication of such a complex system also highlights a key limitation that many feedbacks are omitted (Stive, 2004). The model assumes that all sand transport occurs perpendicularly to the shoreline (cross-shore) and is therefore a strictly two-dimensional (2D) model that does not consider longshore sediment transport. The model also assumes an equilibrium profile and uniform sediment size across the profile. Another key issue of the Bruun Rule is the accuracy associated with determining the values of the input parameters. For example Ranasinghe and Stive (2009) reported a potential variability in predictions of 4,000% considering variations in the quantity of sea-level rise and the slope of the active bed profile for Sydney, Australia.

Overall, the model is deterministic and designed for sandy coasts, therefore it does not reflect the uncertainty and variability associated with the cliff recession process (Hall et al., 2002, Lee and Clark, 2002). Therefore previous comparative applications of the model to cliffed coasts have found the model to overpredict recession including Dickson et al (2007) and Brooks and Spencer (2012).

Where no dissipative beach is present, direct relationships may be formulated to predict recession according to material strength and wave power. Sunamura (1988b) presented a model where these two factors do not need to be explicitly stated as they are encompassed within the second use of the historic retreat term (Brooks and Spencer, 2012). Consequently, the data required to parameterise the model is simplified. However, this necessitates the assumption that there is no change in these two factors over time and subsequently the model is not applicable for sites of changing conditions (Bray and Hooke, 1997).

$$R_2 = R_1 + \frac{(S_2 - S_1)}{h_*/(R_1 + L_*)}$$

Equation 4-7

where, subscripts 1 and 2 denote prior and posterior conditions respectively.

Sunamura's model also assumes, similarly to the Bruun Rule, that the equilibrium cross shore profile is maintained as the shoreline retreats and that sediment does not accumulate at the cliff base (Brooks and Spencer, 2012). However, this is an important feedback mechanism which, as noted in Section 2.2.3, can significantly influence recession rates.

4.1.4.2 Sediment budget methods

To reliably model the three-dimensional (3D) situation, a full sediment budget of the shoreline needs to be calculated. Alternatively, it can be assumed that the historical recession rate represents the net contribution to the sediment budget. Based upon this assumption, Dean (1991) modified the Bruun Rule to provide an adjustment factor which represents the recession increase caused by sea-level rise:

$$R_2 = R_1 + S_c \frac{L_*}{P(B + h_*)}$$

Equation 4-8

where S_c is the change in the rate of sea-level rise and P is the sediment overfill function (the proportion of sediment that is sufficiently coarse to remain in the equilibrium shore profile).

The simplistic consideration of the sediment budget provides a more holistic representation of the coastal system in comparison to the Bruun Rule. In particular it represents feedback between sediments released through accelerated recession, followed by periods of reduced erosion. This is supported by Bray & Hooke's (1997) assessment of a range of prediction methods which concluded that the modified Bruun Rule was particularly suitable for their range of eight case study sites on the south coast of England. However, it is noted that concepts such as the depth of closure and the length of the active profile are difficult to define (Cooper and Pilkey, 2004, Nicholls et al., 1998). This gives rise to significant variability in results. For example, the depth of closure is not independent of timescale, as longer measurement periods, incorporating more extreme events and greater wave heights, are likely to include a greater range of closure depths (Nicholls et al., 1998).

4.1.4.3 Derived empirical methods

Kamphuis (1987) developed an expression to describe shoreline recession of glacial till bluffs at the Great Lakes. This included an expression of the erosion rate (*E*) which is based on consideration of wave power in the breaking zone, the energy contained in each breaking wave and the rate of energy dissipation:

$$E = \frac{H_{bs}^{13/4} T^{3/2} \tan\alpha}{M}$$

Equation 4-9

where H_{bs} is the breaking wave height, *T* is the associated wave period, α is the average slope across the surf zone and *M* represents material resistance and some hydrodynamic constants. The latter is found through calibration.

One disadvantage of this model is that it was developed for application on lake shores. It does not consider tidal effects and does not describe a beach or allow for variation in platform gradient across a shore profile or through time (Walkden and Hall, 2005). Furthermore, erosion in the model is dependent on abrasion as wave action is believed to be insufficient to erode foreshore material at such sites.

Walkden & Dickson (2008) used the equilibrium recession rates predicted from the process-based numerical model SCAPE (Walkden & Hall, 2005 - see Section 4.1.6) to derive an expression to describe the cliffs response to increased sea-level rise:

$$\varepsilon_2 = \varepsilon_1 \sqrt{\frac{S_2}{S_1}}$$

Equation 4-10

where ε refers to the equilibrium rate of recession. The equation is described as a numeric solution to the expression of erosion used within SCAPE and is applicable to soft rock coastlines with low (or absent) beach volumes subjected to an increase in the rate of sea-level rise. The model is only valid in the mesoscale and is not appropriate in the case of non-equilibrium conditions, including accelerating or zero sea-level rise. Another limitation is that it assumes the key driver on cliff recession is sea-level rise, while this may be true for simple cliffs (with limited storage of debris material at the cliff toe), it is questionable if the same generalisations can be made for more complex cliff systems.

Trenhaile (2011) developed a series of regression equations from his process-based model (Trenhaile, 2009, see Section 4.1.7) considering idealised profiles of soft and hard rock coasts in a 2 m tidal environment. Strong relationships between the amount of cliff recession over the 100 years preceding sea-level rise and the amount of recession during the present century. A range of six different scenarios to describe varying combinations of historic and future sea-level rise rates and storm conditions were presented, as highlighted in Table 4-2. Increased storminess was described as a 10% increase in the frequency of the three highest waves.

Table 4-2: Regression equations for erosion in the present (Y, dependent variable) and last (X, independent variable, actual historic recession) centuries (Trenhaile, 2011)

Scenario	Historic century conditions	Future century conditions		Regression Equation
	Sea-level Rise	Sea-Level Rise	Storminess	
1	Constant	Slow[12]	Unchanged	$Y=4.22X^{0.80}$
2	Constant	Fast[13]	Unchanged	$Y=13.47X^{0.47}$
3	Constant	Slow	+ 10%	$Y=4.3X^{0.79}$
4	Constant	Fast	+ 10%	$Y=13.63X^{0.47}$
5	Slow	Slow	Unchanged	$Y=2.52X^{0.90}$
6	Slow	Fast	Unchanged	$Y=8.23X^{0.65}$

The process-based model used to derive the regression equations does not consider the effect of climate change on rates of weathering, mass movement or other subaerial mechanisms that reduce the strength of the rock and modify the

[12] Slow sea-level rise = 0.2m per century
[13] Fast sea-level rise = 1m per century

morphology of cliff or shore platforms. It also did not consider the effect of beach material in eroding or protecting rock surfaces which as demonstrated by Chapter 2 is a key feedback mechanism.

4.1.4.4 Data Based

In recognition of the impact that limited geomorphological data and over-generalised models can have on predictions, Quinn et al (2010) developed an empirical model for the Holderness coast. This was intended to account for the spatial and temporal variations in cliff failure mechanisms and how this is expressed in the aggregated rate of retreat. The model was developed based on cliff monitoring results and analysis using geotechnical modelling.

Intensive cliff monitoring was implemented at six study sites (each 100m in length) considered to be geologically and topographically diverse enough to represent the entire frontage. Monitoring consisted of monthly kinematic digital Geographical Positioning System (dGPS) surveys of the cliff top, cliff toe and beach crest along with seasonal Terrestrial Laser Scanning (TLS) of the entire cliff face. The data was processed and analysed to provide a qualitative overview of the landslides that had occurred and an impression of how the changes in the cliff correlate with alterations in the morphology and the beach. The data was used to validate a finite difference-based geotechnical modelling assessment of the cliff stability, utilising the fast lagrangian analysis of continuum (FLAC) code. The model was then used to simulate a range of scenarios to represent a range of conditions expressed along the study frontage. The results were combined to produce an empirical slope model that derives the rate of landslide induced retreat that would arise from mass failures under various future scenarios, as outlined in Figure 4-3.

The approach demonstrates how a short-term cliff monitoring campaign can be used to devise a site-specific empirical model. Quinn et al (2010) highlight that knowledge of the different failure mechanisms together with an understanding of their causes is important in selecting or developing statistical or process-based models. Therefore the results yielded could be further incorporated within a current process-based retreat model (e.g Walkden & Hall, 2005 or Trenhaile, 2009), with inputs to the empirical slope model specified directly, obtained from probability distributions or derived from marine and sediment transport modules. One disadvantage is that the results are site specific. Consequently they can only be applied to the Holderness region or areas of very similar ground conditions.

Furthermore, there appears to be no validation of the model at this stage which limits its reliability.

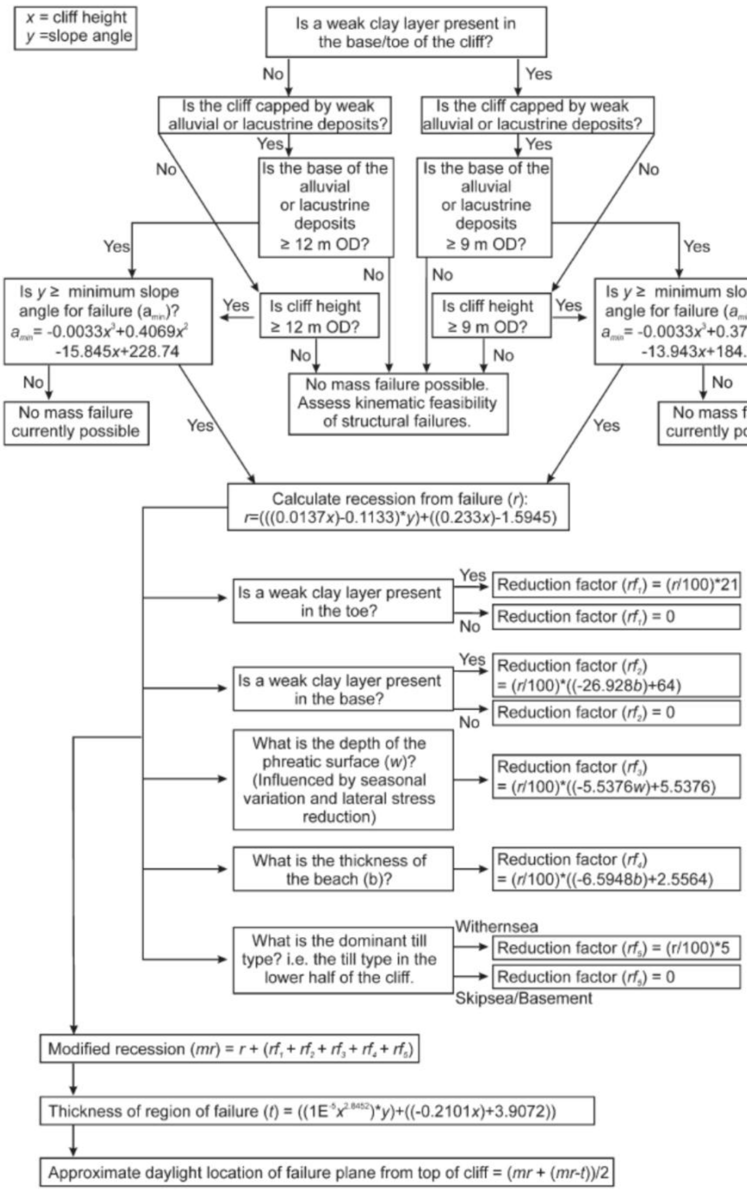


Figure 4-3: Empirical landslide model for the Holderness coast developed through the assessment of the response of numerical geotechnical models to different scenarios (Quinn et al., 2010)

4.1.4.5 Summary of empirical methods

A number of simple empirical methods are available to provide an indication of future rates of cliff retreat, in particular considering the impacts of sea-level rise. They apply basic rules to produce overall estimates of cliff recession. However, their over-simplistic replication of a complex morphodynamic system also forms their major limitation, with many parameters and feedbacks discounted (Stive, 2004). For example, anticipated changes in the frequency of wet year sequences may be considered as significant as sea-level rise in determining cliff behaviour and recession rates (Lee, 2002) but are not considered within any of the models identified in this review.

Empirical models may also be considered deterministic as they do not reflect the uncertainty and variability in the cliff recession process (Hall et al., 2002, Lee et al., 2001). For example, the cliff response to sea-level rise may not be in synergy with that of the shore profile depending on its morphology as highlighted in Section 2.2.1.2 (i.e. a simple cliff may respond rapidly to basal erosion whilst a complex cliff may experience a significant delay in response).

4.1.5 Probabilistic simulation modelling

This section outlines key techniques under the probabilistic approach.

4.1.5.1 Two-distribution models

Two-distribution models use probability distributions to represent the magnitude/frequency of recession events along with the time interval between them (Hall et al., 2002, Lee and Clark, 2002). A stochastic simulation method was described and demonstrated by Hall et al (2002) to reflect the episodic nature of cliff recession. The discrete model for cliff recession *X*, within duration *t* is:

$$X_t = \sum_{i=1}^{N} C_i$$

Equation 4-11

where *N* is a random variable representing the number of cliff falls that occur over time and C_i is a random variable representing the magnitude of the *i*th recession event. This model can be used to simulate a synthetic time series of recession data by sampling two distributions, the:

- **Event timing:** represents the timing between recession events using a gamma distribution. The model incorporates an understanding of the cliff recession process by representing the role which storms have in destabilising cliffs, as described by a density function.

- **Event size:** describes the magnitude of recession events in terms of the mean size and their variability using a log-normal distribution that was developed based on evidence from experimental tests of Damgaard and Peet (1999).

Three typical realisation of the model are shown in Figure 4-4. The time series are stepped, demonstrating that the model captures both the triggering and preparatory landslide factors, along with their timing and sequence. Probabilistic predictions of event size (over a given time) or time to recess a given distance can be extracted from multiple realisations of the model. Furthermore, the model can differentiate sensitivity between various CBU's by representing the number and magnitude of storm events needed to initiate a recession event (Lee and Clark, 2002).

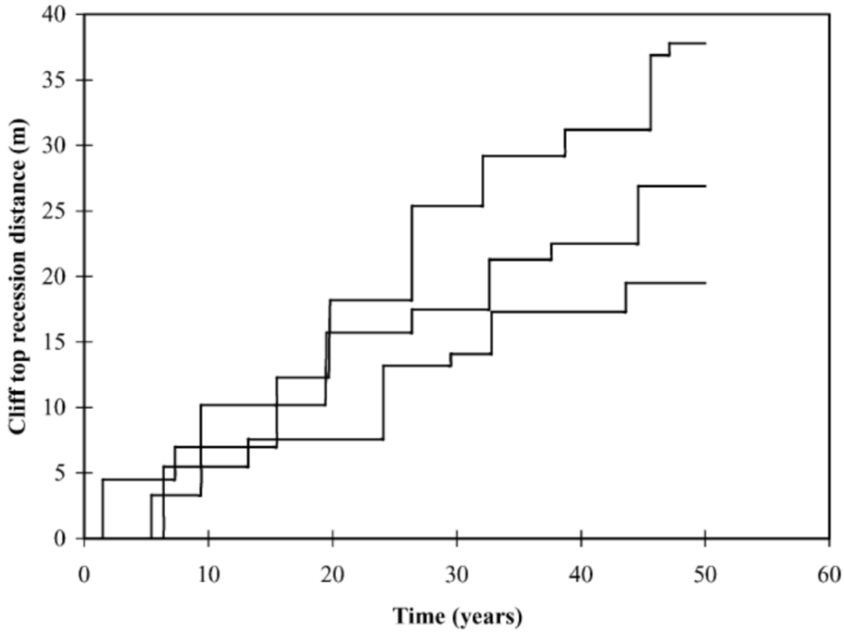


Figure 4-4: Typical realisations of the two-distribution simulation model (Hall et al., 2002)

4.1.5.2 Summary of probabilistic methods

Probabilistic methods overcome the issues associated with the scarcity of historic data (Lee, 2002). The approach also has the advantage of accounting for the potential variability in predictions. In summary, it enables expert geomorphological assessment of local landslide characteristics and measurements of individual cliff falls to be combined with historic records. Predictions can be made even when relatively small quantities of recession data are available. Therefore, this method may be preferable to conventional regression models, which are based on assumptions that are rarely consistent with the physical process of cliff recession. Such models may incorporate an episodic model of recession events which can be closely related to known cliff behaviour. One disadvantage of this method is the high computational cost associated with using maximum likelihood and Bayesian parameter estimation.

4.1.6 Process-response simulation modelling

A relatively recent technique is the development of prediction models based on interactions between nearshore, foreshore and cliff processes. These models provide the user with a formalised abstraction of real-world entities or processes, typically developed within a framework that can be implemented on a computer and which seeks to make assumptions explicit (Lee, 2005). A wide range of models are available that can be adopted and combined, including; slope stability, beach erosion, sediment transport models and wave transformation models (Lee, 2002).

For consistency, each model discussed in this section is referred to by its main publication given that some models do not have an official title.

4.1.6.1 Meadowcroft et al (1999)

Meadowcroft et al (1999) developed the CLIFFPLAN model, which simulates coastal landslide activity using Monte Carlo simulation to build up a probabilistic prediction of cliff recession. The model describes the processes affecting a series of 2D profiles consisting of cliff, beach and talus by considering the following main processes (Figure 4-5):

- Wave transformation and breaking;
- Shore platform lowering and recession (where present);
- Removal or material from the cliff toe by wave action and longshore sediment transport; and,
- Cliff landsliding (governed by the geometry, groundwater, strength of material and the subsequent factor or safety, FoS).

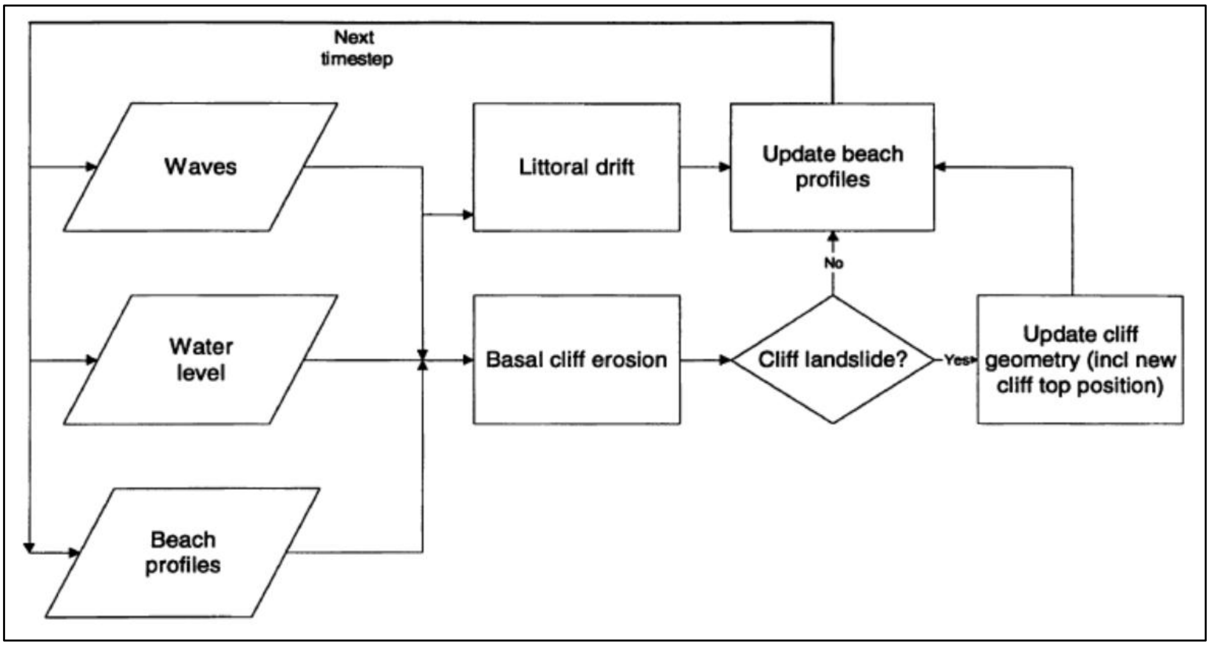


Figure 4-5: Conceptual model of CLIFFPLAN (Lee and Clark, 2002)

The model was developed to simulate the recession of an unprotected slope of London Clay. To make the model suitable for use in probabilistic analysis, each process is represented in a simplistic manner. Therefore demands on processor power are small and multiple simulations are possible (Walkden and Hall, 2005). However, this introduces a trade-off between model complexity and run-time.

Slope stability is determined from a basic model which considers the influence of basal erosion and groundwater level on the FoS, as outlined by T. Therefore the model represents a coupled cliff system, considering both coastal and geotechnical processes to some extent. However, such representation is made possible in this instance owing to the well-studied nature of London Clay. This presents an obvious limitation when considering slopes of different geologies and is further complicated where this may vary along a frontage.

Table 4-3: Sample CLIFFPLAN slope stability table (Lee and Clark, 2002)

Water level	Basal erosion							
	0 m	2 m	4 m	6 m	8 m	10 m	12 m	14 m
0 m	1.26	1.28	1.24	1.17	1.11	1.06	1.02	0.99
2 m	1.22	1.23	1.21	1.15	1.08	1.02	0.98	
4 m	1.15	1.16	1.14	1.09	1.03	0.96	0.92	
6 m	1.06	1.07	1.05	1.01	0.94	0.88	0.83	
8 m	0.96	0.96	0.93	0.90	0.83	0.77	0.72	
10 m	0.84	0.84	0.81	0.76	0.70	0.65	0.61	
New slope (degrees)	18.3	19.3	22	23.3	28.1	29.8	32	34.1
Recession (m)	4.75	4.75	3	3.75	1	1.75	2.5	3

4.1.6.2 Walkden and Hall (2005)

Walkden and Hall (2005) developed the SCAPE (Soft Cliff and Platform Erosion) model to determine the reshaping and retreat of soft rock shore profiles in the mesoscale (a period of 10 to 100 years). This is recognised as a relatively long timescale in modelling terms; however it is achieved by simplifying the system and its processes to only consider those believed to drive recession over this period, subsequently the model can be termed ‘reduced complexity’. It is assumed that the long term rate of recession of the cliff top is primarily determined by that of the cliff toe and interactions with the shore platform, as outlined by Figure 4-6. The erosion processes of the upper cliff are considered only of relevance for the talus material they deposit at the cliff toe.

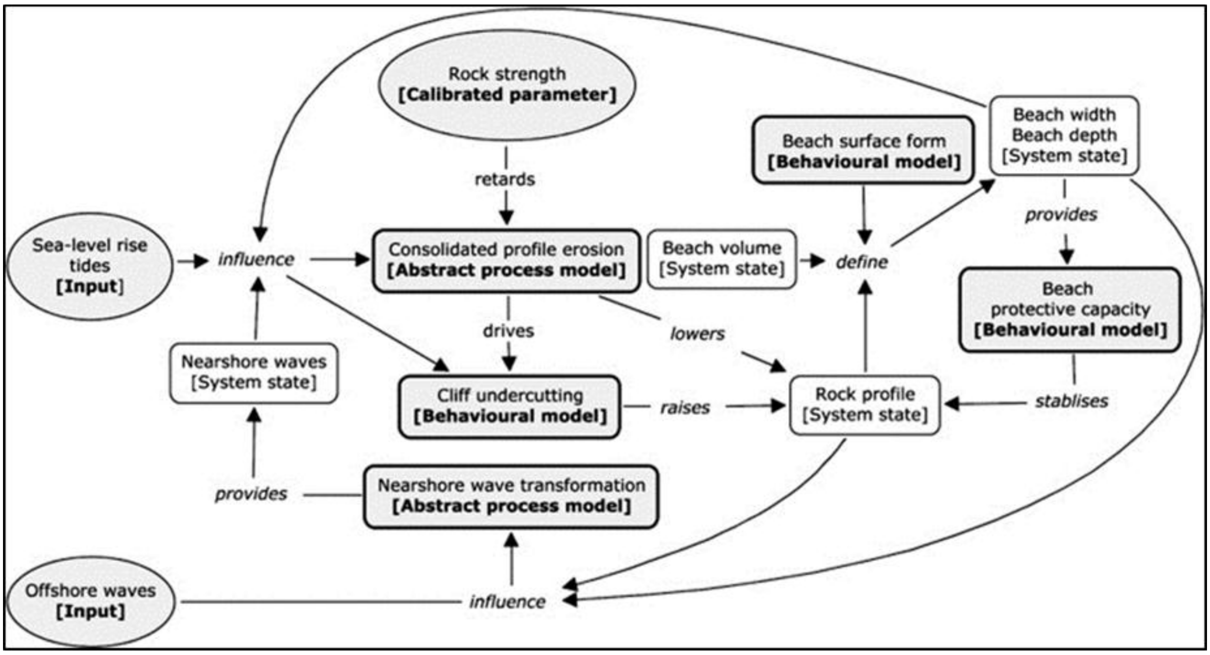


Figure 4-6: Conceptual description of the processes represented in the 2D SCAPE Model (Walkden and Dickson, 2008)

The model was developed based on field observations and a review of existing models (Kamphuis, 1987, Meadowcroft et al., 1999, Trenhaile, 2000). As a result, SCAPE adopts some similar principles but also includes a range of modifications based upon previously identified limitations, to briefly outline:

1. Similarly to CLIFFPLAN (Meadowcroft et al., 1999), SCAPE represents the sediment budget relationship between the cliff and the beach, along with the planshape evolution.

2. Erosion within SCAPE is based on Equation 4-9 of Kamphuis (1987). However, as this was developed for the glacial till bluffs of the Great Lakes the equation was modified within SCAPE to consider tidal and beach effects along with variations in the shore platform both spatially and temporally (see Section 4.3).
3. Finally, it was noted that in Trenhaile's (2000) model of hard-rock shore platform evolution the platform slope emerges as the model iterates, subsequently affecting recession rates as it does so. However, in Trenhaile (2000) recession is only calculated at a small number of points and the predominant processes are acting on the near vertical cliff toe rather than the gently sloping platform. To overcome this issue within SCAPE, the in-situ cohesive material of the shore platform and the cliff is represented within the model as a vertical stack of rows of horizontally aligned layers of a uniform height (d_z), typically 5 to 50mm tall (Figure 4-7). The face of the lower cliff and platform is composed of the seaward surface of these layers. No differentiation is initially made between the cliff face and the shore platform, this boundary emerges through model iteration (Walkden and Dickson, 2008).

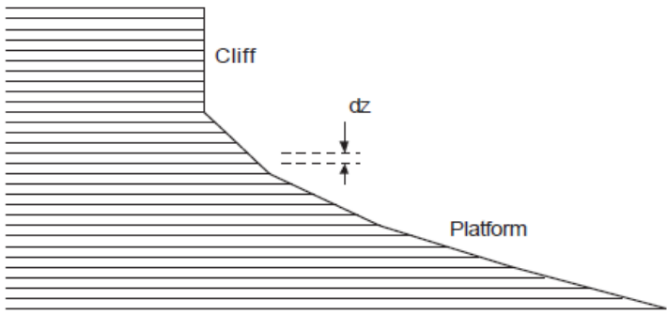


Figure 4-7: Discretisation of a shore section (Walkden and Hall, 2005)

Along with the 2D model described above, a quasi-3D version of SCAPE is available which considers interactions between a series of profiles by a one-line beach module. Figure 4-8 summarises the key differences in the models, which will be further discussed in Section 4.3. Overall, the models simulate a comprehensive coastal system that has been sufficient to validate the model at a number of simple cliff sites including the Naze, Essex, UK (Walkden and Hall, 2005) and north Norfolk, UK (Walkden and Dickson, 2008).

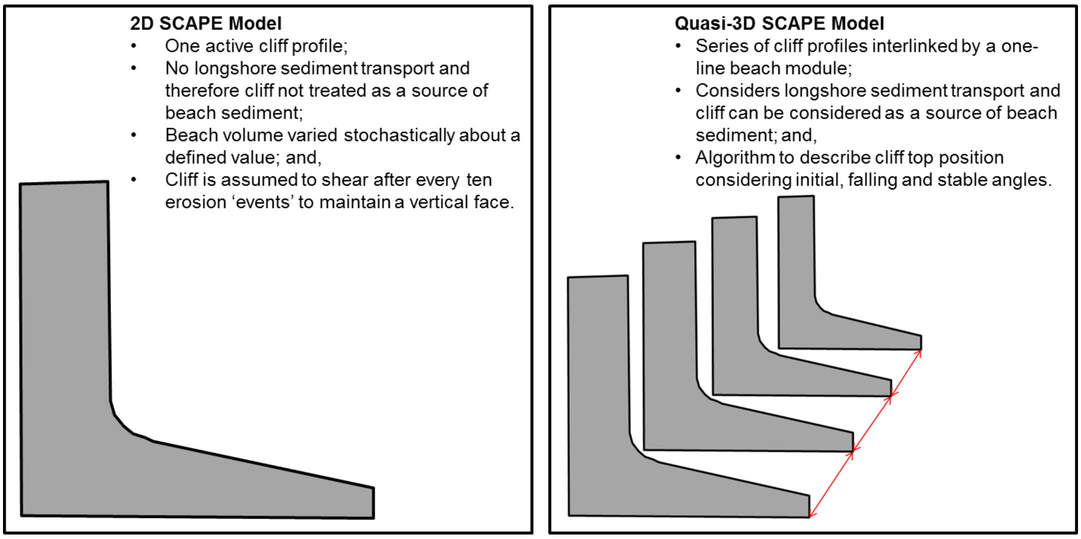


Figure 4-8: Summary of differences between SCAPE 2D and quasi-3D model

4.1.6.3 Valvo et al. (2006)

Valvo et al (2006) developed a numerical model of plan-view coastal evolution (CEM). The model was cell-based and designed to explore interactions between underlying shoreface lithology and longshore sediment transport processes on scales greater than years and kilometres. The governing principles of the model are described below.

Sediment transport related shoreline change was based on the one-line model described by Ashton et al (2001) and Murray and Ashton (2004). The model discretizes an equation governing shoreline change and a semi-empirical formula for longshore sediment flux (Q_s). Divergence of this flux causes changes in the cross-shore position of the shoreline (η):

$$\frac{\partial \eta}{\partial t} = -\left(\frac{1}{h_*}\right)\frac{\partial Q_s}{\partial x}$$

Equation 4-12

where, x is the longshore coordinate and Q_s is the volumetric flux.

Shoreface lithology and composition are incorporated into the model considering a fractional area of sediment (F_s) and rock (F_r). 'Rock' is defined as any material underlying the mobile sediment on the shoreface, even if only slightly lithified. Cells with $F_s + F_r = 1$ correspond to the subaerial coasts, whilst cells where $0 < F_s + F_r < 1$ correspond to the shoreline (see Figure 4-9). Considering the theory that as the shoreface weathers any sufficiently fine sediment will be carried away in suspension, whilst the coarse fraction will be retained in the nearshore system by wave asymmetry (Komar, 1998), the model also considers compositional differences.

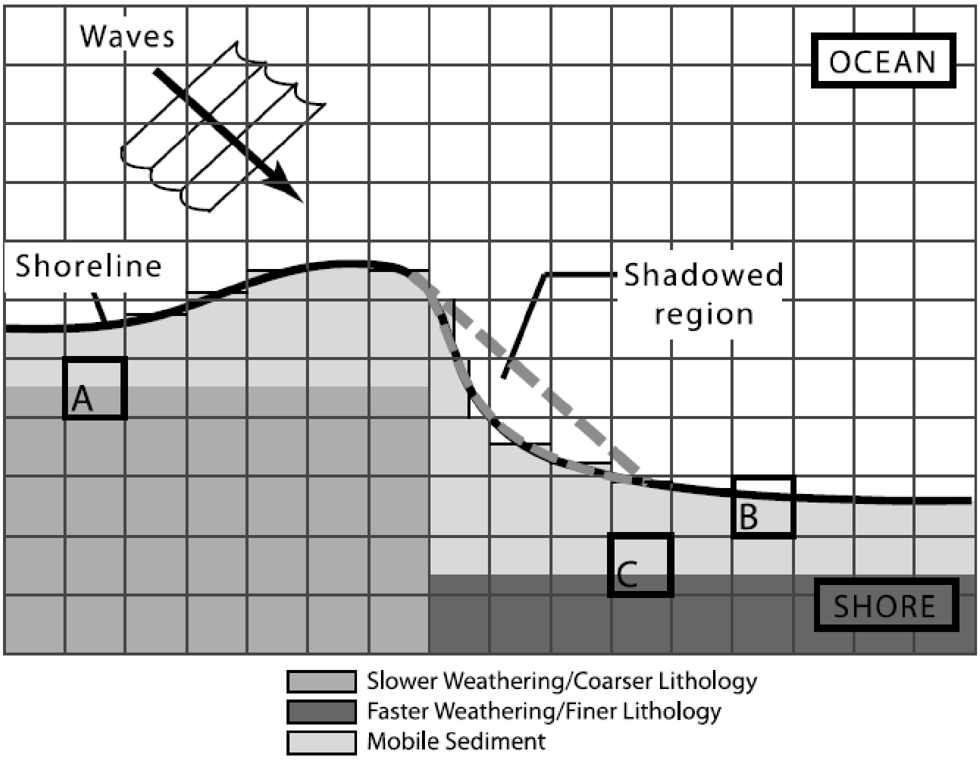


Figure 4-9: Plan-view of model domain, where; Cell A contains F_r = 0.5, F_s = 0.5; Cell B contains F_r = 0.0, F_s = 0.75; and, Cell C contains F_r = 0.25, F_s = 0.75 (Valvo et al., 2006)

The complex physical, chemical and biological processes associated with weathering were not treated explicitly, instead the effects the processes have on large-scale, long term shoreline behaviour were considered. How resistant a lithology is to weathering is represented by the rate at which it transforms into mobile sediment in the absence of any sediment cover and an exponential dependence of the weathering rate on sediment thickness was described:

$$W = W_0 e^{-\xi/d}$$

Equation 4-13

where, W_0 is the weathering coefficient (equal to the maximum amount of rock weathered per year which occurs on bare rock), ξ is the amount of sediment cover in metres and d is a decay constant (= 1 m).

Finally, to model retreating shorelines without explicitly simulating the processes driving retreat (*R*), the model includes a function that removes a small amount of mobile sediment (*l*) uniformly from shoreline cells at every timestep. This can be thought of as representing cross-shore sediment losses from the shoreface profile due to sea-level rise. Valvo et al (2006) note that, when coastal lithology is considered, *l* is not the same as *R* (which refers to the landward migration of the shoreline and results from the combination of divergence of alongshore sediment flux, the imposed removal rate and lithological constraints). Furthermore, R enables relationships between the weathering rate and shoreline thickness to be prescribed, as demonstrated by Figure 4-10.

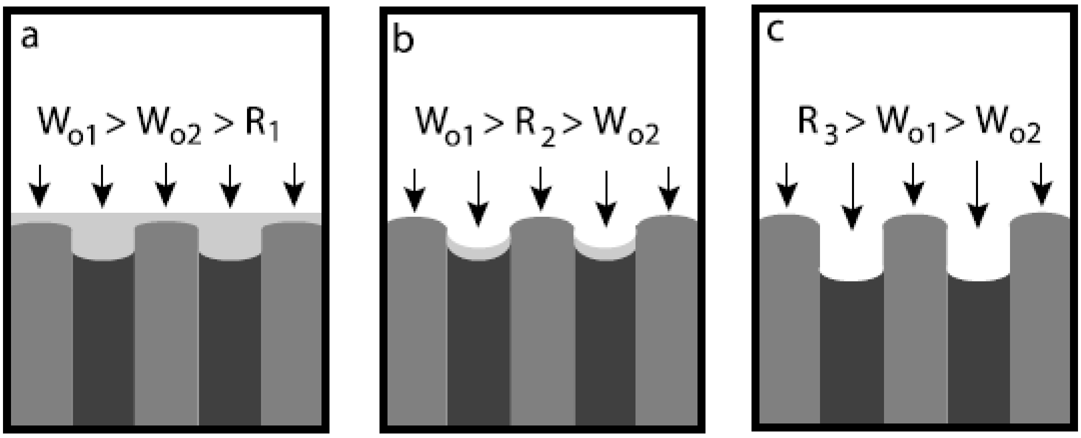


Figure 4-10: Diagrammatic representation of weathering rate/sediment thickness relationship; a) If both weathering rates exceed the retreat rate, equilibrium sediment thickness will develop for both lithologies; b) where the retreat rate exceeds the weathering rate of the second lithology, an equilibrium sediment thickness develops in front of the raster weathering rocks whilst the slower weathering rocks become bare and retreat at their maximum weathering rate; and, c) where the retreat rate exceeds the weathering rate of both lithologies, both become bare and retreat at their maximum weathering rates (Valvo et al., 2006).

The model assumes a sandy coastline where the cross shore profile remains constant and shoreface contours remain parallel. The assumptions limit the application of the model to shoreline changes of long timescales at large spatial scales. Furthermore, such assumptions cannot be applied to sediment poor environments.

4.1.6.4 Trenhaile (2009, 2010)

Developed a 2D model to examine the relationship between variables that effect the erosion and development of cohesive clay coasts in macro- to non-tidal environments. Shore-normal profile retreat and development are determined using expressions that calculate the amount of erosion by wave induced bottom shear stresses and wave abrasion in the sub-tidal and inter-tidal zones, and by stresses generated by surf impact in the intertidal zone and at the foot of bluffs. The key elements of the model are described below and include waves, tides, beach material and erosion.

Waves can be input into the model as a time series or a discrete number of waves sampled from a distribution. Transformation of deep water waves into shallow water and to calculate bottom oribital velocities and the shear stresses generated on the bottom were described by linear wave theory and the USACE (2002) equation for wavelengths in intermediate depths. Friction factors were calculated using Justensen's (1988) data and wave height in the surf zone was calculated using Sunamura's (1985) expression.

The effect of tides on directing the work of waves is recognised; with the focus of wave erosion moving up and down the inter- and sub-tidal zones with the ebb and flow of the tides. Tidal duration describes the absolute (h/yr) or proportional (%) amount of time the surface of the water is within a given range of the elevations of the tidal zone (Trenhaile, 1987).

Considering that soft cliff lithology usually contains a proportion of beach grade material (BGM), the model of Trenhaile (2004) to predict the thickness of beach sediments over clay surfaces under variable wave and tidal conditions is used. Sunamura's (1988b) empirical expression of beachface gradient (α) is also used based on its derivation from analysis of a broad range of field data:

$$\alpha = tan^{-1}\left\{0.12/\left[H_{bs}/\left(g^{0.5}{D_1}^{0.5}T\right)\right]^{0.5}\right\}$$

Equation 4-14

where D_1 is the sediment grain size.

Erosion is considered to be driven by three main factors; excess shear stress, abrasion and mechanical wave erosion. Firstly, excess shear stress can be defined as the amount by which the applied bottom shear stress exceeds the critical shear stress (Tc) for erosion. Trenhaile (2009) considers this in a modified form where:

$$E_{ss} = N_0 K_{ss}(\tau - \tau_c)^p$$

Equation 4-15

Where E_{ss} is the erosion (m/yr) by a single wave type at a single tidal level and N_0 is the number of waves of that type at that tidal level each year (based on tidal duration, wave period and wave frequency). K_{ss} and p are calibration coefficients to convert excess shear into erosional units.

Considering that abrasion is only possible if the abrasives can be moved over the underlying surface; a deposit that is too thick protects the underlying material. Therefore, the model relates the thickness of the mobile sediment layer to the Shields parameter. The expression used to calculate abrasion is based on the ratio of actual sediment thickness to the maximum thickness that can be moved by a given wave at that location:

$$E_a = N_0 K_a(\xi_{tmax}/\xi_t)$$

Equation 4-16

where E_a is the abrasion (m/yr) accomplished by a single wave type operating at a single tidal level, k_a is a coefficient to convert the sediment thickness ratio into abrasional units and ξ_{tmax} is the maximum thickness of the moving layer.

Finally, mechanical wave erosion can also erode exposed surfaces in the intertidal zone (Trenhaile, 2000, Trenhaile, 2001, Trenhaile, 2005) and is the result of the stresses generated at or close to the water surface by the impact of broken waves. It is represented in the model by Trenhaile's (2000) excess surf stress expression.

Overall, the model of Trenhaile (2009, 2010) was not designed to replicate specific shore profiles or predict their rates of recession. Its application for specific sites would therefore require significant calibration with local conditions including the wave regime, tidal range and the threshold strength of the material. Nonetheless, the model contributes towards our understanding of the general relationships involved in cohesive clay coastal erosion. However, it is recognised that the lack of data regarding surveyed clay coasts limits opportunities to confidently determine the various coefficients and to validate the model.

4.1.6.5 Castedo et al. (2012, 2013)

Recognised the need to simulate basal erosion and the resultant movements up the cliff to the backscar within a process-based model. In response their model combines the functional relationships between the dominant physical processes of the coastal cliff system with classic geotechnical limit-equilibrium stability analyses. The model is designed to characterise coasts developed in soft erodible materials with a compressive strength range from very soft (<1.25 MPa) to moderately strong (1.25-1.5 MPa). Figure 4-11 outlines a conceptual flowchart of the influences on the coastal cliff system which was designed to support the model development. The flowchart was organised considering:

- Environmental activation mechanisms – accounting for the inheritance of past processes such as climate, tectonic history and geology;
- Primary responses – varying in response to changes in the activation mechanisms and including factors such as rainfall, tidal range and groundwater.

The activation mechanisms considered the most important for the conditioning and triggering of the primary responses within the CBU are represented and are highlighted by the shaded boxes in Figure 4-11. Mechanical wave erosion is considered the most significant marine mechanism as supported by Sunamura (1992) and Del Rio and Gracia (2009).

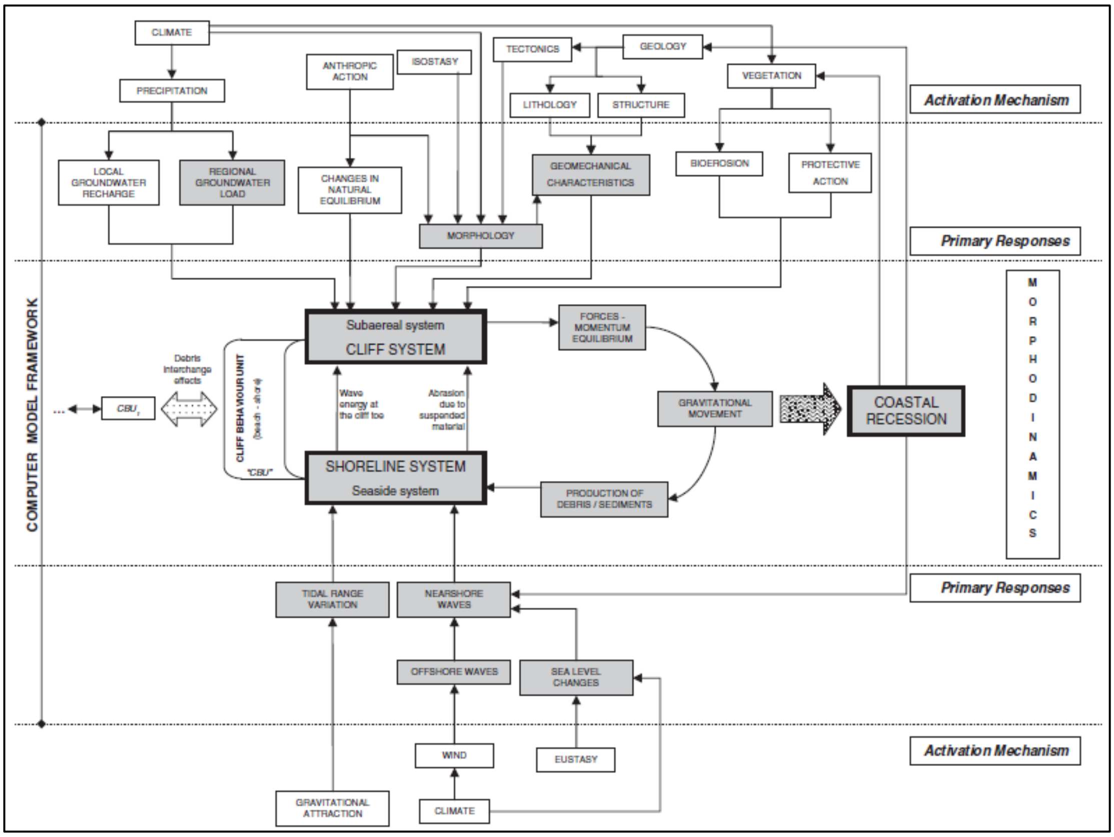


Figure 4-11: Conceptual flowchart illustrating the activation mechanisms and their primary responses in the coastal cliff system (Castedo et al., 2012)

The material resistance calibration parameter of Kamphuis (1987) and Walkden and Hall (2005) was modified and split into two separate terms to represent the Uniaxial Compressive Strength (UCS) of the rock mass and the calibration constant respectively. The UCS of the in-situ cohesive material is calculated using the Hoek-Brown failure (Hoek, 1990), while the calibration constant is determined by historic recession rates. This modification bounds the uncertainties in the lithological description of the rock mass and reduces the significance of the calibration constant (Castedo et al., 2012).

The model uses a limiting equilibrium method to incorporate slope stability analysis to determine the critical condition for failure considering the 'OMS' (Ordinary Method of Slices) or 'Fellinius' method of slices (Fellinius, 1936, U.S.A.C.E, 2003). The effects of groundwater are included along with a range of geotechnical parameters to describe the mass resisting forces of the cliff (e.g. cohesion, friction angle, unit weight etc.). The collapse of overhanging material is based on a cantilever beam model which derives the distribution of stress inside the cliff (Kogure et al., 2006, Kogure and Matsukura, 2010). Finally, the model solves the colluvial wedge (talus material) at the cliff toe for a circular failure based on the material balance between the volumes of erosion and deposition in the cross-section of the slope using three different solutions which are sequentially implemented and evaluated (Castedo et al., 2012).

The slope failure mechanisms used in the model are projected to characterise coastlines composed of relatively unjointed material which behave as a granular or where mass is not controlled by discontinuities. Castedo et al. (2012) tested and validated the model on sections of the Holderness coast, UK. However they noted the difficulty in verifying the model, which relies on historical recession data to calibrate the model. The frontage is composed of three main types of Glacial Till, the geotechnical properties of which are well-studied. However, prescribing UCS values for less studied or more complex geologies may be more challenging and increase uncertainty in model results.

4.1.6.6 Summary of process-response methods

Process Response Methods can simulate changing future conditions and how they interact with the cliff mass, providing they can be described in numerical terms (Hall et al., 2002, Quinn et al., 2010). However, the complexity associated with the interrelating processes has, until recently, inhibited their development (Walkden and Dickson, 2008). Therefore, many applications are still criticised for the generalised manner in which they treat cliff behaviour, which commonly limits their validity to specific sites (Trenhaile, 2009). This method also requires considerable expertise; the practitioner must have a sound understanding of the interrelationships between the various processes and be able to objectively analyse model results. Furthermore, such models require a broad range of high quality information to adequately describe the system (Lee, 2002).

4.2 Selection of an appropriate prediction method and model

Based on the review of available prediction methods this section evaluates the range of approaches combined with a comparative model assessment to identify an appropriate method to carry forward in this study.

4.2.1 Advantages and disadvantages of prediction approaches

Table 4-4 provides a summary of the advantages and disadvantages of each prediction approach. The key issues relate to the level of data required for analysis and the degree of time and understanding needed by the practitioner to successfully apply the method, the demands of which progressively increase.

Table 4-4: Advantages and disadvantages of prediction approaches

Approach	Advantages	Disadvantages
Extrapolation from Historic Data	• Simple approach to determine an aggregated rate of recession for a steady system. • Limited data required. • Uncertainty of results can be derived by implementing a probabilistic framework.	• Does not take into account the stochastic and episodic nature of cliff recession and thus cannot explain the pattern of recession events. • Data issues related to sampling period and accuracy can lead to under- or over-estimation of recession. • Cannot consider changes in future environmental, geological or climatic conditions.
Structured Use of Expert Judgement	• Can be applied when extrapolation is considered unacceptable e.g. for analysis of complex cliff systems or where changing conditions will influence the site. • Considers multiple causal effects. • Limited data required. • Event trees provide an organised method for determining recession responses. • Results can be probabilistic or deterministic.	• Judgements strongly rely on individual(s) expertise and are therefore subjective. • A large number of experts are required to reduce bias. • Difficult method to validate.
Empirical Prediction Methods	• Application of simple system rules to produce overall estimates.	• Generally deterministic. • Defining some parameters can be ambiguous. • Model may over simplify the cliff system; many methods are limited to the impact of sea-level change whilst other conditions are omitted. • Methods may not capture the lag in cliff response to

Approach	Advantages	Disadvantages
		changing conditions. • Response to basal erosion and other processes may result in a change of the CBU type and subsequently an alteration of behaviour from that originally observed. • Supporting field monitoring campaigns may be costly.
Probabilistic Simulation Modelling	• Limited data required. • Accounts for potential variability in predictions. • Can consider the episodic nature of cliff recession. • Enables knowledge about the CBU to be incorporated in to the model.	• More difficult to apply than traditional regression analysis. • Requires Monte Carlo simulation software. • Can result in high computational costs when using maximum likelihood and Bayesian parameter estimations
Process-Response Simulation Modelling	• Enables interactions and feedback mechanisms to be replicated. • Can consider multiple causal effects. • A wide range of models are available for application and adaptation. • Models can be either deterministic or probabilistic. • Ability to simulate future changing conditions and how they may interact with the cliff system. Hence improving our understanding of the system response to climate change. • As the model is based on physical processes, it does not rely heavily upon historical data other than for model calibration.	• Methodologies can treat cliff behaviour in a generalised manner and subsequently limit their application (Trenhaile, 2009). • Few models appear to provide a holistic representation of the cliff system. The majority of models appear to omit sub-aerial processes on the grounds that hydrodynamic forces are the main driver. • Technique requires considerable expertise; the practitioner must have a sound understanding of the interrelationships between the various processes and be able to objectively analyse results. • Requires a broad range of high quality information to adequately describe the system.

4.2.2 Comparative model assessment

This Section presents a short study to assess the accuracy of a range of prediction methods. Each method has been applied to the Isle of Wight (IoW) study frontage to enable comparison between known and predicted rates of retreat. This will allow for further model evaluation to assist in the identification of an appropriate model for application at the study frontage within this research.

4.2.2.1 Introduction

It can be recognised from the review of specific techniques that, with respect to climate change, assessment is typically limited to sea-level rise. This may be attributed to the past assumption that cliff retreat is predominantly driven by basal marine erosion and the difficulty in defining relationships to other climatic factors (e.g. wave climate, rainfall). As recognised in Chapter 2, feedback is a key factor within the cliff system and the ability of a prediction method to consider this is recognised by Ashton et al (2011).

To demonstrate how feedback influences results, this section considers actual versus predicted retreat rates for a range of prediction methods which consider different cliff responses to the impacts of changing sea-levels. The models applied are:

- Historic Extrapolation – No feedback, extrapolation
- Bruun (1962) – instant feedback, empirical
- Sunamura (1988) - instant to no feedback, empirical
- Dean (1991) – instant – no feedback, empirical
- Walkden & Dickson (2008) – damped feedback, empirical but derived from the results of the process-based model SCAPE.
- Trenhaile (2011) –instant feedback, empirical but derived from the results of the process-based model of Trenhaile (2009)[14]

The performance of these models has been evaluated considering actual versus predicted retreat at seven locations across the IoW study frontage.

[14] Scenario 5, slow sea-level rise and unchanged storminess has been used in predictions.

4.2.2.2 Determination of parameter values for study frontage

Table 4-5 provides a summary of the parameter values used as model inputs for the assessment.

Table 4-5: Parameter values used for prediction of shoreline position in response to accelerating sea-level rise for the IoW study frontage (sources explained in text)

Parameter	Location Value						
	1	2	3	4	5	6	7
Historic (1866-1909) Sea-level rise, S_1 (mm/yr)	0.82						
'Future' (1909-2008) Sea-level rise, S_2 (mm/yr)	1.4						
Historic (1866-1909) Rate of Retreat, R_1 (m/yr)	0.5	0.54	0.30	0.44	0.54	0.80	0.36
'Future' Retreat (1909-2008), R_2 (m/yr)	0.76	0.69	0.40	0.33	0.84	0.71	0.63
Cliff Elevation, B (m)	25	20	15	22	20	37	40
Depth of Closure, h_* (m)	10.4						
Length of Active Cross Shore Profile, L_* (m)	1700	2200	2500	1800	1500	1560	1000
Proportion of Sediment Retained within the Active Profile, P (%)	10	22	15	7	5	20	38

The historic rate of Sea-level rise (S_1) has been taken as 0.82 mm/yr based on the historic tide gauge data for Brest, France. This station was selected as it has a long span of data from 1907-2010. The value was derived considering the 'best fit' line through the data between 1807 and 1910, which yields a value of 0.92 mm/yr. This rate was corrected to consider the rate of vertical land movement on the south coast of England using a value of 0.10 mm/yr from Haigh et al (2011). The 'future' (or post 1909) rate of sea-level rise (S_2) of 1.4mm/yr $\pm$ 0.54 was based on the results of Haigh et al (2009) for Southampton. No attempt was made to transfer either rate to the IoW for the purpose of this short study.

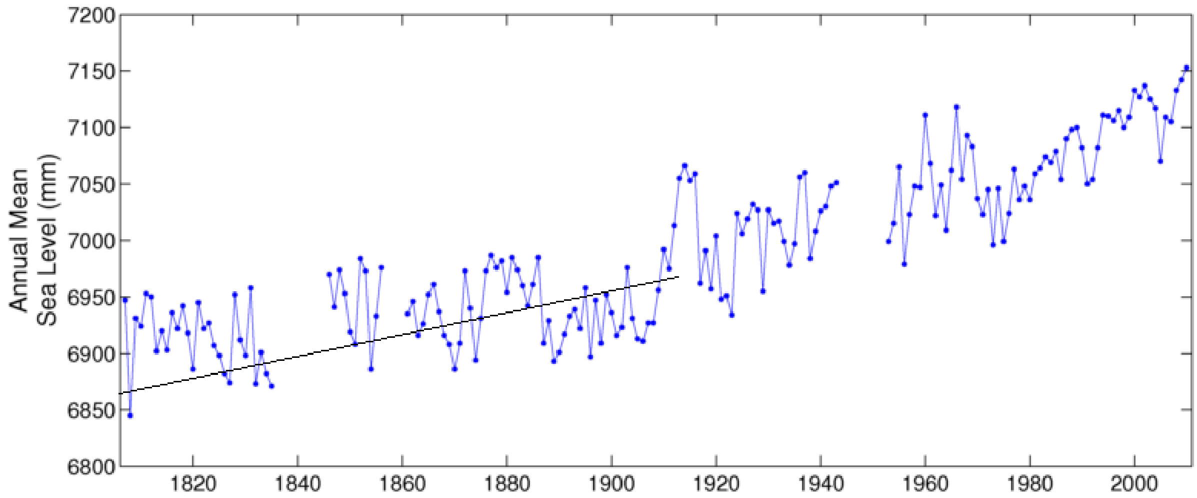


Figure 4-12: Annual mean sea-level data for Brest, France with best fit line for 1807 – 1909 (Permanent Service for Mean Sea Level, 2010)

The baseline retreat rate was established for the 'historic' period (R_1), using the Digital Shoreline Analysis Method, DSAS (Thieler et al., 2009) for available historic maps and aerial photography data for the frontage from Stuiver (2010). Based on these results the 'future' retreat rates, with accelerating sea-level could be predicted using the range of cliff recession models. These predictions were then compared to actual retreat rates for the same period, again determined using the result of Stuiver (2010).

The depth of closure has been estimated based upon Equation 4-6 (Hallermeier, 1981b) using a significant wave height (H_s) of 5.5 m and wave period (T) of 10 s. These values were taken from the Met Office 12km grid model, located just offshore of the study frontage, yielding a value of 10.4m. The length of the active profile associated with this was found from bathymetry data available from CMAP.

Cliff elevations were extracted from 2007 LiDAR data (supplied by the CCO). The proportion of sediment of sufficiently large particle size to remain in the active coastal profile (P) was determined from field estimates for each main geological group present along the frontage (Stuiver, 2013).

4.2.2.3 Results

Figure 4-13 shows the retreat predicted by the range of cliff retreat models plotted against actual retreat for the same period. The following general conclusions can be made:

- Historical extrapolation typically under-predicts recession by as much as 29 m in the worst case scenario as the method does not take into account the impacts of sea-level rise on the cliff recession process over the last century.
- The results of Sunamura (1988) similarly under-predict retreat rates. The model is categorised as instant – no feedback as it considers the influence of some other parameters on the recession process e.g. length of the active cross shore profile and depth of closure. However, the results prescribed to reflect the IoW frontage are low and subsequently push the results more towards the 'no feedback' category.
- The Bruun Rule (1962) generally over-predicts recession rates by as much as 42 m. While the model considers the impacts of sea-level rise on the cliff system it does not consider any of the associated feedback mechanisms which may act to hinder retreat rates (i.e. increased inputs of sediment from the cliff system contributing to beach volume and in turn affording some protection to the cliff toe). This is supported by the categorisation of the Bruun Rule as an 'instant response' model. Similar results and conclusions can be made for the modified Bruun rule of Dean (1991) and the regression equation of Trenhaile (2011) which both over predict retreat by as much as 60 m.
- The Walkden & Dickson (2008) formula shows variable scatter around the 1:1 line. Its improved fit may be attributed to its 'damped feedback' and its development using the SCAPE numerical model, which was specifically developed for soft rock cliffs.

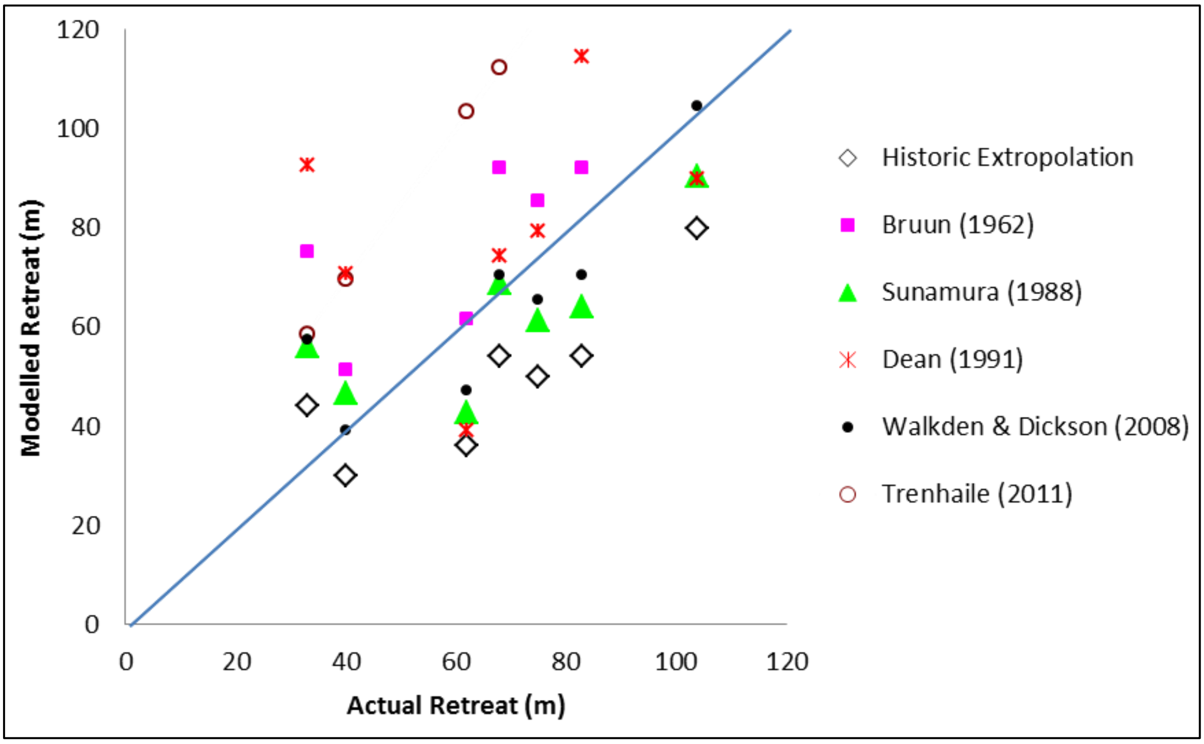


Figure 4-13: Modelled versus actual retreat for a range of shoreline response models. Note 1:1 line.

Table 4-6 presents the Root Mean Square Error (RMSE) for each of the models. Supporting the results of Figure 4-13, the poorest fit arises from Trenhaile (2011), while the closest fit is provided by Walkden & Dickson (2008), with a RMSE of 12 m. However, while the results indicate that this model provides the most accurate prediction (when compared to known rates of retreat) there is still significant scatter in the data.

Table 4-6: RMSE comparing predicted and actual retreat

Recession Model	RMSE (m)
Historical Extrapolation	21
Bruun (1962)	23
Sunamura (1988)	15
Dean (1991)	30
Walkden & Dickson (2008)	12
Trenhaile (2011)	44

4.2.2.4 Conclusions of comparative model assessment

The results of this investigation demonstrate that damped, negative feedback models appear to present the most accurate representation of the cliff systems response to sea-level rise. Model comparisons also support a similar study undertaken by Brooks & Spencer (2012) for the Suffolk cliffs, UK; historical extrapolation under-predicts, Bruun Rule (1962) over-predicts and Walkden & Dickson (2008) shows the best-fit.

While the application of Walkden & Dickson (2008) for Suffolk expressed a much closer fit with the 1:1 line. The results suggest that cliff toe processes are the most significant in the meso-scale, considering the equations simple relationship between retreat and sea-level rise. However, the scatter in the data emphasises the need to consider the cliff system in more holistic terms. This supports the application of the more complex SCAPE model, from which the Walkden and Dickson (2008) formula was derived, within this study.

4.2.3 Evaluation of prediction methods

A wide range of prediction methods are available, this enables coastal engineers/managers to exercise some freedom when selecting an appropriate technique. By evaluating each method a preferred prediction method can be identified:

- **Historical extrapolations** are absolutely linked to past conditions with no feedback (system is considered unresponsive to changing conditions). Consequently results typically under-estimate recession rates;
- **Structured use of expert judgement** can only provide qualitative, site specific speculation of impacts. Considering the uncertainty of climatic impacts it is questionable that reliable predictions can be made through this method alone;
- **Empirical methods** are characteristically simplistic and hence do not consider the full range of controls or describe them to a sufficient level of detail;
- **Probabilistic simulation methods** can account for the potential variability but cannot describe the interrelating processes in detail (i.e. the magnitude and frequency of recession events is pre-determined by the practitioner);

- **Process-response methods** are complex and data intensive but can enable the key interactions in the cliff system to be modelled and changing conditions to be simulated. For the study of actual versus predicted retreat rates (Section 4.2.2), the rule of Walkden and Dickson (2008) derived from results of the process-based model SCAPE yielded the most accurate results which can be attributed to its consideration of 'damped feedback'. However, there was still a significant margin of error which highlights the need to consider process relationships in more detail, particularly for composite or more complex cliff systems of variable lithology such as the IoW study frontage

Process-response methods are considered the most appropriate for application within this study. This approach provides an opportunity to gain insight into the response of the cliff system to changing conditions. However, at present there are still a number of limitations to this method as introduced in Section 1.1 and documented in Table 4-4. Existing models are frequently criticised for the simplistic manner in which they treat the cliff system and the lack of coupling between driving coastal and sub-aerial factors. These limitations will be further discussed in the following section considering a critical appraisal of the available models.

4.2.4 Selection of an appropriate model

Table 4-7 provides a summary of each of the models introduced in Section 4.1.6 compared against the sub-systems and factors of cliff recession introduced in Chapter 2. This provides an indication of the level of integration of each model, which is important considering the multifaceted nature of the cliff system. However, the trade-off between including an increased range of parameters and processes and model complexity is noted.

Table 4-7: Summary review of existing process-response models

System	Factors	Model				
		Meadowcroft et al. (1999)	Walkden & Hall (2005)	Valvo et al. (2006)	Trenhaile (2009, 2010)	Castedo et al. (2012, 2013)
Geotechnical, Geological and Hydrogeological	Geology, lithology and structure	✓[15]	✓[16]	✓[17]	✓	✓
	Cliff Geometry	✓[18]	✓[19]			✓
	Strain Softening					
	Groundwater and pore water pressure	✓[20]				✓
Sub-Aerial	Slope Vegetation					
	Weathering			✓		
Coastal and	Wave Exposure and Talus Removal	✓	✓	✓	✓	✓

[15] Developed specifically for London Clay slopes.
[16] Treats material strength as a calibrated parameter. The model also considers the percentage of beach building material within the cliff face at each profile.
[17] Considers the composition of underlying lithology by specifying a percentage of fine and coarse grained material within each cell.
[18] Only considers a 10m cliff slope but with the influence of changing slope angle on FoS.
[19] Both cliff height and slope can be considered within the Q3D model. An initial slope angle along with pre and post failure angles can be specified.
[20] Look up tables for the factor of safety are used considering the extent of basal marine erosion and pore water pressure.

System	Factors	Model				
		Meadowcroft et al. (1999)	Walkden & Hall (2005)	Valvo et al. (2006)	Trenhaile (2009, 2010)	Castedo et al. (2012, 2013)
Marine		✓				
	Shore Platform Protective Capacity	✓	✓		✓	✓
	Beach Protective Capacity	✓	✓	✓	✓	✓
Meteorological and climatic	Rainfall					
	Tides and sea-level rise	✓	✓	✓ [21]	✓	✓
	Storms	✓	✓			
Human	Engineering structures at cliff toe		✓			

[21] Sea-level rise can be considered within the model by altering the imposed removal rate of sediment.

Table 4-7 highlights that the range of currently available models focus on four key factors:

- Geology and lithology of the slope;
- Exposure to wave energy;
- Protective capacity of the beach and shore platform;
- Influence of tides and sea-level rise.

This emphasises the current bias towards driving coastal processes, with sea-level rise assumed to be the main climatic influence on future recession. However, as demonstrated by Chapter 2 cliff recession is controlled by a diverse range of interrelating factors which should be considered if accurate predictions are to be made.

The representation of the geotechnical and geological system is typically limited to material resistance while the internal processes governing slope stability are frequently omitted or poorly represented. This may be owing to the complex and stochastic nature of slope stability (which does not easily yield itself to description in numerical terms) and the common development of models by practitioners with coastal as opposed to geotechnical expertise. The only models which consider slope stability are Meadowcroft et al. (1999) and Castedo et al. (2012). However, these models were developed for specific simple cliff systems of relatively homogenous geologies of London Clay and Glacial Till respectively. The geotechnical properties of which have been well studied. Therefore it is possible to make assumptions of its FoS under a range of scenarios. Such assumptions cannot be applied to other soft cliff geologies expressing different properties and this limits the application of the models.

The Trenhaile models (2009, 2010) were developed to investigate relationships in the cohesive cliff system. However, they only consider rock strength as influencing submarine wave erosion rates as opposed to overall slope stability. The model iterations cannot be converted into real time units owing to the uncertainty over the value of some of the model constants. While this is acceptable for the models application to investigate process relationships, it limits its application as a prediction/coastal engineering tool.

The SCAPE model is developed for generic soft rock cliffs. A homogenous, material resistance calibration parameter can be prescribed to each 2D profile which is based on Equation 4-9 of Kamphuis (1987). The Q3D model also includes a coastal landsliding module to determine the overall cliff top position.

The model of Valvo et al (2006) considers geological strength and composition by assigning a weathering rate and percentage of fine and coarse grained material to each cell. However, the model was not developed as a prediction tool but rather to investigate how changes in the underlying geology can affect sandy coastline change. It was also used to develop an analytical model and hence the underlying model is highly simplistic.

Finally, the model of Castedo et al (2012) includes a similar range of parameters and processes to Walkden and Hall (2005). It has also been extended to describe more detailed mass movement and talus delivery processes. However, the model was developed for glacial till cliffs and the difficulty in prescribing appropriate UCS values for cliffs of variable lithology was noted.

Based on the above review, Walkden and Halls (2005) SCAPE model has been selected as the most appropriate model to carry forward within this study because:

- It has been successfully applied to numerous sites including the Naze, Essex and the cliffs of North Norfolk, UK, which provides confidence in the model as a coastal engineering and geomorphological tool;
- It includes a range of parameters and processes identified as key drivers within the cliff recession process (Chapter 2, Figure 2-9). Furthermore, the model considers a range of feedback mechanisms which will be fundamental to identifying the effect of environmental and climate change on the system;
- It has been developed for generic soft rock cliffs as opposed to a specific geology. Consequently the model will be more appropriate for the consideration of cliffs of variable lithology and the future application of the model to further soft rock cliffs sites will not be constrained;
- The model has the required flexibility to be applied, evaluated and advanced within this research;
- The model is available in 2D and Q3D format enabling both crosshore and longshore analyses.

4.3 Critical appraisal of selected model

The following sub-sections outline the key principles of the SCAPE model (2D and Q3D) through a description of their technical development (theory) and initial applications (practice).

4.3.1 Technical development

The following sections describe the governing principles behind the 2D and Q3D versions of the SCAPE model introduced in Figure 4-8.

4.3.1.1 2D Model

SCAPE 2D is a reduced complexity model designed to simulate the emergence and retreat of soft rock shore profiles in the mesoscale. On this basis only the processes considered dominant over this timescale are represented. Therefore the long term recession rate of the cliff top is assumed to be primarily determined by that of the cliff toe and interactions with the shore platform. This is based on the assumption that a higher proportion of incident wave energy is expended on the shore platform in comparison to the cliff face (Kamphuis, 1987). Erosion of the upper cliff is considered relevant only for the talus material deposited at the cliff toe.

The components of the coastal cliff system described by the 2D model were outlined in Figure 4-6 These are represented by both process-based and behavioural modules representing hydrodynamic loads, shore platform, cliff and beach morphodynamics. Such a holistic representation is necessary to capture the interactions and feedback on the shore profile that regulates the behaviour of soft cliff coasts. The process descriptions are relatively abstract to allow simulation of long periods and exploration of model sensitivities (Walkden and Dickson, 2008).

The governing principles of the 2D model are described below. Further detail is given by Walkden and Hall (2005), Walkden and Dickson (2008) and Walkden and Hall (2011).

Waves and transformation

Inshore wave transformation processes including; refraction, diffraction and shoaling are represented using linear wave theory (Kamphuis, 1992, Kamphuis, 2000). Wave breaking occurs when the ratio of significant wave height to water depth is 0.78. Wave diffraction is only used in models that include groynes or hard point structures (Walkden and Hall, 2005).

Beach module

The beach is represented as a surficial layer resting on the shore platform, which defines its lower boundary. Therefore the beach depth, width and volume are quantified (Walkden and Hall, 2005). The beach is assumed to have an unvarying profile, consisting of a flat berm at the limit of wave run-up, fronted by a Bruun profile (1954), where:

$$d = ax^{\frac{2}{3}}$$

Equation 4-17

where *d* is the depth below the berm level, *a* is a constant coefficient found through beach surveys of the study site and *x* is the distance seaward of the berm edge. The curved profile of Bruun was used as opposed to a slope of a single gradient as this is believed to be more realistic.

The depth of the beach is required to contribute towards the calculation of the cross shore distribution of platform erosion. SCAPE considers the results of Ferreira at al (2000) assuming that beach depths greater than $0.23H_{bs}$ are fully protective and that the beaches protective ability varies linearly for depths less than this (Walkden and Dickson, 2008, Walkden and Hall, 2005). Because the beach slope is greater than the platform profile, the beach tends to rest close to the cliff toe. This localised protection causes the platform shape to tend towards that of the beach surface, i.e. a Bruun profile (Kamphuis, 1990).

Cross-shore motion

SCAPE was originally developed to model a site with a sparse beach at which cross-shore sediment motion could be neglected (see Walkden and Hall, 2005). However, it was recognised that this assumption is not appropriate for all sites. Therefore a module representing cross shore motion was developed. The sediment transport model COSMOS (Nairn and Southgate, 1993) was used to identify the conditions under which beach material moves seaward, and the rates of transport as functions of wave height and period (Walkden and Hall, 2011). This cross-shore distribution of sediment transport is calculated at every timestep by integrating over a tidal cycle of quasi-instantaneous distribution describing sediment transport on Bruun beach profiles (McDougal and Hudspeth, 1984). The COSMOS simulations did not account for wave reflection at structures or at the face of cliffs.

Numerical description of erosion

Within SCAPE the cliff is represented as a stack of horizontally aligned layers of uniform height (d_z). The face of the lower part of the cliff and platform is formed by the seaward surfaces of these layers as was illustrated in Figure 4-7. However, initially, no differentiation is made between the cliff face and the shore platform; this junction emerges from a vertical cliff through the interaction of the processes modelled including marine action near mean sea level (Walkden and Dickson, 2008).

The cliff and platform erosion rate is based on Equation 4-9 of Kamphuis (1987), which was developed for glacial till bluffs. Erosion is calculated for each layer (d_z) and the rock profile is eroded by wave action, the vertical influence of which fluctuates with the tidal cycle. Figure 4-14 illustrates the conceptual shore profile and the integration of erosive potential for a single semi-diurnal time-step. At every stage, the breaking wave field has the potential to erode the rock surface, represented by the erosion shape function (f_1), a dimensionless distribution derived from physical model tests by Skafel (1995) in which pseudo-random waves shoaled and broke over a glacial till shore. While the results relate to this specific lithology it seems reasonable to suppose that the relative distribution of wave scour will be similar regardless of lithology and the seaward extent of f_1 is approximately equal to the depth at which waves begin to break.

To obtain the total erosive potential throughout a tide the instantaneous distribution of erosion must be integrated over the tidal period. As demonstrated by Figure 4-14, this potential tends to be concentrated near the tidal extremes (where the water level is for the most time). The erosion experienced by each layer (d_z) also depends on (the tangent of) its slope with more gently sloping elements tending to erode less than steeper elements (Walkden and Hall, 2011).

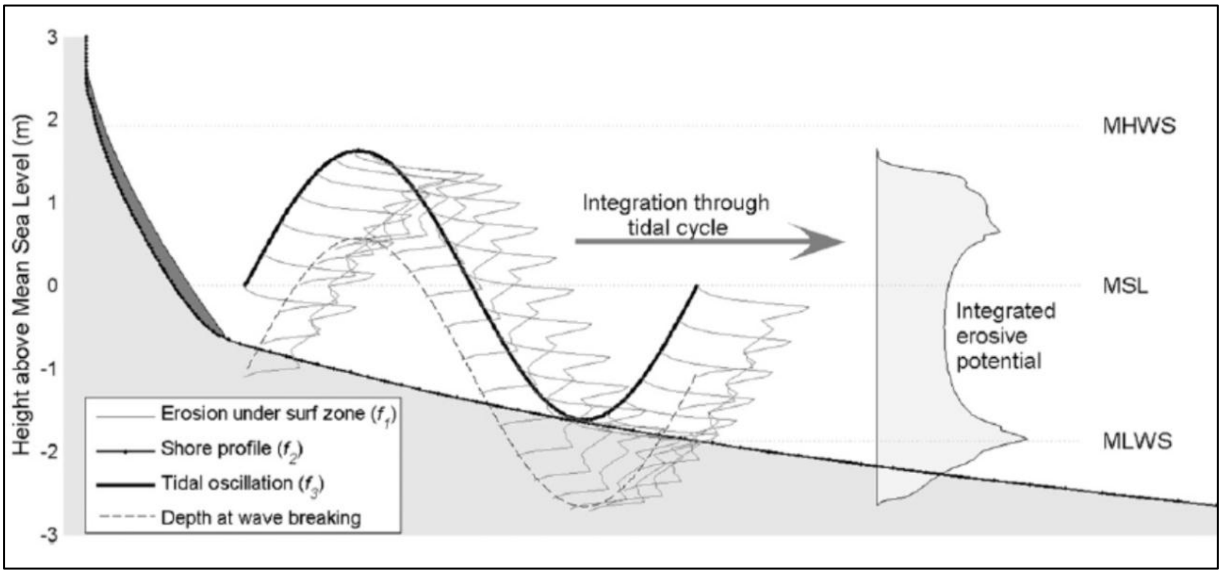


Figure 4-14: Integration of the erosion pattern of a breaking wave field during a tidal timestep (Walkden and Dickson, 2008)

More formally, at every time-step, erosion of each element (Δy) is calculated using Equation 4-18 (Walkden and Dickson, 2008):

$$\frac{\Delta y}{\Delta t} = H_{bs}^{13/4} T^{3/2} M^{-1} f_1(f_2(t) - z) \tan\big(f_3(z)\big)$$

Equation 4-18

where *y* and *z* are horizontal and vertical dimensions respectively, *t* is time, f_1 is the erosion shape function (as described above), f_2 is the slope of each rock element which changes throughout the simulation in response to the calculated erosion, and f_3 is the tidal variation of the water level which is represented as a sinusoid about Mean Sea Level (MSL). These functions are described in further detail in Appendix A. As previously stated, M is based on Equation 4-9 of Kamphuis (1987), representing material strength and some other hydrodynamic constants ($m^{9/4}$ $s^{3/2}$).

The model gradually timesteps towards a profile form that is in dynamic equilibrium with the input conditions. Sea-level rise is implemented as a shifting frame of reference.

Talus material

Sub-aerial cliff failure, delivery of talus material and the temporary protection it affords to the cliff toe from marine processes is described by a basic module. The cliff is treated as a vertical block of material that shears to maintain a vertical face when undermined every ten recession events. To save processor time, the collapse of the cliff takes place after every ten erosion events. The parameter *M* has no effect on this process beyond the erosive potential of the material (e.g. structural controls and more complex mass movement processes such as rotational slumps and slab failure are not included).

This sheared material forms a talus wedge at the cliff toe with a surface slope of 45° (Walkden and Hall, 2005). The talus is assumed to be ineffective at resisting wave attack due to its disturbed nature and steep profile and therefore is assumed to have resistance of 0.1M. However, the material is believed to have some effect when reworked by waves.

Inclusion of engineering interventions

As a coastal engineering tool SCAPE also has the ability to consider the effects of some engineering interventions, namely; seawalls, groynes and beach nourishment. This will not be discussed in further detail as it is beyond the remit of this study.

4.3.1.2 Quasi-3D model

The quasi-3D SCAPE model describes a series of 2D cliff profiles (described by the 2D model above) interlinked by a one-line beach module (Figure 4-8). As summarised in Figure 4-6: , this results in a more complex model which includes for the processes of longshore sediment transport and cliff top position. These additional modules are described below.

Beach volume and longshore sediment transport

Beach volumes are essential to provide continuity in the sediment budget. For each 2D section they are determined and quantified at each time-step considering the influx from erosion of the cliff, talus and platform versus the out-flux through longshore sediment transport. Whilst all of the eroded material adds to the volume of the talus, only the proportion of beach grade material contributes towards the beach volume. It is presumed that the remainder is transported away in suspension and subsequently lost from the system.

Long-shore sediment transport is described using a one-line model, an approach originating from the analytical solutions of the diffusion equation (Pelnard-

Considere, 1956) and described by the Shore Protection Manual (Hanson and Kraus, 1989). It is calculated using the CERC equation of Hanson and Kraus (1989):

$$Q_P = K_1 H_{bs}^2 C_g sin2\theta$$

Equation 4-19

where Q_p is the potential sediment transport rate (m³/s) integrated across the surf zone, K_1 is the CERC coefficient, H_b is the significant wave height at the breaker line (m), C_g is the wave group celerity at the breaker line, and θ is the angle (°) between the wave crests and the shoreline at the breaker line.

Cliff failure

Q3D SCAPE combines knowledge of the rate of cliff toe retreat with an assessment of the geotechnical characteristics of the slope to generate an approximate probability distribution of the possible cliff top position following failure (Hall et al., 2000). The approach is based on the concept of CBU's where within each unit the cliff can be expected to fail when it reaches an average angle α_f and will, after failure, adopt an angle of α_s, as demonstrated by Figure 4-15.

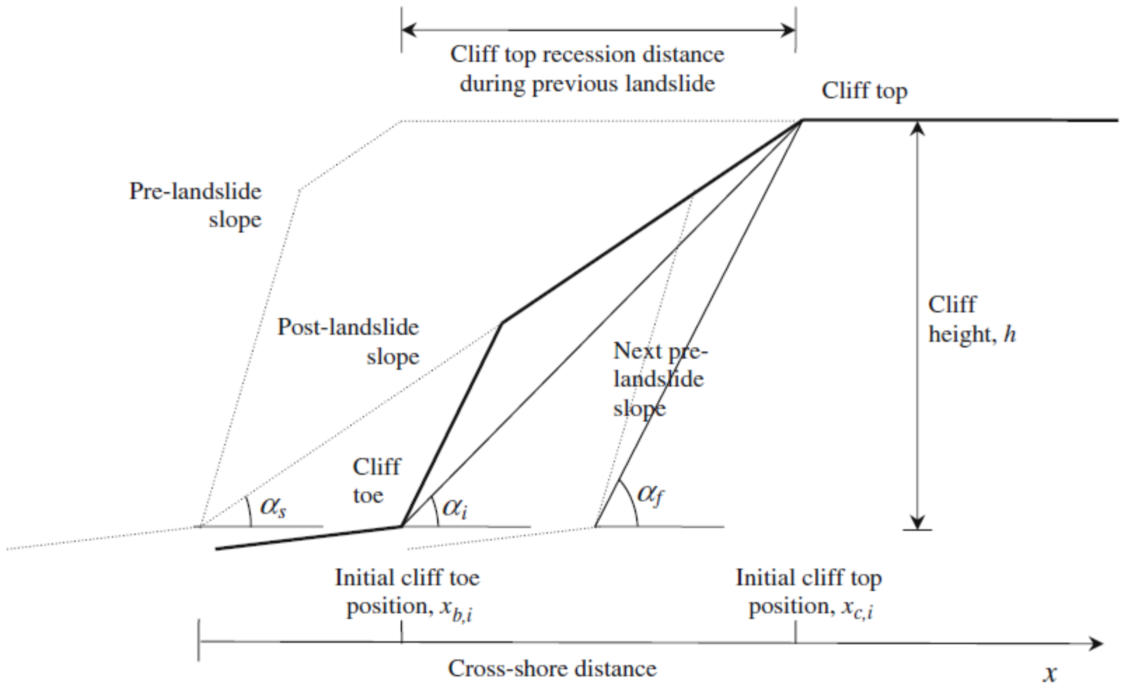


Figure 4-15: Diagrammatic representation of the coastal landsliding model (Dawson et al., 2009)

Neither α_f or α_s can be predicted precisely as they will vary depending on temporal and spatial variations in pore water pressure, cliff strength and composition combined with the uncertainties in understanding the process of coastal landsliding. However, this uncertainty is included in the analysis by representing both values as Normally-distributed random variables, with means and variances obtained from a geomorphological assessment. Further uncertainty is also apparent in the initial cliff angle (α_i) where within any CBU there will be a range of initial angles. Therefore α_i is similarly represented as a normally distributed random variable, with mean and variance based on measurement of cliff angle at the site (Dawson et al., 2009). The cliff top position is calculated relative to the SCAPE cliff toe predictions.

Considering Figure 4-15 the distance the cliff toe has to retreat until the first landslide is $h(\cot\alpha_i - \cot\alpha_f)$ and the distance lost between each subsequent landslide to the next is $h(\cot\alpha_s - \alpha_f)$. For year $t+1$, the pre-landslide slope is taken from the post-landslide slope of year t.

While it is recognised that the processes of upper cliff erosion and landsliding are of relevance in determining the position of the cliff top; SCAPE has been developed based upon the assumption that the long-term rate of cliff-top recession is primarily determined by that of the cliff-toe and interactions with the shore platform. SCAPE considers that that the erosion processes of the upper cliff are only of relevance for the material they deposit as fallen talus.

4.3.2 Model behaviour and sensitivity analysis

The following sub-sections describe the initial application of 2D and Q3D SCAPE, to further understand model behaviour and provide a sensitivity analysis of the model parameters. This process will provide applied insight into model interactions.

4.3.2.1 2D model

The process of initial profile development is outlined to provide a practical example of model behaviour, followed by a sensitivity analysis of the key parameters within this version of the model. The simulations provide an opportunity to compare results with previous model investigations, checking for continuity in model set-up and providing further background to readers unfamiliar with the model.

2D model set-up

These experiments consider the development of an initially vertical, idealised cliff of homogenous material resistance, plunging into deep water (a highly unrealistic shape on a soft-rock shore). As previously introduced, the 2D model allows a dynamic equilibrium shore profile to emerge based upon the prevailing conditions. Table 4-8 provides a summary of the input parameters used.

Table 4-8: SCAPE 2D input parameters to investigate model behaviour on an idealised shore profile (data sources explained in text)

Purpose	Preliminary Inputs	Units	Value Range
Profile evolution	Wave Height Wave Period Run-up Limit	m s m	Variable with time: 0 to 4.86 (0.93 mean) Variable with time: 1.8 to 9.7 (4.18 mean) 1.75
Beach characteristics	Beach Volume Bruun Constant	m^3/m -	20 0.1
Cross-shore distributions of sediment transport and erosion	Tidal Amplitude Sea-level rise	m mm/yr	Variable with time (1.17 mean) 5
Calibration variable	Material Resistance	$M^{9/4} S^{3/2}$	$5x10^6$

Prevailing conditions (waves and tides) broadly representative of the north Norfolk coastline were used at this stage as they were readily available and wave run-up is calculated in the model based upon the prevailing conditions. As sediment transport is not represented in the 2D model, to prevent continual beach growth the cliff is not treated as a sediment source.

The beach volume is varied stochastically about the defined average value prescribed above. The average value was chosen to be comparable to the threshold beach volume identified from previous studies (e.g. Lee, 2008, Walkden and Dickson, 2008, Walkden and Hall, 2011). The pattern of random variation was taken from a Q3D version of the model developed by Walkden and Hall (2005).

A conservative sea-level rise value of 5 mm/yr was selected considering projections of Defra (2006). A material resistance parameter was selected considering the output equilibrium rate of recession. This yielded a value of 1.43m/yr, reflecting a soft rock cliff experiencing a high rate of retreat.

Model behaviour: initial profile development

Figure 4-16 illustrates the emergence of a 2D SCAPE profile with no sea-level rise. Part a shows profile development every 100 years (from right to left, year 0 – 500). Owing to the steepness of the initial cliff, high rates of retreat (approximately 490m) can be observed between the year 0 and 100. However, this diminishes to approximately 85 m retreat between year 400 and 500. The emergence of the junction between the shore platform and cliff toe at approximately MHWS can also be observed. Figure 4-16b shows the further development of the profile every 1,000 years (from right to left, year 1,000 – 5,000), demonstrating the shore platform widening. Surface irregularity decreases over time resulting in the emergence of a characteristically smooth profile (as previously highlighted by Walkden & Hall, 2005 and supported by Sunamura, 1992).

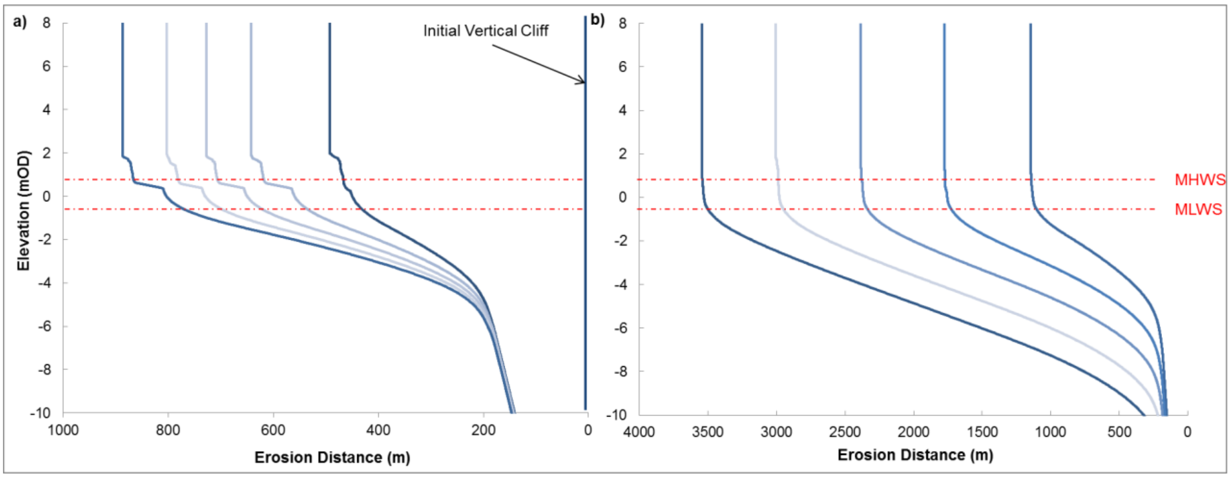


Figure 4-16: Emergence of the Shore Platform and Cliff Toe a) profile every 100 years (year 0 – 500), b) profile every 1,000 years (year 1,000 – 5,000)

Figure 4-16 also shows the overall slope of the profile reducing over time. This is accompanied by a fall in the average rates of cliff toe retreat. The retreat rate decays asymptotically over time, as shown in Figure 4-17 owing to the emergence of the shore profile from an unrealistic, initial vertical cliff face. Therefore the model takes approximately >1,000 years to stabilise (otherwise known as the 'spin-up' time).

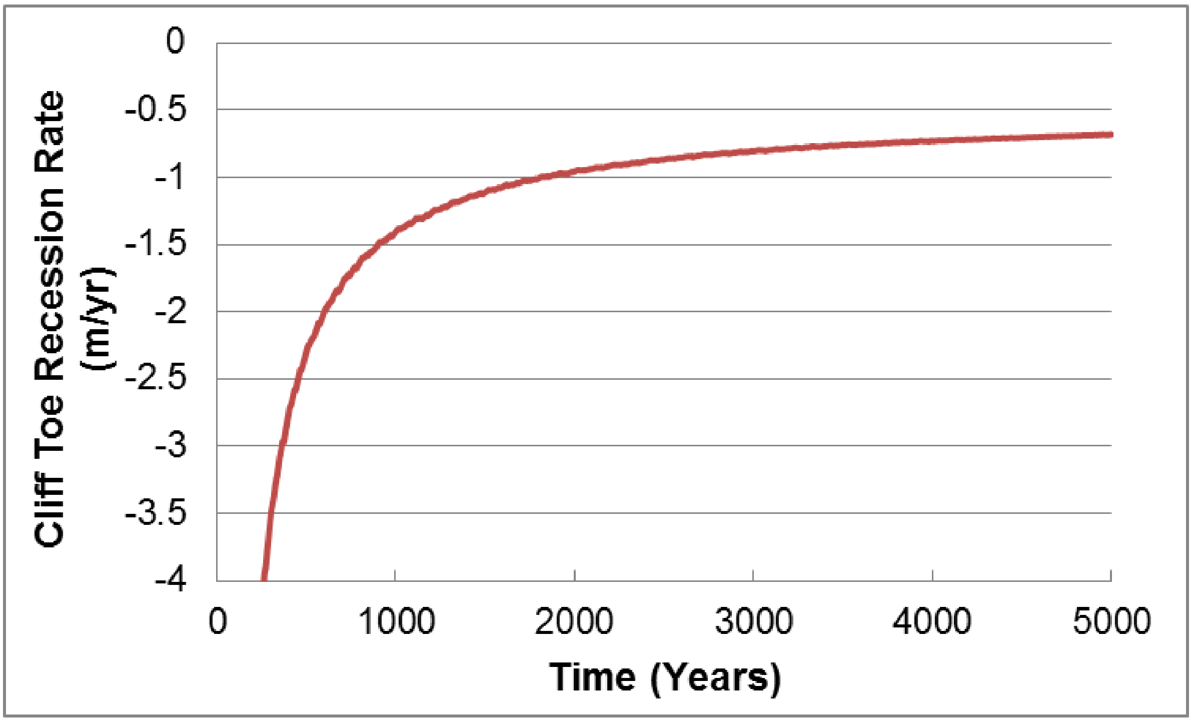


Figure 4-17: Asymptotic decay of recession rate with time

The similar trends in profile evolution support previous applications of the 2D SCAPE model (including Walkden and Hall, 2005 and Walkden and Dickson, 2008) and therefore the appropriate model set-up within this research.

Sensitivity analysis

This section provides a sensitivity analysis of the key input parameters a within SCAPE 2D:

- Material resistance;
- Beach presence;
- Sea-level rise;
- Wave climate;
- Tidal range.

Material resistance

The results exploring the models sensitivity to material resistance (*M*), are shown in Figure 4-18a. As would be expected from Kamphuis's (1987) description of the erosion rate (Equation 4-9); lower values of *M* cause greater recession. Figure 4-18b shows the corresponding variance in shore profile slope; lower values of *M* cause more gently sloping profiles. The results are in agreement with similar model tests of Walkden and Hall (2005), again confirming model set-up.

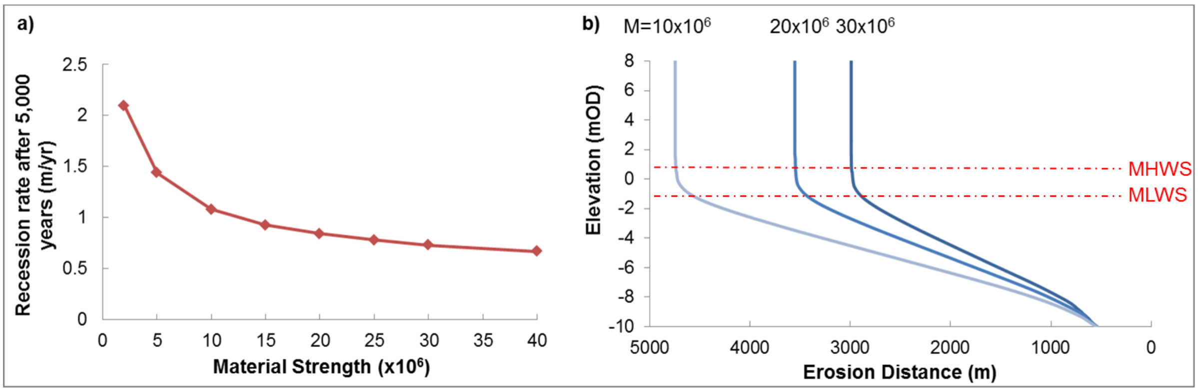


Figure 4-18: Model sensitivity to change in material resistance; a) equilibrium recession rate, b) shore profile

Beach presence

A range of fixed beach volumes were next tested. Figure 4-19a shows the recession rate to be independent of beach volumes below 10 m^3/m, owing to the limited protective coverage provided by the beach. This threshold is lower than that proposed by Walkden and Dickson (2008) of 30 m^3/m owing to the variations in prevailing conditions used in each study. Figure 4-19b shows variance in the shore profile with increasing beach volume; larger beach volumes cause steeper profiles as the introduction of a beach results in reduced recession rates above approximately mean sea level whilst lower down profile erosion rates are generally unaffected (Walkden and Hall, 2005, 2010)

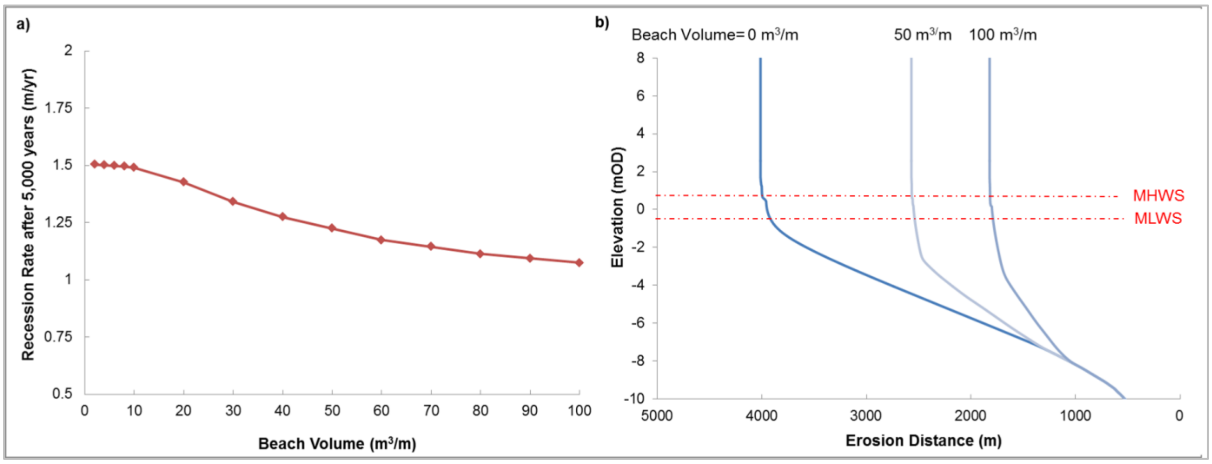


Figure 4-19: Model sensitivity to change in beach volume; a) equilibrium recession rate, b) shore profile

Wave climate and tidal range

Figure 4-20a and b shows the effect of increased wave height and increased tidal range on the cliff toe retreat rate, respectively, As would be expected from the review conducted in Section 2.2.3.1, increased wave heights result in increased rates of retreat. This also results in the development of shallower shore profile slopes. In contrast, a higher tidal range was found to reduce recession. It is hypothesised this is owing to the reduced time wave action is concentrated at any point on the profile, as supported by shore platform steepening in this case.

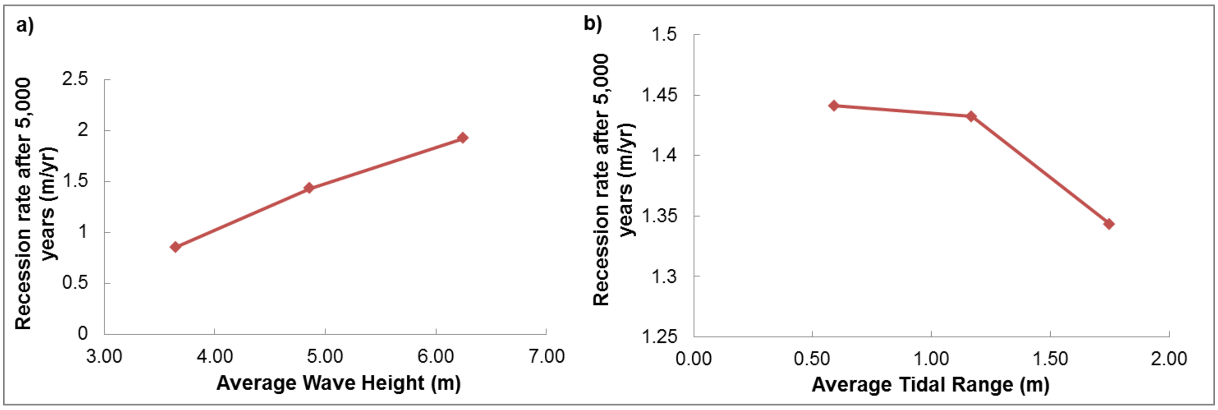


Figure 4-20: Model sensitivity to change in ; a) wave height, b) tidal range

Sea-level rise

Finally, Figure 4-21 a and b shows how cliff toe recession varies with sea-level rise; higher rates of inundation cause greater recession. On Figure 4-21b, each line initially expresses a curve and then becomes straight. This represents stages of profile development before and after dynamic equilibrium is reached.

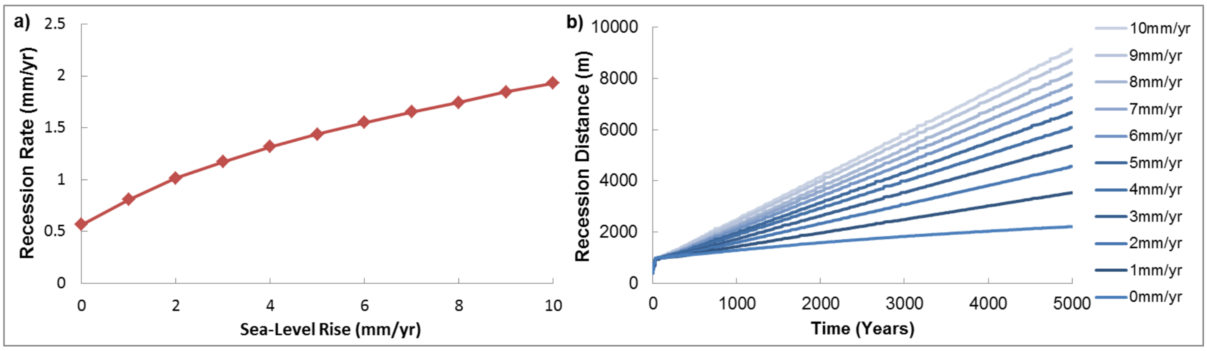


Figure 4-21: Model sensitivity to change in sea-level rise rate; a) equilibrium recession rate, b) total recession

Figure 4-22a shows the variance in shore profiles with different rates of sea-level rise. The higher the rate of sea-level rise, the steeper the profile owing to the reduction in duration of wave attack (Walkden & Dickson, 2008). Figure 4-22b illustrates the effect 2 mm/yr sea-level rise has on profile development over time; the average cliff toe level rises at the same rate as mean sea level.

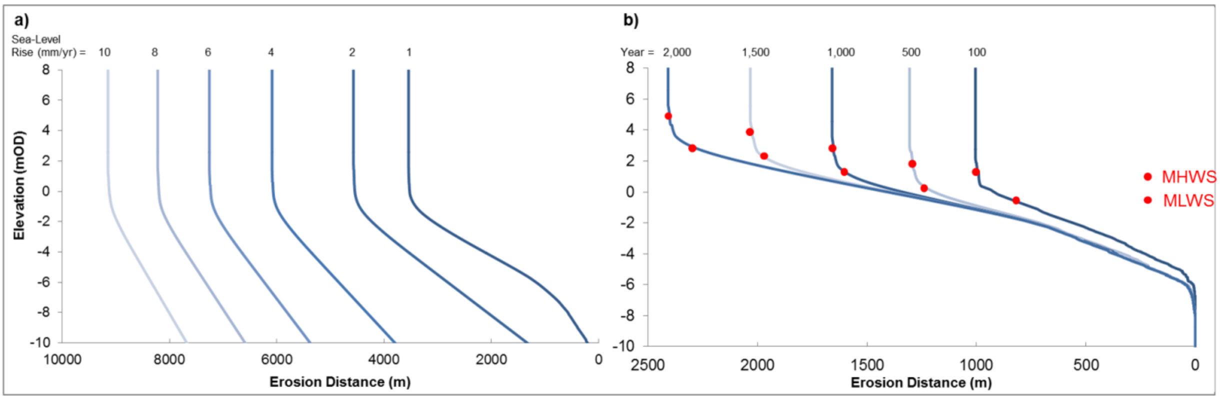


Figure 4-22: a) Changes in shore profile with varying sea level rise rates (note cliff toe position has been normalised in each case to aid comparisons), b) profile development with 2mm/yr sea-level rise

Within the SCAPE model, the actual retreat at any level within the limits of wave action is composed of both mechanical wave erosion and inundation (*i*) by the rising sea-level (Walkden and Hall, 2005). The latter is equal to Equation 4-20. At depths below the limit of wave action, erosion is assumed to be entirely due to inundation (*i*):

$$i = \frac{S}{tan\alpha}$$

Equation 4-20

where, S is the rate of sea-level rise and α is the average slope across the surf zone.

4.3.2.2 Quasi-3D model

This section presents a sensitivity analysis of the additional parameters in Q3D SCAPE and investigates appropriate model set-up considering the models inclusion of a one-line beach module.

Quasi-3D model set-up

An idealised, hypothetical linear coastline of 10km was set-up. For consistency, input parameters were kept consistent with those used in the 2D model sensitivity analysis (Table 4-8). Table 4-9 summarises the input values for the additional parameters within the Q3D model. For the purpose of the sensitivity analysis, homogenous input parameter values were used across the frontage. A shorter run duration of 1,000 years was used to enable sufficient time for the coast to emerge and fronting beach volumes to develop.

Table 4-9: Quasi-3D SCAPE input parameters to investigate model behaviour across an idealised frontage (data sources explained in text)

Purpose	Preliminary Inputs	Units	Value Range
Beach Characteristics	Beach volume	M^3/m	Allowed to emerge
For the calculation of beach sediment volumes released from the cliff	Cliff top elevation Cliff beach grade material	m %	35 20
Calibration variable	CERC coefficient	$S^{3/2}$	0.77

As the Q3D model can simulate longshore sediment transport and interactions between a series of 2D profiles the beach volume was allowed to emerge over time from $0m^3$ at year 0 of the model simulation. Considering the dependence of beach emergence on cliff top elevation and the proportion of sediment available from the eroding cliff, conservative values of 35m and 20%, respectively were applied across the frontage based on Dickson et al (2007).

As with the 2D model sensitivity analysis, prevailing conditions broadly representative of the north Norfolk coastline were used. The model was set to a baseline angle of 90º (from north, 0º). However, as the model uses the CERC equation, assuming sediment transport is driven by the longshore component of wave energy flux, a synthetic random wave direction travelling to the coastline at 135˚ (from north, 0˚) with a standard deviation of 5 has been used. This causes sediment to move along the frontage from west to east, see Figure 4-23. Furthermore, as the coefficient acts as an amplifier of gradients in the sediment transport rate, the parameter was set to 0.77, the upper limit of the range recommended by Hanson and Kraus (1989) assuming an all sand, mobile coast.

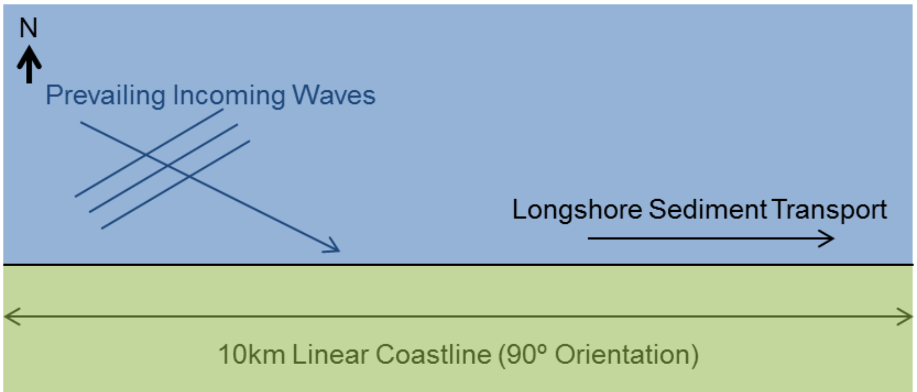


Figure 4-23: Diagram of Quasi-3D SCAPE model coastline and wave orientation

Sensitivity analysis

This section provides a sensitivity analysis of the additional parameters within the Q3D model. As the model includes a one-line beach module, the additional parameters relate to the development of fronting beach volumes. Therefore, this analysis is predominantly concerned with the effect of constant changes (across the entire coastline) in cliff height and composition (% beach grade material, BGM) on average rates of cliff toe retreat. The effect of variability in conditions in the longshore will be considered later in the thesis.

Cliff height

Figure 4-24 shows the variance in the average rate of cliff toe recession with changing cliff height by the end of the model simulation. Higher cliff heights result in lower rates of recession. This is owing to negative feedback between cliff recession and beach volumes; with larger cliffs producing a greater volume of debris material available to form a protective fronting beach. However, while this relationship is valid (as highlighted by Section 2.2.1) increased cliff heights also result in greater cliff instability which may contrastingly increase recession rates.

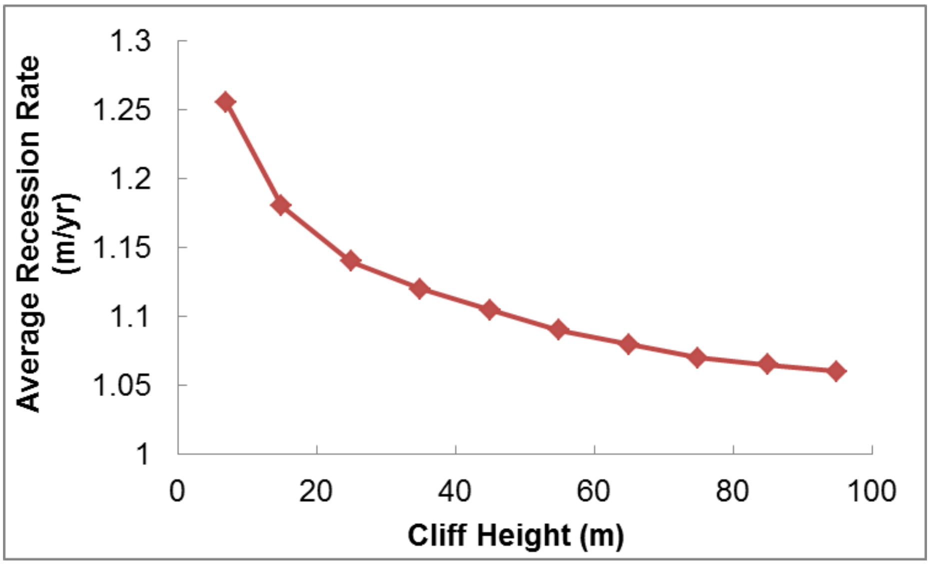


Figure 4-24: Change in in average recession rate with cliff height

Cliff composition

Figure 4-25 shows the variance in the average cliff toe recession rate with a varying proportion of BGM available from the eroding cliff. As would be expected, the higher the percentage of material available, the lower the recession rate as a larger protective beach volume can develop.

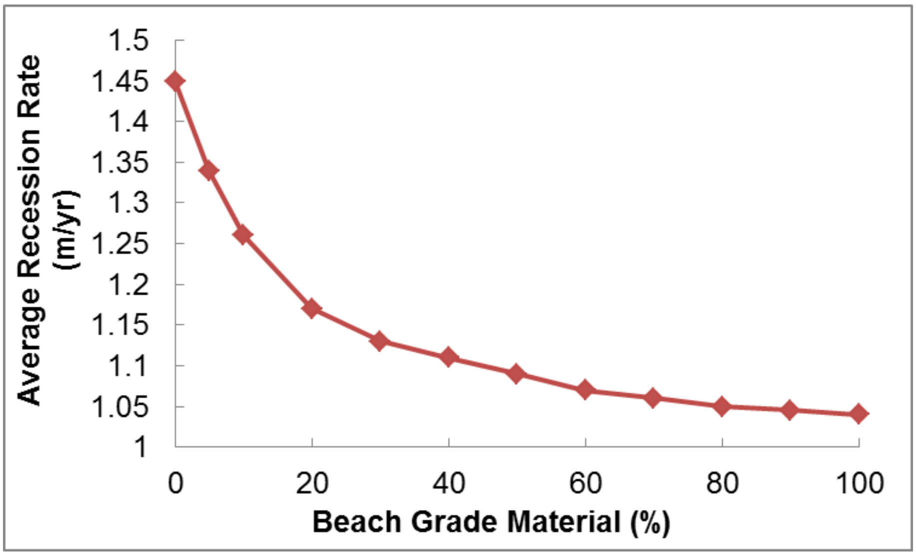


Figure 4-25: Change in average recession rate with cliff composition

Coastal landsliding

This research is primarily concerned with the cliff toe processes considering it as a key link between the terrestrial and marine portions of the cliff system (Section 2.3). Therefore, as variation in the initial, falling and stable angle of the cliff relate to the cliff top, these additional parameters are not considered.

Quasi-3D model capability investigations

Additional model investigations were conducted on account of Q3D SCAPEs inclusion of a one-line model to test:

1. What resistance multiples can the Quasi-3D SCAPE model simulate?
2. What are appropriate model grid dimensions?

Question one will enable the limitations of applying the SCAPE model to coasts of variable resistance in the longshore to be understood. It is envisaged that this will provide justification for the application of the model to the study frontage. Question two will provide insight into the scales which can be explored with the model and appropriate profile spacing to explore longshore variations.

Resistance Magnitude Investigations

For the purpose of these investigations the relative resistance of the central 2 km of the model (chainage 4 to 6 km) was increased in comparison to that of the adjacent coast. The models performed for the entire simulation period indicating that the model can cope with up to a tenfold change in the magnitude of resistance. However, this threshold may change with interactions between; material resistance, sediment content and prevailing conditions.

Figure 4-26 shows the results of the longshore resistance sensitivity test based on coastal planshape development by the end of the simulation. As expected, an increase in resistance results in a reduction in the rate of retreat. Over time this results in the formation of a protrusion (approximately 70m offset) which can be likened to headland formation at chainage 4 to 6km. However, it can be noted that this only corresponds to an approximate change in retreat rate of 16% despite up to 10x changes in relative resistance. It is hypothesised that this limited impact is owing to the development of protective fronting beach volumes as the frontage retreats over time, as will be further explored in Section 5.2.

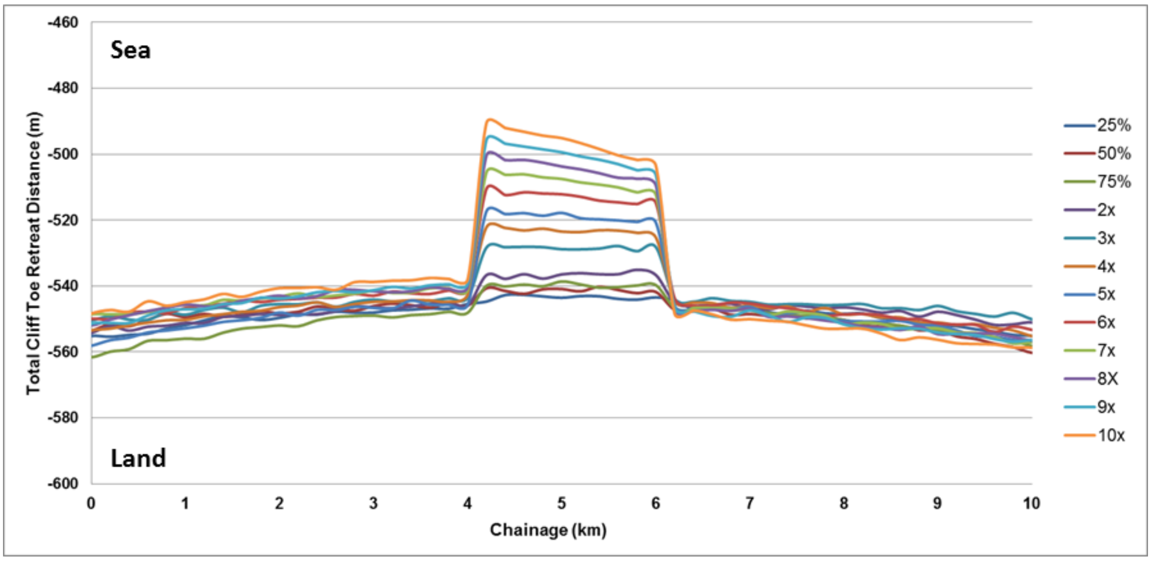


Figure 4-26: Coastal planshape at year 1,000 with varying degrees of resistance

The variation in cliff toe position on the adjacent stretches can be explained by the change in beach volume across the frontage, which is associated with the varying offset of the headland and its influence on longshore sediment transport. As resistance increases the western side of the headland is growing disproportionately to the eastern side despite having the same resistance value. This is owing to the build-up of beach volumes updrift of the headland which further reduce retreat rates.

Grid dimensions investigations

To investigate appropriate model grid dimensions for coasts of longshore variable lithology (such as the IoW study frontage), a 2 km central section of variable (2x) resistance was created based on the previous results. However, the profile spacing (d_x) was varied and the corresponding resistance values of each profile were varied accordingly. For example, with 2 km profile spacing, one profile of increased resistance was introduced but with 500 m spacing four profiles of increased resistance were required to represent the 2 km 'headland'.

As the Q3D model consists of a series of interlinked profiles, the coastal planshape is determined by interpolation between the cliff toe positions at each profile. Figure 4-27 demonstrates the influence of 2 km and 250 m d_x on the output coastal planshape. A finer resolution enables more detail to be captured; highlighting the importance of considering geographical scale and appropriate grid set-up. For example, for an extensive straight coastline of homogenous characteristics a coarse d_x may be sufficient, while for a coastline consisting of a series of headlands and bays with variable lithology a finer d_x will be required.

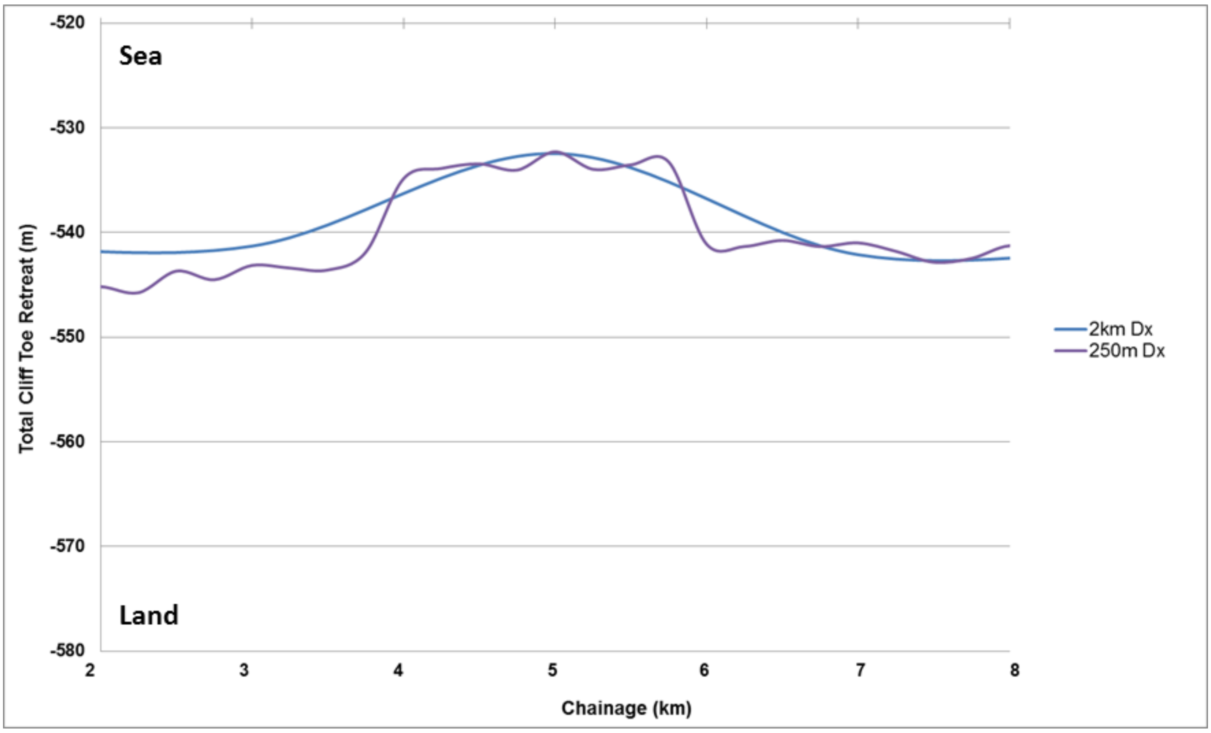


Figure 4-27: Effect of profile spacing on output coastal planshape at year 1,000 with a 2km wide 'headland'

4.3.3 Preliminary evaluation of selected model

This section has provided a critical appraisal of the 2D and Q3D SCAPE model based on its technical development and initial investigations regarding model behaviour and sensitivity. The preliminary findings are discussed below.

4.3.3.1 Evaluation of model behaviour and sensitivity

The assessment of 2D model behaviour demonstrated the process of shore profile development from an initial vertical cliff. The sensitivity analysis of the effect of a range of 2D model parameters on the development of an idealised cliff profile has confirmed some key geomorphic relationships previously highlighted in Chapter 2. The model agreement with previous studies (Kamphuis, 1987, Taylor et al., 2004, Trenhaile, 2009, Walkden and Dickson, 2008, Walkden and Hall, 2005) supports the governing principles used in the development of the SCAPE model and the appropriate set-up of the model within this research.

The sensitivity of the cliff toe recession rate to each parameter is further demonstrated by the tornado chart presented in Figure 4-28. It shows how a 25 % increase/decrease in the model parameters from the baseline conditions (outlined in Table 4-1) influence the baseline retreat rate of 1.43 m/y. Changes to the average wave height appears to be the most dominant prevailing condition, while changes in the material resistance parameter are the most dominant in-situ parameter on rates of cliff toe retreat within the SCAPE model.

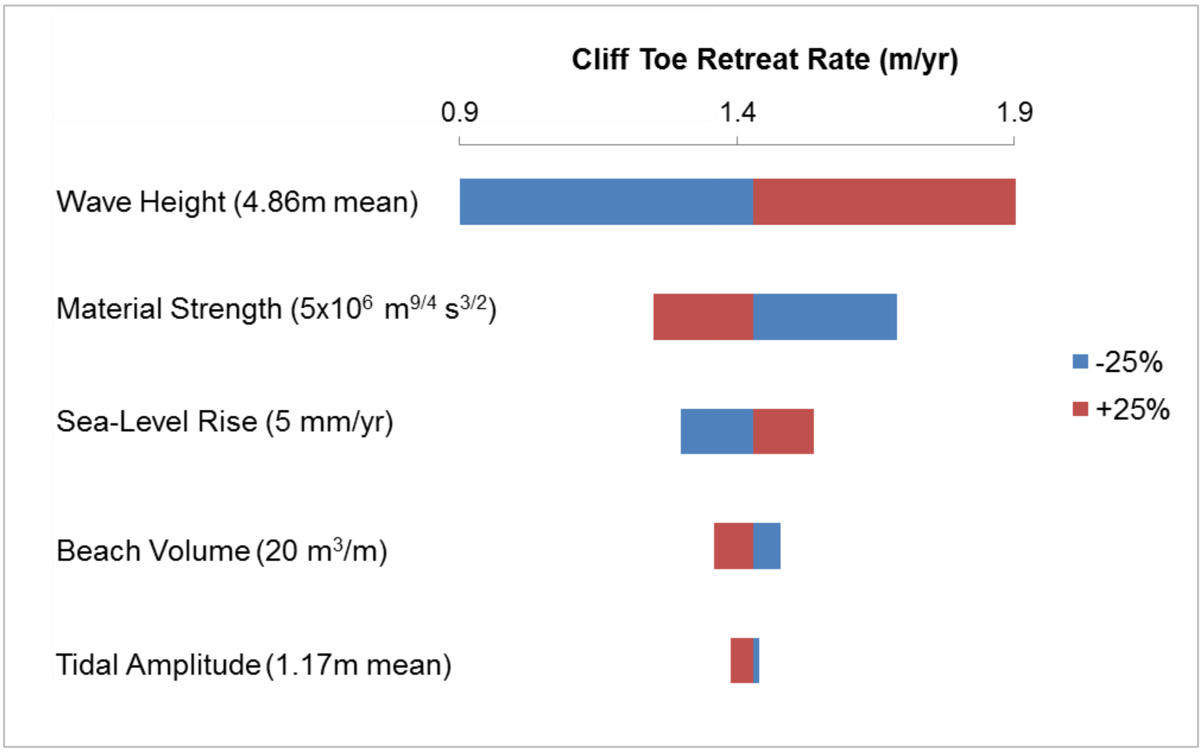


Figure 4-28: Tornado chart of SCAPE 2D sensitivity to a range of input parameters

Further sensitivity analysis of the additional parameters included within the Q3D model highlighted the importance of the development of fronting beach volumes on controlling the recession rate of the coast. As would be expected, greater beach volumes result in reduced erosion of the cliff toe owing to its protective nature. The sensitivity analysis has demonstrated how cliff erosion contributes to the beach from both the volume of the cliff eroded (considering its height) and the percentage of BGM.

Q3D investigations have also identified that a range of magnitudes in relative resistance can be considered (from a baseline resistance of $5x10^6$ $M^{9/4}S^{3/2}$), which is important considering the application of the model to a site of variable lithology. However, this range may change with varying prevailing and in-situ conditions. Furthermore, model-set up has highlighted the importance of an appropriate profile spacing to accurately represent the study frontage in question.

4.3.3.2 Comparisons with the systems-based model

Chapter 2 presented a systems-based model of the soft cliff system (Figure 2-9) intended to be a useful foundation to provide an initial assessment of a CBU or prediction method. Figure 4-29 compares the parameters and processes currently considered within the Q3D SCAPE model (which is the most comprehensive) on this systems-based model. The figure further emphasises the broad coastal system represented by SCAPE, which provides a sound foundation for model development. However, Figure 4-29 also highlights the limited range of geological and sub-aerial parameters and processes included.

4.3.3.3 Summary of identified strengths and weaknesses

Table 4-10 summarises the key strengths and weaknesses of SCAPE identified throughout this chapter. This highlights the benefits of its application but also makes apparent its flaws. However, upon recognition of the latter they can also be viewed as potential opportunities for model improvement within this research as will be further addressed in the following chapter.

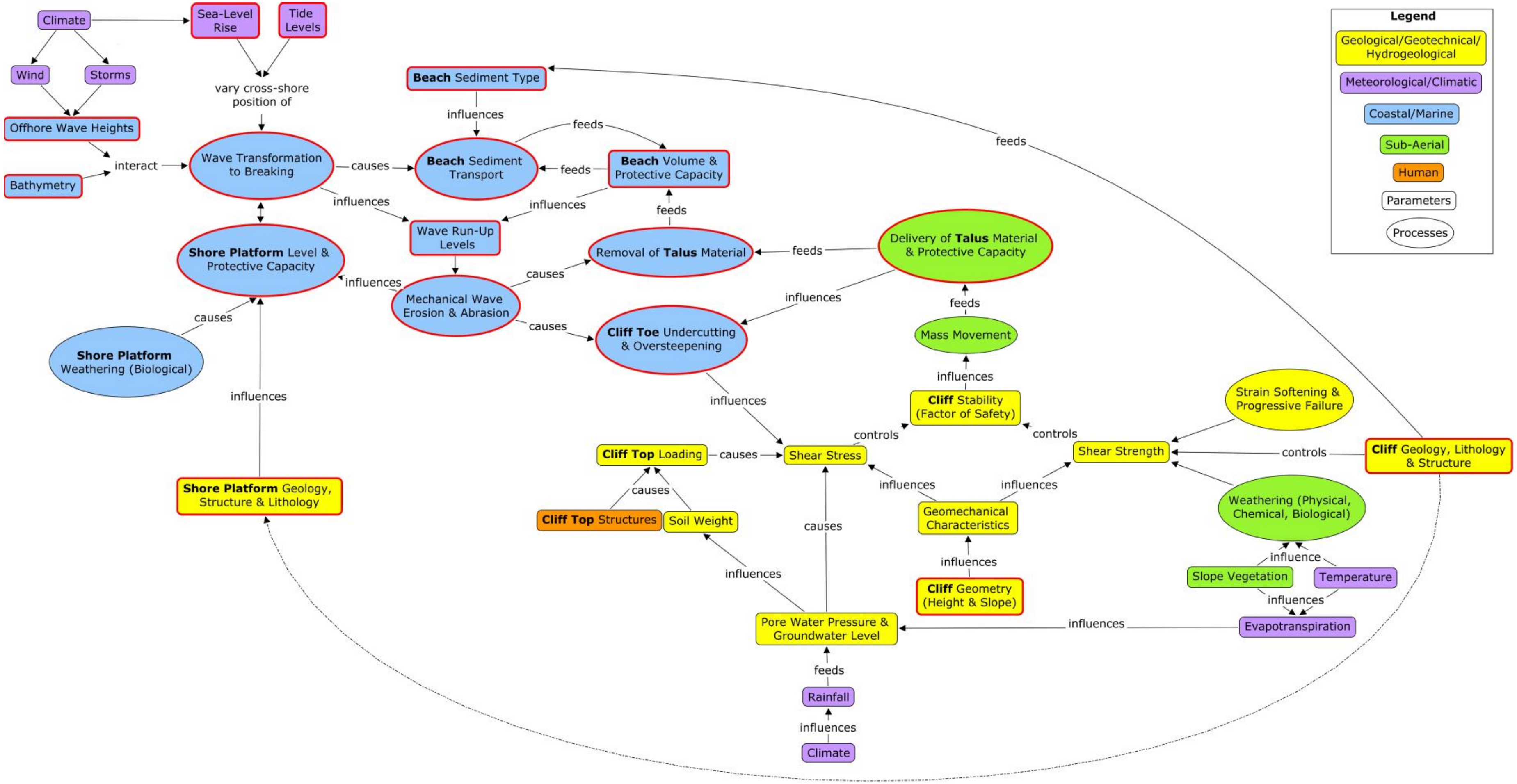


Figure 4-29: Identification of SCAPE parameters and processes within the generalised conceptual model[22]

[22] SCAPE also considers the presence of coastal engineering structures which are not reflected within the conceptual model

Table 4-10: Evaluation of the SCAPE model

Strengths
• Developed based on a review of previously existing models. • Validated against a number of simple cliff sites. • Provides quantitative mesoscale predictions. • Represents a broad coastal system including both erosional and depositional environments. • Includes a range of interactions and feedback mechanisms. • Assists in understanding the response of the soft cliff system to changing conditions i.e. climate change. • Can consider longshore variations in material resistance, cliff height and beach grade material. • Quantifies the relationship between the shore platform and the beach as opposed to considering an infinitely deep beach. • Enables the sediment budget to be quantified. • Incorporation of a curved Bruun Profile as opposed to a single gradient slope. • Short model run times.
Weaknesses

• Incorporates the results of Skafel (1995) for Glacial Till cliffs, limiting the use of the model to soft rock shores.
• Is limited to sites where a one-line beach module can accurately represent the processes of sediment transport.
• Confidence in the model results and calibration of some of the parameters is primarily based on its ability to replicate cliff recession for known periods of time. Such 'tuning' does not necessarily mean that parameters are correct and poses questions regarding the models ability to successfully replicate past and future conditions.
• Simplification of the system with limited role of geotechnical and sub-aerial processes:
  o Model is deterministic and therefore more suitable to predict an aggregated rate of erosion as opposed to individual events.
  o The 2D model considers cliff recession to occur every ten recession events.
  o Within the Q3D model cliff geometry is represented to determine cliff top position considering a simplified rule of slope

stability based upon the initial, falling and stable angles of the cliff. It does not consider the factor of safety of the slope or the process of mass movement in any further detail.

- It is assumed that the only climatic influence on recession is via the shoreline. It cannot simulate the effects of hydrological changes on cliff stability.
- Geology is only considered as a material resistance calibration parameter which is homogenous in the vertical. As a result, within SCAPE the cliff and shore platform resistance are linked. However, in the field this is likely to vary; the shore platform may be formed of a more resistant layer of stratigraphy than the rest of the cliff face and is subjected to different forces which may alter its geotechnical properties.
- Lithology is only considered in terms of the percentage of material within the cliff face which can contribute to the fronting beach volume upon erosion. As with material resistance, this is treated as a homogenous value in the vertical. Furthermore, to avoid the build-up of unrealistic fronting beach volumes, the cliff is only considered as a source of sediment within the Q3D version of the model which considers sediment transport.
- Cliff structure is not considered.

4.4 Research methodology: closing comments and proposed model application

This chapter has contributed towards objective two of this research: *to assess the limitations of existing cliff retreat models*. Initially, a detailed review of the range of currently available cliff recession prediction approaches was carried out. The advantages and disadvantages of each approach were evaluated and combined with a study assessing the treatment of sea-level rise feedback within the cliff system.

Process-based numerical modelling was identified as a key method as it can simulate a range of parameter and process interactions (an important requirement considering the systems-based model previously developed in Chapter 2). Furthermore, the approach can simulate changes provided they can be described in numerical terms; a key requirement owing to the focus of this research on the impacts of environmental and climatic change.

The SCAPE model was selected as the most appropriate process-based model for assessment and development within this study, based on:

- Previous successful application to a range of soft-cliff sites;
- Broad range of parameters, processes and feedback mechanisms included;
- Generic application to soft rock geologies;
- Flexibility of the model and its potential for extension;
- Best fit of modelled versus measured historic rates of retreat using the Walkden and Dickson (2008) formula (which was derived from the SCAPE model) along the study frontage (Section 4.2.2.4).

To further understand the SCAPE model a critical appraisal and sensitivity analysis of the range of parameters available within the original 2D and quasi-3D (Q3D) models was undertaken. Generic applications supported the trends identified in previous SCAPE model publications and the literature review (Chapter 2). Changes in wave height and material resistance were identified as the most influential prevailing conditions and in-situ conditions, respectively on modelled rates of cliff toe retreat.

It was noted that SCAPE, as with all numerical models, presents an abstraction of reality. Many of the processes within the coastal cliff system have been simplified in accordance with mesoscale reduced complexity modelling. For example, geological properties were recognised as a key parameter through the systems model (Figure 2-9). However, within SCAPE:

- Resistance is only considered as a calibration parameter which is homogenous in the vertical direction (2D and Q3D model);
- Cliff face structure is not considered (2D and Q3D model);
- Lithology is considered as the percentage of beach grade material within the cliff and is also homogenous in the vertical direction (Q3D model);
- Cliff geometry is treated by a simple module of initial, falling and stable angles to determine the cliff top position in the (Q3D model).

Potential model limitations will be confirmed and developed through further application of SCAPE to the study frontage of the south west coast of the Isle of Wight. The site consists of variable lithology in both horizontal and vertical directions. This has not been considered in previous applications of SCAPE, which have focussed on simple cliff systems of homogeneous lithology fronted by healthy protective beach volumes. Therefore, it is envisaged that application and assessment of the current SCAPE models will identify appropriate methods for model extension. Table 4-11 outlines the proposed methodology for the following chapter.

Table 4-11: Overview of proposed model simulations

Chapter	Section	Model	Purpose
5: Application and assessment of selected model	5.1	2D	To evaluate the models ability to replicate a series of profiles representative of the main headland and bays across the study frontage and understand their cross-shore evolution.
	5.2	Q3D	To understand the role of longshore interactions on the potential for headland and embayment formation.

5. Application and Assessment of Selected Soft Cliff Model

This chapter presents the preliminary results considering the application of the current 2D and Quasi-3D (Q3D) SCAPE models, driven by study frontage conditions. This is crucial considering the need to assess the model performance for an actual site (as highlighted by objective two) and to use the findings to inform appropriate methods to improve the model (objective three). The chapter layout is as follows:

- Section 5.1 describes and evaluates the application of SCAPE 2D to the study frontage;
- Section 5.2 similarly applies Q3D SCAPE to understand longshore interactions;
- Section 5.3 identifies model refinements and subsequent methods based on the above findings;
- Section 5.5 summarises the chapter.

5.1 2D model application

This section describes the application of the current 2D SCAPE model to investigate how localised conditions are represented. The model will be applied to a series of seven profiles across the study frontage of the Isle of Wight (IoW), selected as representative of the main headlands and bays across the frontage (as outlined in Figure 5-1).

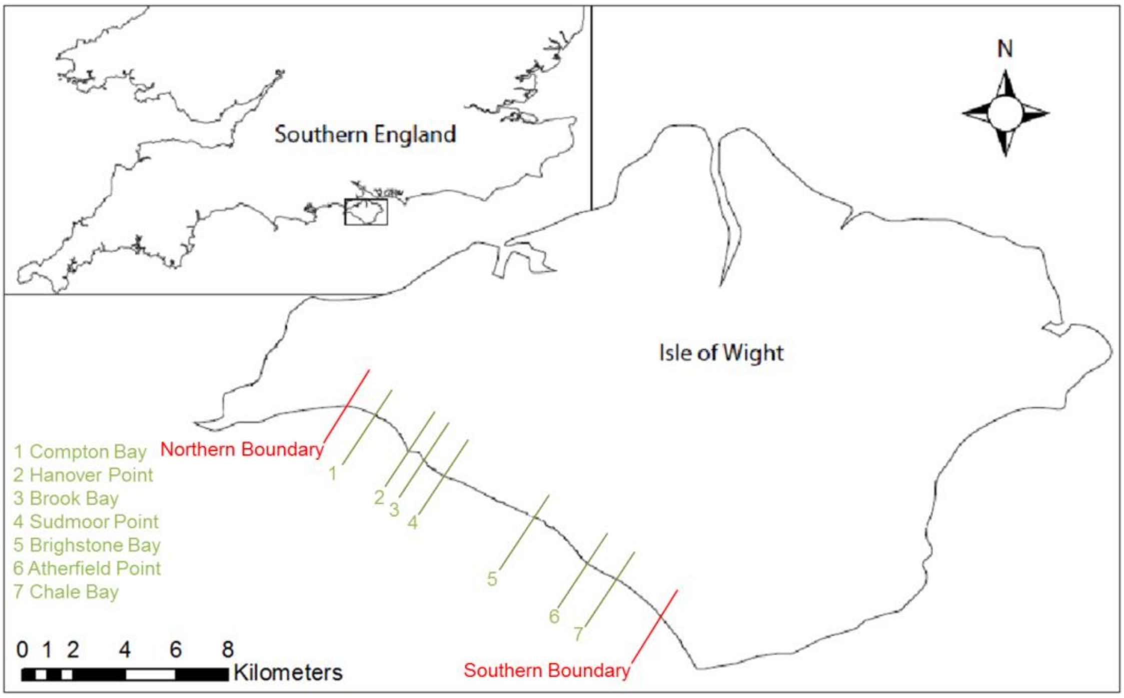


Figure 5-1: Map of representative 2D profiles along the study frontage

5.1.1 Model set-up

A staged approach to 2D model development is required as follows:

1) Profiles are initially allowed to emerge from a vertical cliff to dynamic equilibrium considering prevailing and in-situ conditions, as described in Section 4.3.3;
2) Models are calibrated using the material resistance parameter (*M*) to establish a value which provides correct average rates of retreat over a known historic period for the site in question; and
3) Finally, since model validation cannot be based on the average recession rate, comparisons are made between the modelled and measured profile shape.

Table 5-1 summarises the input parameters common for each of the 2D models. Wave and tide data for the Milford wave buoy (Latitude: 50˚ 42.75'N, Longitude: 001˚ 36.91'W) and Sandown pier tide gauge (Latitude: 50˚ 39.0666' N, Longitude: 01˚ 9.18960'W) respectively were used (locations highlighted on Figure 3-1). The wave data was hourly and included the significant wave height, period and direction. The buoy is deployed at a water depth of approximately 10m CD (Chart Datum) and records span the period of 1996 to present. Tide level data was recorded at 15 minute intervals from 2006 to present and was interpolated to represent the IoW study frontage. The tide data was then filtered to obtain the high tide values to be used as the model input. As the wave and tide files were shorter than the modelling period (approximately 10,000 years to dynamic equilibrium) the files were recycled. No attempt was made to represent extremes not already in the records. However, considering the length of records at the site, this was deemed sufficient to replicate the present day shoreline considering previous applications of the SCAPE model (e.g. Walkden and Hall, 2005). The historic rate of sea-level rise of 1.4 mm/yr applied was based the results of Haigh (2009) for Southampton.

Table 5-1: Generic input parameters for study frontage 2D models

Purpose	**Preliminary Inputs**	**Units**	**Value Range**
Profile evolution	Wave Height Wave Period Run-up Limit	m s m	Variable with time: 0.01 to 5.71 (0.65 mean) Variable with time: 1.7 to 25 (8.33 mean) 2.07
Cross-shore distributions of sediment transport and erosion	Tidal Amplitude Sea-level rise	M mm/yr	Variable with time: 0.2 to 1.34 (0.66 mean) 1.4

Along with the prevailing conditions described above, a range of site specific values were also input into each model, as summarised in Table 5-2. The baseline angles were taken from Ordnance Survey Maps available from Edina Digimap. A depth of closure of 10.4m was derived from Equation 4-6, as previously detailed in Section 4.2.2.2. The angle of the offshore contour at this depth was taken from bathymetry data available from CMAP.

Initial beach volumes for the profiles were determined from LiDAR data available for the study frontage for 2007 from the Channel Coastal Observatory (CCO). The slope and curve of the beach for each 2D profile was defined by setting the Beach Bruun Constant (a) in Equation 4-9. This value was determined using Dean (1987) and Hallermeier (1981a) and the median grain size of sediment at the profile derived from field data of Stuiver (2012).

Table 5-2: Site specific input parameters for study frontage 2D models

Input	Location						
	Compton Bay	**Hanover Point**	**Brook Bay**	**Sudmoor Point**	**Brighstone Bay**	**Atherfield Point**	**Chale Bay**
Baseline Angle (degrees)	315	321	323	307	298	328	310
Angle of Offshore Contour (degrees)	330	329	327	314	303	317	309
Beach Volume (m^3/m)	7	4.5	6.5	5	15	9	27
Bruun constant	0.1	0.09	0.1	0.1	0.2	0.19	0.2

5.1.2 Study frontage investigations

The following sub-sections describe the process of model calibration and validation for each site which will enable an evaluation of the model performance.

5.1.2.1 Model calibration

The 2D models were run to dynamic equilibrium from an initial vertical cliff over a 10,000 year simulation period (considering the spin-up period previously described in Section 4.3.1.1) with the conditions described in Table 5-1 and Table 5-2. Upon development of equilibrium profiles, different values of the material resistance parameter (*M*) were trialed to calibrate the models against historic average rates of retreat for each site. The models were constructed to represent the study frontage in 2008, considering its development over the preceding 142 year period (from 1866 when the first accurate map was produced). Historic rates were determined from the results of Stuiver (2010) using the DSAS (Thieler et al., 2009) for the historic maps and aerial photographs available. Table 5-3 summarises the calibration process indicating the various parameter values trialed and their respective recession rates. The optimised value is highlighted in bold.

Table 5-3: Summary of model calibration process

Location	Measured Historic Recession Rate (m/yr)	Material Resistance Parameter ($m^{9/4}$ $s^{3/2}$)	Modelled Historic Recession Rate (m/yr)
Compton Bay	0.49	• 11 $\times10^6$ • 12 $\times10^6$ • 14 $\times10^6$ • 18 $\times10^6$ • 22 $\times10^6$ • 24 $\times10^6$ • 26 $\times10^6$ • 28 $\times10^6$ • **30 $\times10^6$**	• 0.86 • 0.82 • 0.80 • 0.62 • 0.56 • 0.53 • 0.52 • 0.51 • **0.49**
Hanover Point	0.71	• 16 $\times10^6$ • 15 $\times10^6$ • **14 $\times10^6$**	• 0.67 • 0.69 • **0.71**
Brook Bay	0.52	• 25 $\times10^6$ • 27 $\times10^6$ • 26.5 $\times10^6$ • **26 $\times10^6$**	• 0.53 • 0.51 • 0.51 • **0.52**
Sudmoor Point	0.41	• 25 $\times10^6$ • 32 $\times10^6$ • 35 $\times10^6$ • 42 $\times10^6$ • 44 $\times10^6$ • **45 $\times10^6$**	• 0.57 • 0.49 • 0.47 • 0.43 • 0.42 • **0.41**
Brighstone Bay	0.68	• 17 $\times10^6$ • 15 $\times10^6$	• 0.63 • 0.71

Location	**Measured Historic Recession Rate (m/yr)**	**Material Resistance Parameter ($m^{9/4}$ $s^{3/2}$)**	**Modelled Historic Recession Rate (m/yr)**
		• **16 x10^6**	• **0.68**
Atherfield Point	0.76	• 14 x10^6 • 12 x10^6 • 11 x10^6 • **11.5**	• 0.69 • 0.74 • 0.77 • **0.76**
Chale Bay	0.43	• 23 x10^6 • 35 x10^6 • 37 x10^6 • **40 x10^6**	• 0.56 • 0.46 • 0.45 • **0.43**

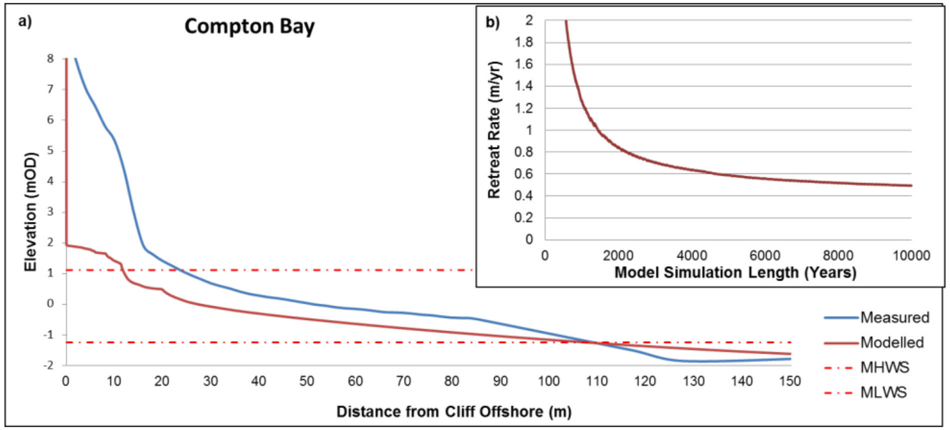
5.1.3 Model validation

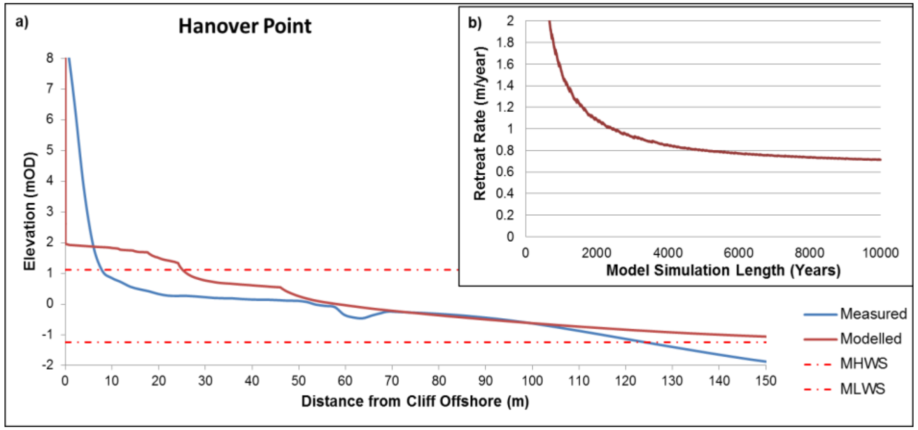
As validation cannot be based on the average recession rate (which has been fixed by the calibration process), comparisons were made between the output modeled shore profiles for each site compared to those measured from 2007 LiDAR data, Figure 5-2a. The measured data corresponds to the penultimate year of the model validation period and was the most recent data available at the time. Figure 5-2b shows the corresponding cliff toe retreat rate for each model simulation. As previously demonstrated in Section 4.3.2, Figure 4-17 the retreat rate decays asymptotically over time as the profile develops from an initial vertical profile.

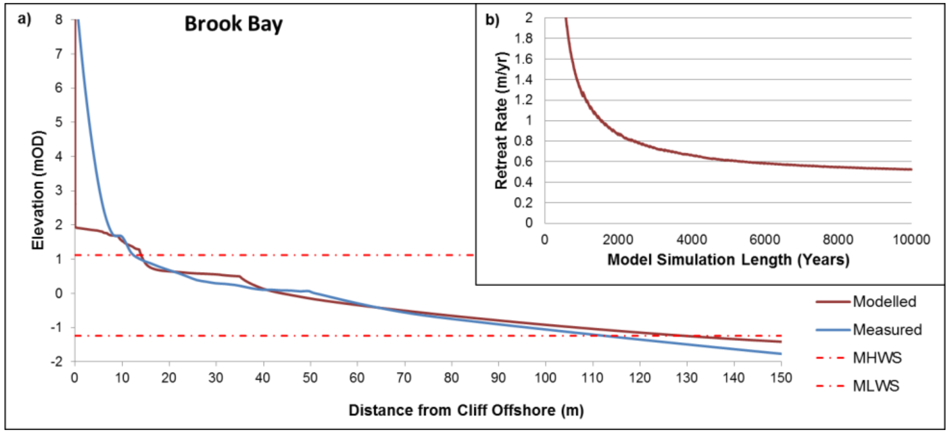
The modelled profiles also show a vertical cliff face, this is a relict feature of SCAPE 2D (as described in Section 4.3.1.1) and can be discounted as the focus of this study is on the cliff toe and shore platform. In comparison to the measured profiles, the modelled slopes do not contain as much cross-shore detail. This is because the SCAPE model tends towards a smooth shore profile (as demonstrated in Section 4.3.2) over time. However, the emergence of the cliff toe/shore platform junction just above MHWS (1.12 m OD) within both modelled and measured profiles combined with negligible variation in shore profile slope indicates that the principal shore erosion processes are being adequately represented in the model.

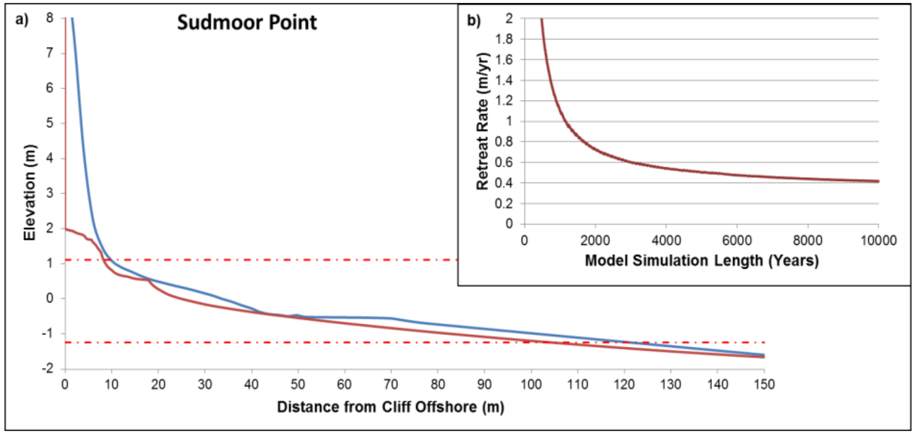
As the same prevailing conditions (e.g. waves and tides) are being used to drive each of the simulations, the variation in model results can be attributed to the varying in-situ input parameters at each site (e.g. beach volume and material resistance). It can be noted that the modelled shore profiles appear lower than those measured. This may be a result of model 'spin-up' from an unrealistic vertical profile with a constant historic rate of sea-level rise of 1.4mm/yr.

The SCAPE 2D results can be further analysed considering the area below MLWS further offshore compared against extracted bathymetry data for the frontage (taken from CMAP), as shown in Figure 5-3. As with Figure 5-2, the model outputs are smoother than those measured. In particular there are fluctuations in the bathymetric data with a range of varying slopes which are not reflected in the model results. Furthermore, in 5 out of 7 cases the modelled profile also expresses a higher elevation than that recorded on the measured data owing to the replication of a shallower platform slope than that observed. As platform slope is related to material strength (as previously demonstrated in Section 4.3.2.1), this discrepancy may be due to a variation in material strength below MLWS which is not accounted for within the homogenous description of material strength used in the calibration process. Such variations in offshore modelled and measured data may cause limitations in the accuracy of SCAPE model results as the processes of wave transformation cannot be accurately described by this simpler representation of the offshore profile.


a)
Compton Bay
Elevation (mOD)
Distance from Cliff Offshore (m)
Measured
Modelled
MHWS
MLWS
b)
Retreat Rate (m/yr)
Model Simulation Length (Years)


a)
Hanover Point
Elevation (mOD)
Distance from Cliff Offshore (m)
Measured
Modelled
MHWS
MLWS
b)
Retreat Rate (m/year)
Model Simulation Length (Years)


a)
Brook Bay
Elevation (mOD)
Distance from Cliff Offshore (m)
Modelled
Measured
MHWS
MLWS
b)
Retreat Rate (m/yr)
Model Simulation Length (Years)


a)
Sudmoor Point
Elevation (m)
Distance from Cliff Offshore (m)
b)
Retreat Rate (m/yr)
Model Simulation Length (Years)

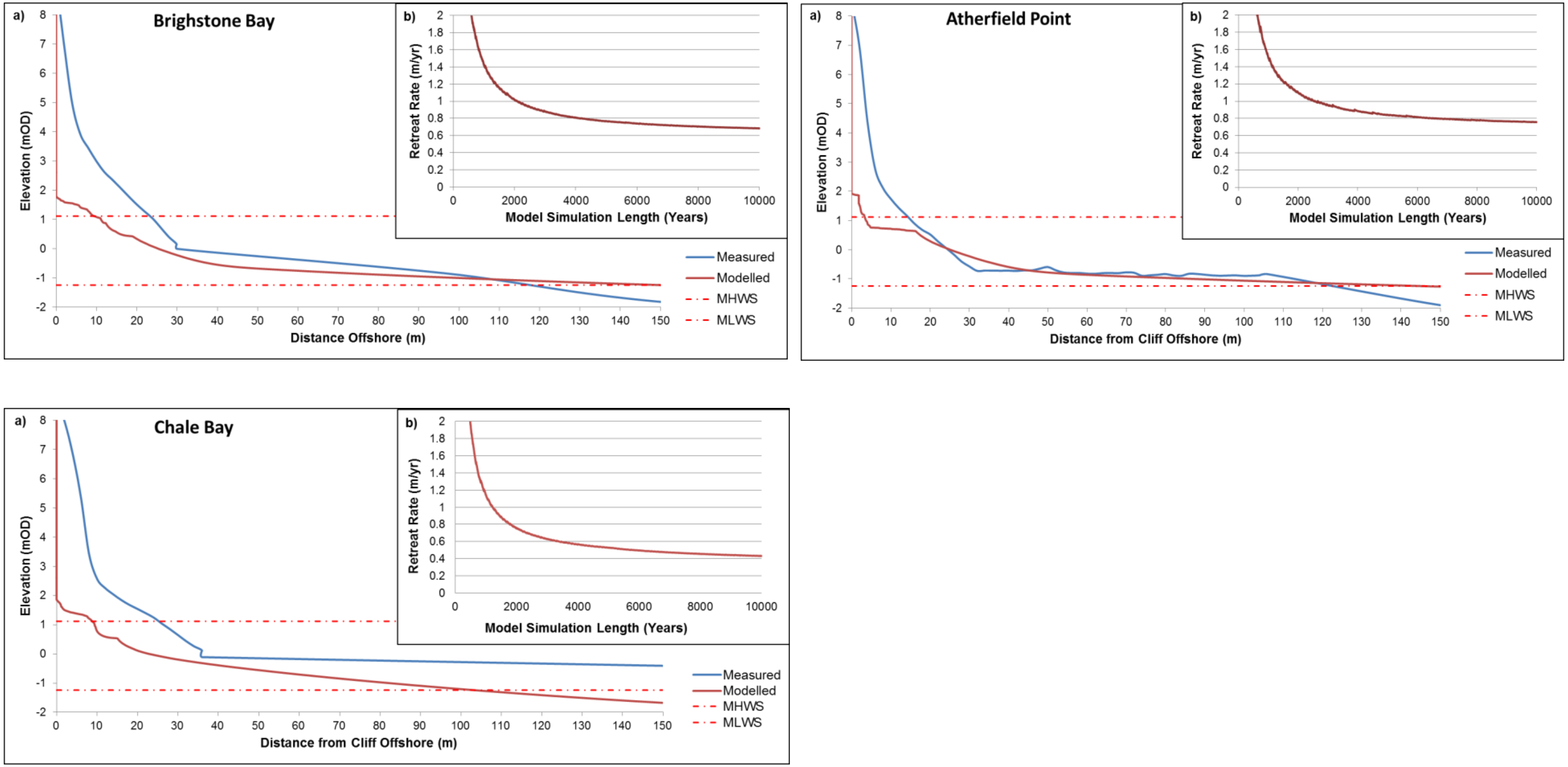
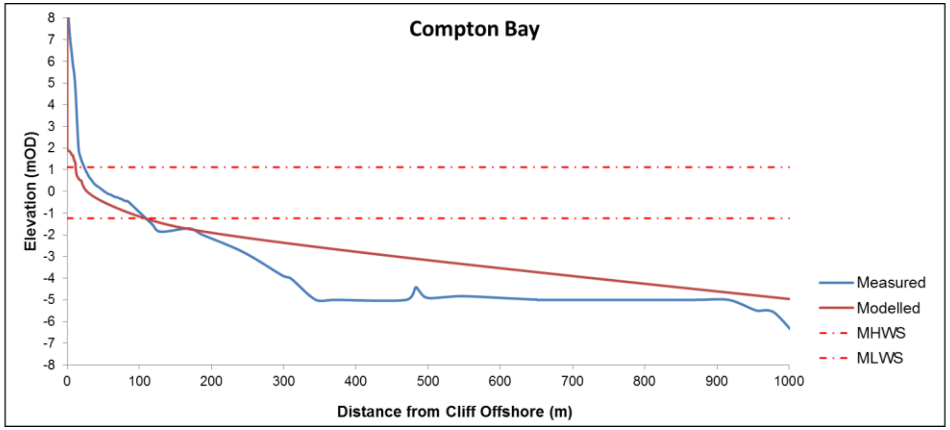
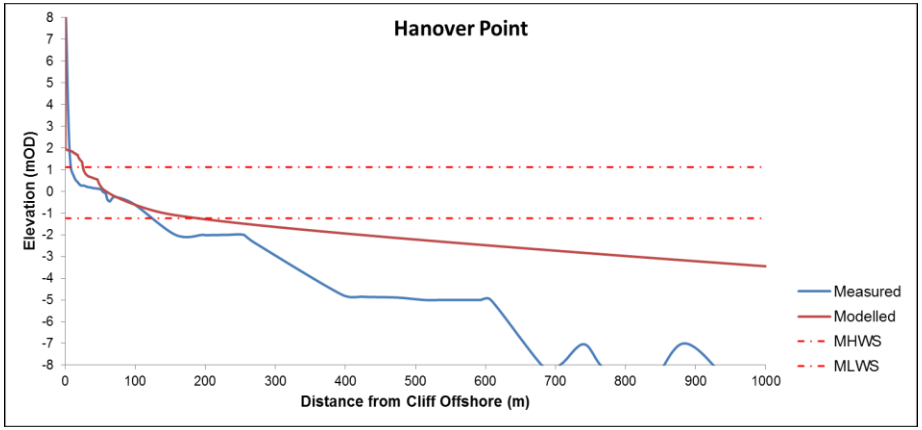
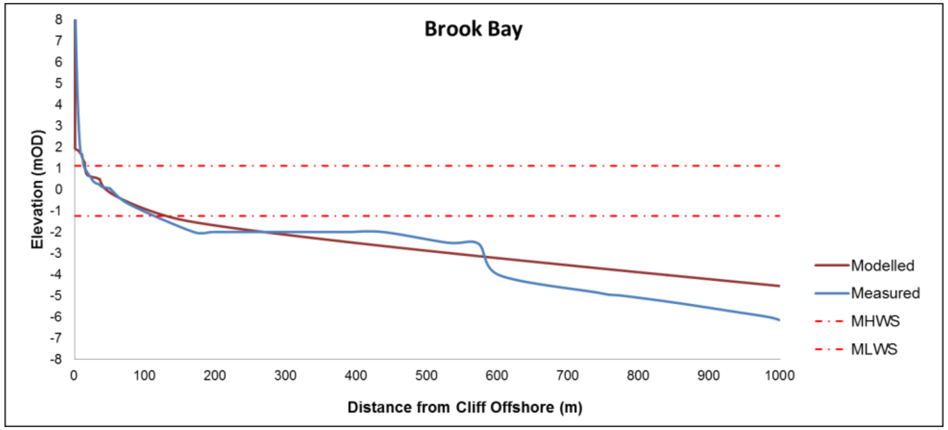
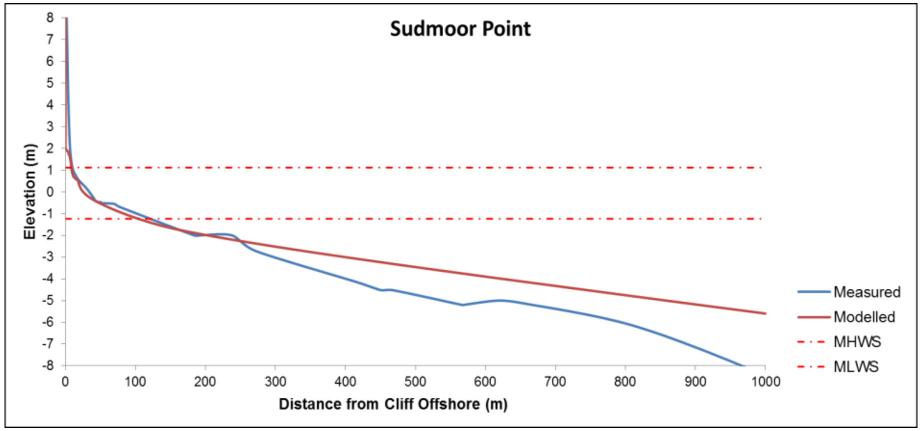


Figure 5-2: Model validation, comparisons of modelled versus measured shore profiles, b) corresponding retreat rates over model simulation period from initial vertical cliff


Compton Bay
Elevation (mOD)
8 7 6 5 4 3 2 1 0 -1 -2 -3 -4 -5 -6 -7 -8
0 100 200 300 400 500 600 700 800 900 1000
Distance from Cliff Offshore (m)
Measured
Modelled
MHWS
MLWS


Hanover Point
Elevation (mOD)
8 7 6 5 4 3 2 1 0 -1 -2 -3 -4 -5 -6 -7 -8
0 100 200 300 400 500 600 700 800 900 1000
Distance from Cliff Offshore (m)
Measured
Modelled
MHWS
MLWS


Brook Bay
Elevation (mOD)
8 7 6 5 4 3 2 1 0 -1 -2 -3 -4 -5 -6 -7 -8
0 100 200 300 400 500 600 700 800 900 1000
Distance from Cliff Offshore (m)
Modelled
Measured
MHWS
MLWS


Sudmoor Point
Elevation (m)
8 7 6 5 4 3 2 1 0 -1 -2 -3 -4 -5 -6 -7 -8
0 100 200 300 400 500 600 700 800 900 1000
Distance from Cliff Offshore (m)
Measured
Modelled
MHWS
MLWS

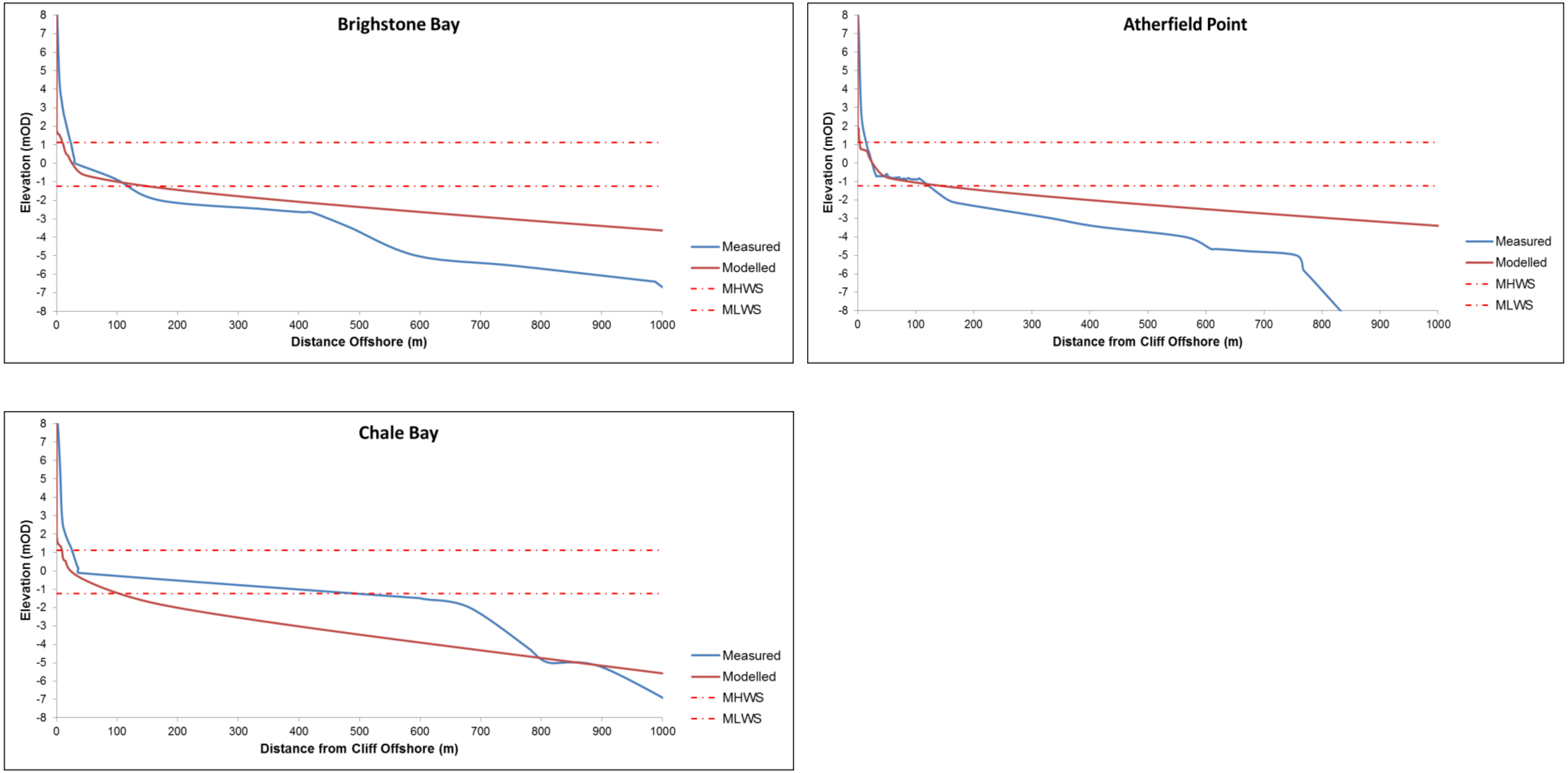


Figure 5-3: Offshore profile model validation

5.1.4 Discussion of study frontage investigations

The current 2D SCAPE model has been applied to a series of sites along the study frontage to evaluate its performance at replicating shore profiles and historic rates of retreat for cliffs variable lithology. This has demonstrated how the model is calibrated through an iterative process using the material resistance parameter (*M*) considering measured historic rates of retreat over a known period.

M relates to both material resistance and some other hydrodynamic constants (Kamphuis, 1987). However, some comparisons can be made between the final calibration value used in each model and site observations of material coherence. The latter has been determined from the geological mapping from Stuiver (2012) and knowledge of the associated geological properties of each formation presented in Table 3-1. Figure 5-4 demonstrates a qualitative link. However, it can be noted that M is generalised up the entire profile (Carpenter et al., 2012). Therefore, variations in material resistance in the vertical cannot be simulated in the current 2D SCAPE model.

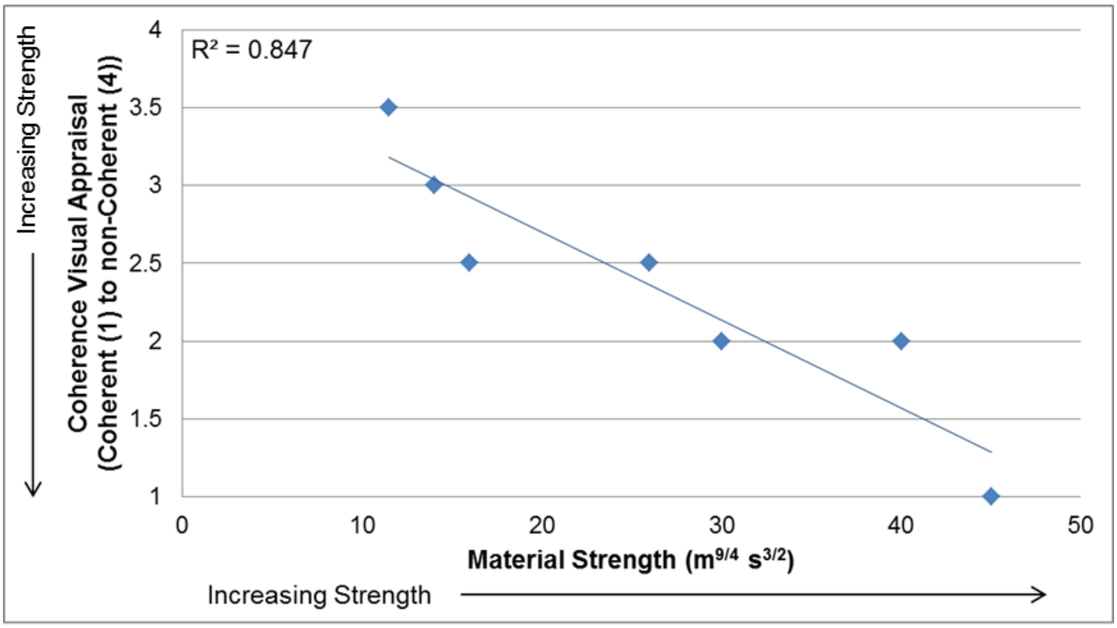


Figure 5-4: Model calibration parameter plotted against visual field observations of coherence (for the entire cliff face)

On the basis of the 2D study frontage model set-up a number of limitations of the input data can be noted:

- A uniform tidal range was applied across the entire frontage considering interpolation from the Sandown Tide Gauge. As the study frontage is near an amphidronic point there is a gradient in tidal range across the frontage which was not captured in these model runs.
- Wave data from the Milford wave buoy, to the north west of the study frontage was used. A limited data range from 1996-2011 was available for this site and the data were recycled over the modelling period. Furthermore, no attempt was made to capture extremes not represented in the data.

Despite these limitations, Section 5.1.3 has demonstrated that the model describes the prevailing conditions sufficiently to replicate the measured shore profiles (between the cliff toe and MLWS) along the study frontage when compared to extracted LiDAR data for the same sites. This is supported by correlations between modelled and measured data for:

- The emergence of the junction between the cliff toe and shore platform;
- The slope of the shore platform.

The output model profiles can be validated in a more quantitative manner based on the Root Mean Square Error (RMSE) of the modelled versus measured profile vertical elevation compared to distance offshore. When considering the accuracy of the shore profile, results have been calculated using values every 10 m from the cliff toe up to 150 m offshore. The results are summarized in Table 5-4 but overall, show a low average RMSE of 0.69 m.

Average vertical errors of the area further offshore (up to 1,000 m from the cliff toe) and below MLWS (up to -8 m OD) in comparison to measured bathymetry data can also be considered. As highlighted by Figure 5-3 the offshore profiles had smoother shore profiles of higher elevation, owing to the formation of shallower profiles slopes in comparison to measured data. The effect of this on the RMSE is also demonstrated in Table 5-4, with results calculated using values every 100 m showing a higher average RMSE of 2.22 m.

Table 5-4: Summary of root mean square errors for modelled versus measured shore and offshore profile vertical elevation

Location	RMSE Shore Profile (m)	RMSE offshore Profile (m)
Compton Bay	1.22	1.81
Hanover Point	0.25	3.84
Brook Bay	0.31	0.83
Sudmoor point	0.53	2.15
Brighstone Bay	0.88	1.95
Atherfield Point	0.62	3.20
Chale Bay	0.96	1.75
Average	**0.68**	**2.22**

The higher RMSE's associated with the offshore profile can be attributed to:

1. Shallower modelled profile slopes compared to those measured (with a range of 12 to 7 degrees compared to 20 to 6 degrees respectively). As previously discussed in Section 4.3.2, Figure 4-18, lower values of *M* result in more gently sloping profiles. Site specific values of *M* have been determined through calibration. However, to replicate measured angles more accurately it appears a higher value of *M* is required below MLWS.
2. Smoother modelled profiles compared to measured data, which commonly expresses undulations within the profile. For example, at Brook Bay a significant ledge at approximately -2 m OD can be observed (Figure 5-3) which is not replicated within the model.

Undulations in the measured offshore slope and the development of emergent ledge features can be attributed to the presence of harder rock layers within the shore platform stratigraphy. Such layers can be observed along the study frontage at Lowest Astronomic Tide (LAT). The varying lithology in the vertical is also confirmed by the geological mapping of the study frontage by Stuiver (2012). This is outlined in Figure 5-5, which highlights the geological cross sections for each of the modelled profiles. As previously demonstrated by Table 3-1, each geological strata has differing levels of coherence owing to their varying lithology. This confirms that the development of emergent features along the study frontage can be attributed to this variation. For example, at Sudmoor point the presence of the headland is controlled by the stronger outcropping Sudmoor Point Sandstone which is overlain by intermediately coherent Wessex Marl and topped by a thin of layer of less coherent Brick Earth. The influence of this mixed geology was also highlighted by the study of Jenkins et al. (2011) as documented in Section 2.2.1.

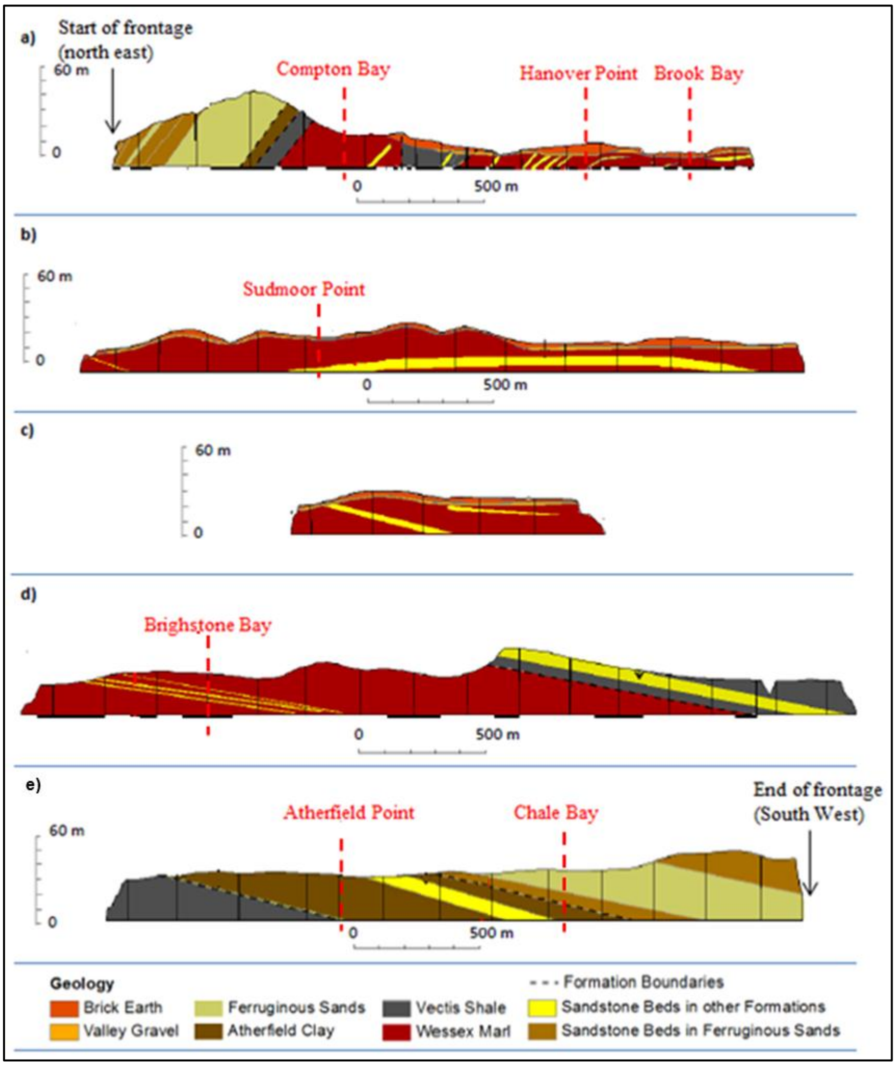


Figure 5-5: Geological mapping of the study frontage, from north east (a) to south west (e) highlighting the 2D profiles (adapted from Stuiver, 2012)

In contrast to these field observations of variable lithology, within SCAPE *M* is currently only considered as a calibration parameter which is homogenous in the vertical. Figure 5-4 showed that a qualitative link between this parameter and site observations of coherence can be identified. However, as the parameter is generalised across the entire profile, it does not reflect vertical variations in resistive strength and develops a characteristically smooth shore platform over time. Consequently, the model cannot currently identify relationships between different hard rock layers in the cliff toe and shore platform (Carpenter et al., 2012) and how such changes may influence changes in retreat rates and cliff morphology over time.

As noted by Jenkins et al. (2011) this provides a major control on erosional processes at the site; susceptible units which are interbedded with more competent layers affect the rate and style of failure by providing natural reinforcement. Furthermore, such hard rock layers may form emergent features which influence both the attenuation of wave energy and interact with sea-level rise over time. Such factors will have important implications for future land-use management. For example, along the study frontage it has been hypothesised that the discrete headlands have shifted spatially over human timescales as a result of the positioning and dip and strike of stronger stratigraphic units outcropping in the intertidal zone that cause an increase in shore platform elevation (Stuiver, 2012).

The variation in resistive strength is also an important factor when considering the modelled slope of the area further offshore. As highlighted by the sensitivity analysis, lower material resistance causes more gently sloping profiles. Figure 5-3 showed SCAPE producing shallower bathymetric gradients than those measured. This could potentially be amended by adjusting the material resistance parameter below MLWS to higher values and therefore produce a more steeply sloping bathymetry.

5.2 Quasi-3D model application

Section 5.1 has recognised the importance of vertical variations in lithology in replicating the study frontage. Moving on to consider the application of the Q3D model, the frontage also includes longshore variations in lithology (Figure

5-5), which may account for the presence of the series of persistent headlands and bays across the frontage (as introduced in Chapter 3).

The review of the cliff system undertaken in Chapter 2 emphasised the importance of cliff lithology but also highlighted the role of longshore interactions and protective fronting beach volumes in controlling coastal planshape evolution. However, the behaviour of low sediment coasts expressing longshore variations in lithology (such as the study frontage) is poorly understood. On this basis, this section will apply Q3D SCAPE to answer three questions relating to large-scale (greater than kilometres), long-term (up to 1,000 years) geomorphic evolution:

1. Can cliff lithology (availability of beach grade material from the eroding cliff and material resistance) be used to distinguish between high and low sediment coasts and how does their behaviour vary?
2. How do longshore variations in cliff lithology influence coastal planshape evolution?
3. By what means can coasts exhibiting longshore variations in lithology reach dynamic equilibrium, in particular considering the potential for headland and embayment formation and persistence over time?

Based on these questions it is envisaged that low sediment coasts of variable lithology (such as the study frontage) and the application of the Q3D model can be further understood.

5.2.1 Model set-up

An idealised linear coastline of 12 km was set-up. As the quasi-3D SCAPE model consists of a series of 2D profiles interlinked within a one-line beach module, 48 identical profiles at 250 m spacing were specified (as outlined in Figure 5-6).

Table 5-5 summarises the Q3D model input parameters. For the purpose of the analysis, homogenous values were applied across the frontage (with the exception of the parameter being tested, as will be explained later).

Table 5-5: Summary of quasi-3D model input parameters

Purpose	Preliminary Inputs	Units	Value Range
Profile evolution	Coastline orientation Wave height Wave period Wave Direction Run-up Limit	Degrees m s Degrees m	307 Variable with time: 0.65 mean Variable with time: 8.33 mean Variable with time: 212 mean 2.07
Beach Character	Beach volume Bruun constant	M^3/m -	Allowed to emerge 0.15
Cross-shore distribution of sediment transport and erosion	Tidal amplitude Rate of sea-level rise	m mm/yr	Variable with time: 0.65 mean 0
Calculation of beach sediment volumes released from the cliff	Cliff top elevation Cliff beach grade material	m %	35 20
Calibration variables	Material resistance CERC coefficient	$M^{9/4} S^{3/2}$ -	3×10^6 0.77

Consistent with Section 5.1 (Table 5-1 and 5-2), the coastal orientation and prevailing conditions (waves and tides) were representative of the study frontage. However, as this section is predominantly concerned with the sensitivity of the cliff system to the process of longshore interactions (and their description within Q3D SCAPE) it was not the intention to model this site explicitly. Therefore changes in relative sea-level that may affect shoreline behaviour were not considered; the study represents a coast that has evolved over a sea-level highstand. It can be noted that this condition induces a lower rate of retreat than that observed with the calibrated 2D models introduced in Section 5.1. Therefore the material strength parameter has been lowered by an order of magnitude in this section of the study.

Sediment transport along the study frontage is in a south easterly direction as shown in Figure 5-6. As with Section 4.3.2.2, the CERC coefficient was set to 0.77. To understand the development of protective beach volumes solely as a result of cliff lithology, no initial fronting beach was specified and all sediment was assumed to be supplied by the eroding cliffs. Furthermore, 4 km lateral boundaries were set up to enable sediment to leave but not enter the model domain.

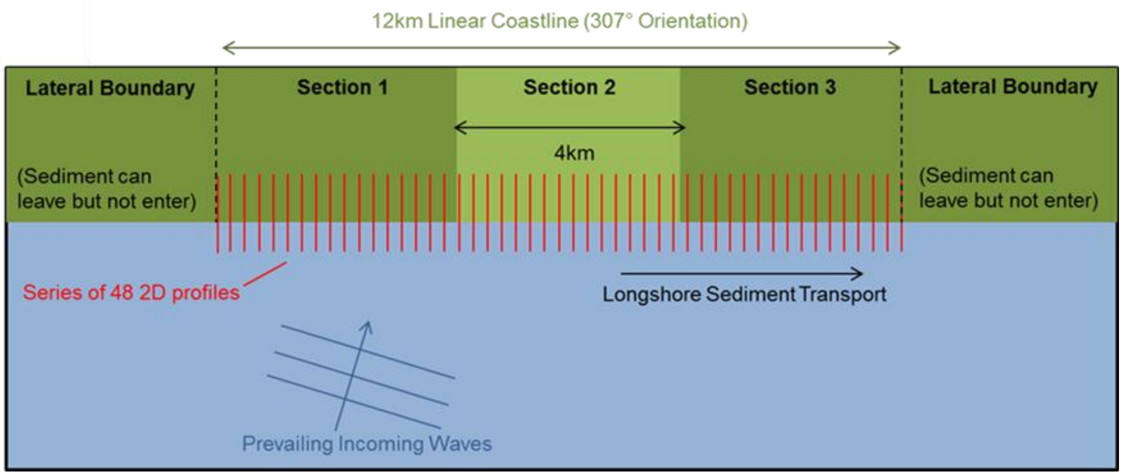


Figure 5-6: Plan-view schematic of quasi-3D SCAPE model. Sections 1 to 3 can have the same or different cliff lithology properties (see text)

Specific model simulations are described along with the results in the following section and summarised in Table 5-6 in the discussion (Section 5.2.3). All models were run over a period of 1,000 years in view of the geomorphic timescales being addressed, the time for the coastal planshape to emerge and fronting beach volumes to develop.

5.2.2 Longshore investigations

The SCAPE model was run multiple times to address the three key geomorphic questions. First, to distinguish between low sediment and high sediment coasts, the following Section considers varying degrees of homogenous cliff lithology. Secondly, Section 5.2.2.2 considers how longshore variations in lithology can control coastal planshape evolution. Thirdly, Section 5.2.2.3 considers whether and how coasts of variable lithology can reach dynamic equilibrium.

5.2.2.1 Determination of high and low sediment coasts

As introduced in Section 2.2.3.3, Walkden and Hall (2011) identified two contrasting modes of shoreline behaviour:

- **Mode A** (rock strength limited erosion): where recession is regulated by the adjustment of foreshore slopes which are controlled by the material strength properties of the cliff;
- **Mode B** (transport limited erosion): where the beach is sufficiently large and waves are subsequently unable to attack the foreshore unless its volume is denuded by a local gradient in longshore sediment transport.

However, considering longshore interactions, there is a need to understand whether the threshold between these two conditions can be characterised by changes in cliff lithology (availability of Beach Grade Material, BGM, and material resistance of the eroding cliff). To assess this, models with homogenous changes in BGM availability across the idealised frontage were first run. The material resistance and cliff height were kept constant as indicated in Table 5-5.

If the only source of sediment is from the eroding cliff, with no availability of BGM the cliff retreats in parallel at a steady rate, as no sediment accumulations can influence the cliff system and no variations in cliff resistance are present. As increasing degrees of BGM (10-80%) are introduced across the frontage, retreat rates begin to decline and undulations in the coastal planshape appear as a result of developing protective fronting beach volumes. This loosely supports the model findings of Limber and Murray (2011) of how variations in coastal planshape may develop even in the absence of longshore changes in material resistance. However, over the timescale considered in this study (one thousand years versus Limber and Murrays, 2011 fifteen thousand years) the locations of these undulations varied over time.

Figure 5-7 compares the trends over time for varying degrees of BGM availability (10, 20, 40 and 80 %). Figure 5-7a compares the average rates of retreat and shows how, in all cases, there are initially high rates of retreat as the frontages responds to the prevailing conditions with no initial fronting beach volume. Figure 5-7b compares the development of average annual beach volumes across the frontages and shows how threshold beach volumes increase with an increasing proportion of BGM available. The results can be used to distinguish between Mode A and Mode B coasts on the basis of the long term trends in the rate of retreat.

- **Mode A:** With 10% BGM, retreat rates stabilise (0.72 m/yr) by year 600, implying that sufficient sediment is available at the cliff toe from this point to provide protection against basal marine erosion. This corresponds to an average annual beach volume of 48 m^3/m (Figure 5-7b). However, by year 800 the retreat rates begin to increase again, which can be attributed to a decline in fronting beach volumes (< 40 m^3/m) as a result of the low availability of BGM supplied by the eroding cliff. Sediment outputs exceed inputs.
- **Mode B:** With 20% BGM the retreat rate stabilises to a lower rate (0.53 m/yr) as larger protective fronting beach volumes can accumulate with the greater proportion of BGM available. From year 800 the retreat rate and beach volumes continue at an approximately steady rate as sediment inputs and outputs appear balanced. When the BGM exceeds 20 % the retreat rate continues to decrease after year 800 as sediment inputs exceed outputs.

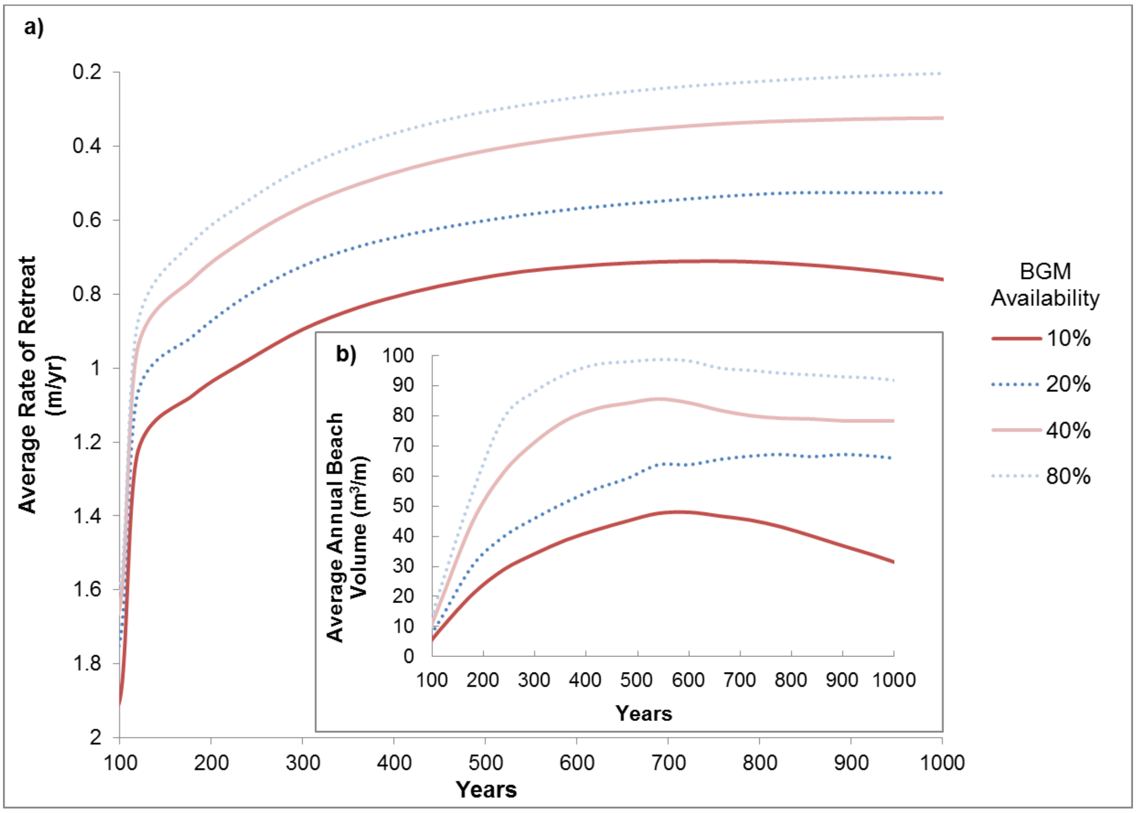


Figure 5-7: Comparing trends with varying availability of BGM, a) average rate of retreat over time, b) average annual beach volume over time

The trends in the long term rates of cliff retreat demonstrate the important feedback mechanism between the availability of BGM from the eroding cliff and the role of protective fronting beaches. On this basis, it can also be recognised that variations in resistance and cliff height (which control the erodibility of the cliff and the volume of eroded material available, respectively) will also influence the sediment conditions identified. Previous sensitivity analyses of cliff height have shown how this parameter influences sediment availability similarly to BGM availability (Section 4.3.2); the higher the cliff the greater volume of BGM available.

Changes in cliff resistance induce more complex negative feedbacks as indicated by Figure 5-8, which shows how the retreat rate at the end of the model simulation varies for different combinations of BGM availability and resistance. With 10% BGM availability, an eight times relatively more resistant cliff (which could correspond to a coherent sandstone) actually experiences slightly higher rates of retreat than a weaker cliff (e.g. a less coherent clay). While the increased resistance reduces the erosive potential of the cliff face it also yields a lower proportion of BGM to the cliff system, which in turn reduces the maximum potential beach volumes and their protective capacity. The increased material resistance also induces steeper slopes, leading to the seaward migration of beach material and a subsequent reduction in beach thickness (Walkden and Dickson, 2008). Therefore the more resistant but steeper slope is more vulnerable to wave attack in conditions of low sediment availability. As the proportion of BGM available increases, the emergent beach volumes become less dependent on the erodibility of the cliff, significant fronting beach volumes can develop independently of variations in material resistance, and retreat rates begin to converge.

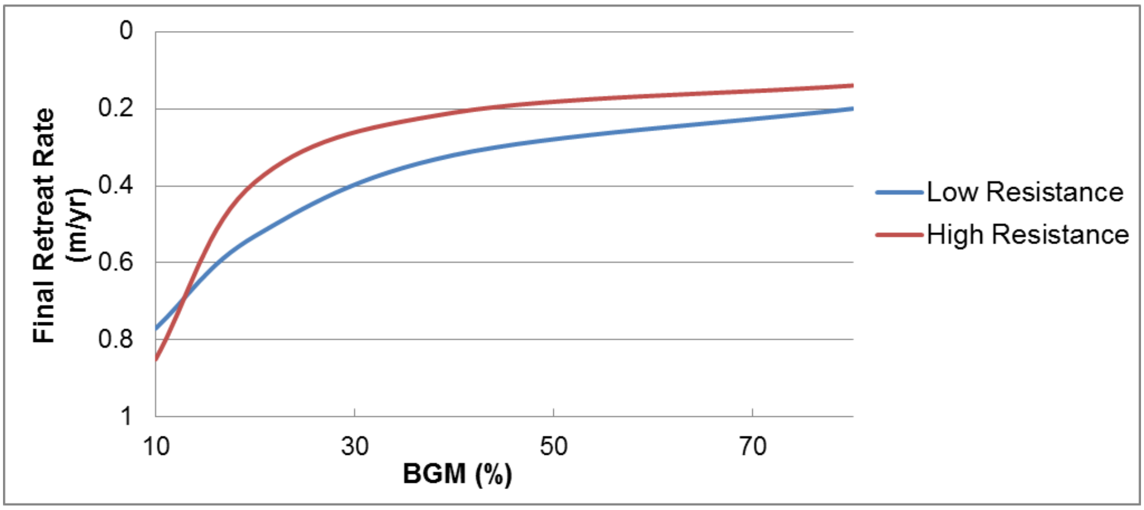


Figure 5-8: Comparing the effect of beach grade material availability and cliff resistance on final year rates of retreat

5.2.2.2 Understanding lithological controls on longshore evolution

This section addresses the second key geomorphic question: considering that many cliff systems feature longshore variations in lithology, how do such variations influence coastal planshape evolution and what is the more dominant lithological control? To investigate this, the linear frontage was split into three sections of equal length (4 km) with alternating properties of cliff lithology as illustrated in Figure 5-6 (this set-up was adopted to enable the effects to be clearly identified and considering the geographical scales of interest in this study).

Effect of longshore variations in availability of beach grade material from the cliff with homogenous resistance

Simulation 3 considers whether variations in coastal planshape can emerge as a result of longshore variations in BGM independently of variations in resistive strength. Such a situation could correspond to a discordant, sandstone coastline where the resistive strength of the cliff remains similar but variations in the proportion of BGM are present. For example, Stuiver (2013) identifies a range of coherent sandstones (as defined by the visual appraisal scale developed by Soares, 1993) but with varying degrees of BGM (0 to 75%) along the south west coast of the Isle of Wight, UK.

The results shown in Figure 5-7 imply that, with homogenous resistance but longshore variations in BGM, sections of low sediment availability will retreat at a higher rate than adjacent sections of high sediment availability. Figure 5-8a shows the coastal evolution over the 1,000 year period modelled with alternating sections of 10% and 80% BGM, representing low and high sediment availability, respectively (as previously determined from Figure 5-7a). The results show subtle indentations developing in the sections of low sediment availability. Section 1 exhibits the highest retreat due to the combined effects of no sediment inputs from the boundary and longshore sediment transport sweeping sediment downdrift. However, in general no significant offsets (the cross-shore distance between the shoreline position of the indentations and those of adjacent sections) relating to longshore changes in BGM can be identified relative to the geographical scale of the frontage. This is further supported by the average annual beach volumes across the frontage (Figure 5-8b), which show no distinct correlation between sections of high BGM and higher beach volumes. This is because the effect of BGM availability from the cliff diffuses along the frontage owing to the effect of longshore sediment transport.

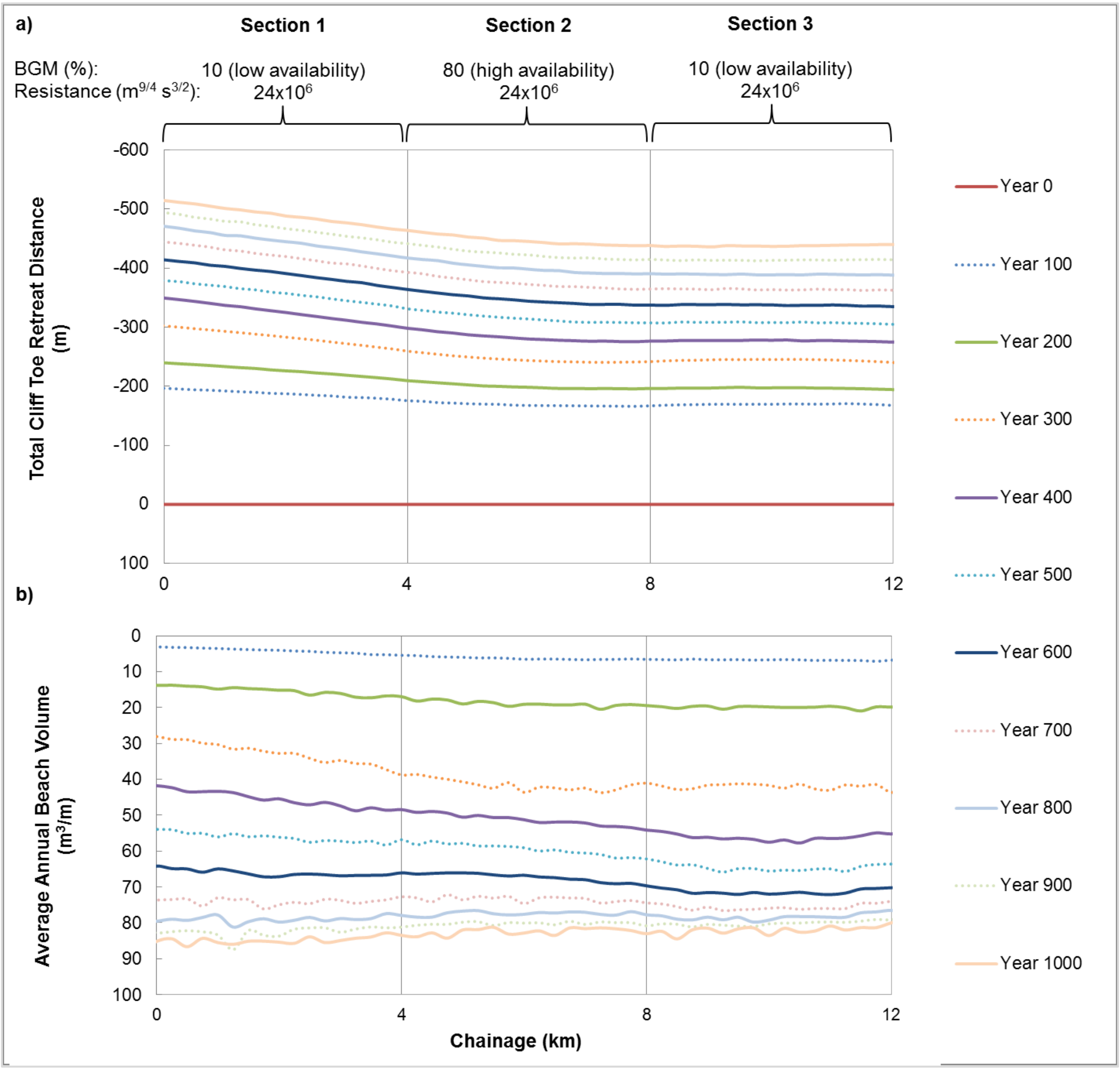


Figure 5-9: a) Cliff toe position with heterogeneous beach grade material, b) Corresponding average annual beach volumes

Effects of longshore variations in resistance with homogenous availability of beach grade material

In a contrasting situation, simulation 4 assesses the effect of longshore variations in cliff resistance on coastal planshape evolution. Figure 5-10a gives the results for a central section of eight times relatively more resistant rock, perhaps representing a coherent chalk outcropping adjacent to a less coherent glacial till such as at Flamborough Head, Holderness, UK. BGM availability was set to a constant value of 20% to consider changes in resistance independently of sediment availability in view of the results of Figure 5-7. Supporting the theory of headland and embayment formation, protrusions are forming in the more resistant section owing to their lower erosive potential, while the weaker sections experience increased rates of retreat leading to the formation of embayments (Trenhaile, 2002). Figure 5-10b shows the associated average annual beach volumes; their accumulation is strongly influenced by the emergent coastal planshape and the associated process of longshore sediment transport. Sediment is swept away from the more resistant headland owing to their increased exposure to wave energy and is transported to infill the weaker embayments as described by Limber and Murray (2011). Longshore beach volumes are also influenced by the higher availability of sediment from the weaker sections.

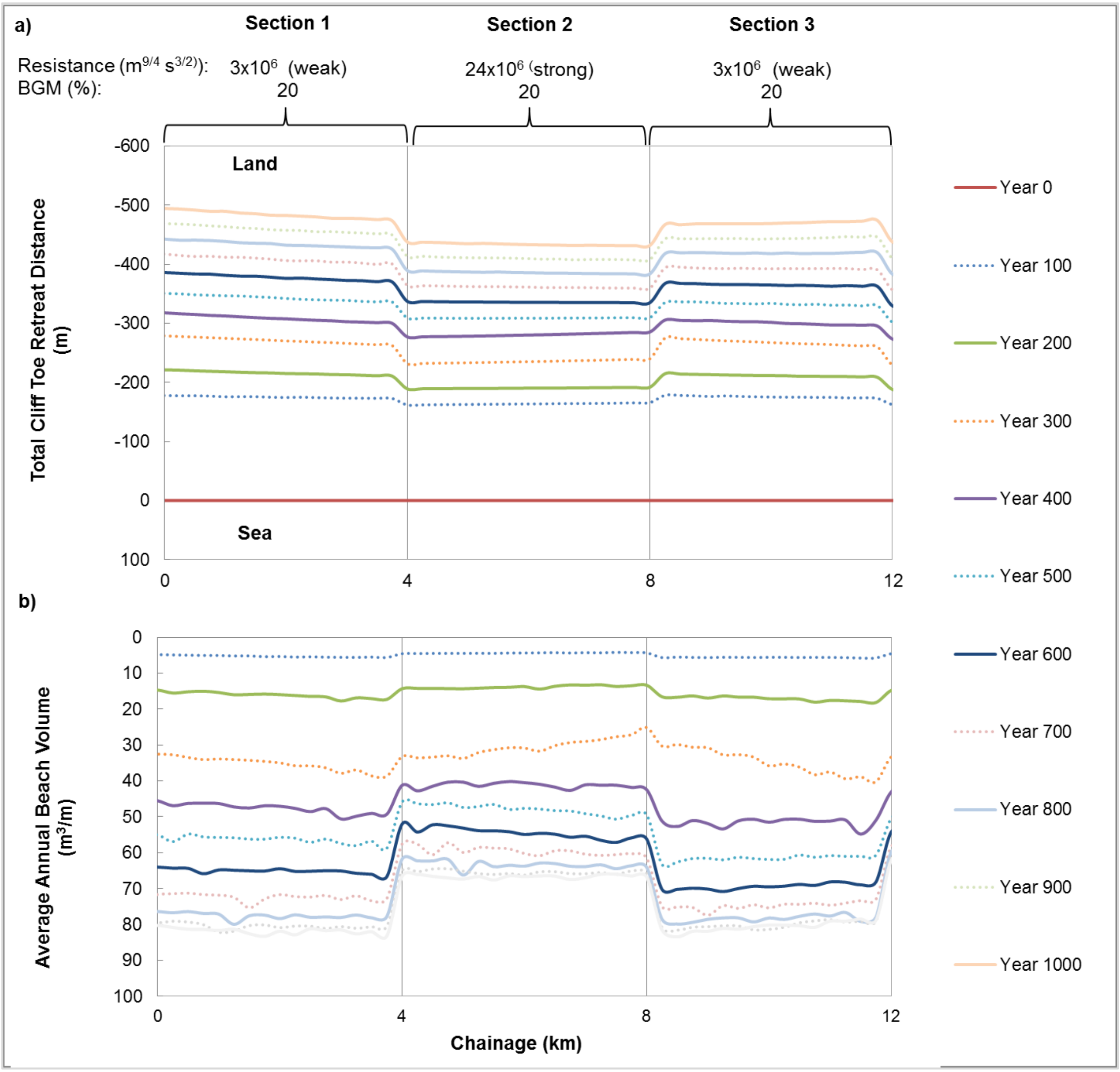


Figure 5-10: a) Cliff toe position with longshore variations in material resistance and homogenous beach grade material, b) Corresponding average annual beach volumes

The model results show that the influence of heterogeneous resistance is more readily identified through the emergent coastal planshape than that of BGM availability as the properties are fixed in space.

Effect of combined longshore variations in beach grade material availability and resistance

The relationships identified above indicate that heterogeneous sections of less resistant material of low BGM will retreat at a greater rate than adjacent sections of more resistant material of high BGM. Simulation 5 considers the contrasting scenario of a more resistant material of low BGM next to a less resistant material of high BGM. As noted by Valvo et al (2006), this could correspond to a highly compacted marsh deposit next to a poorly lithified river deposit. Figure 5-11a shows the output coastal planshape over the total modelled duration. A headland feature is emerging at the more resistant section despite the lower availability of BGM. As would be expected, lower beach volumes are also observed at the more resistant section (Figure 5-11b) owing to the combined influence of lower BGM and the exposed nature of the developing headland.

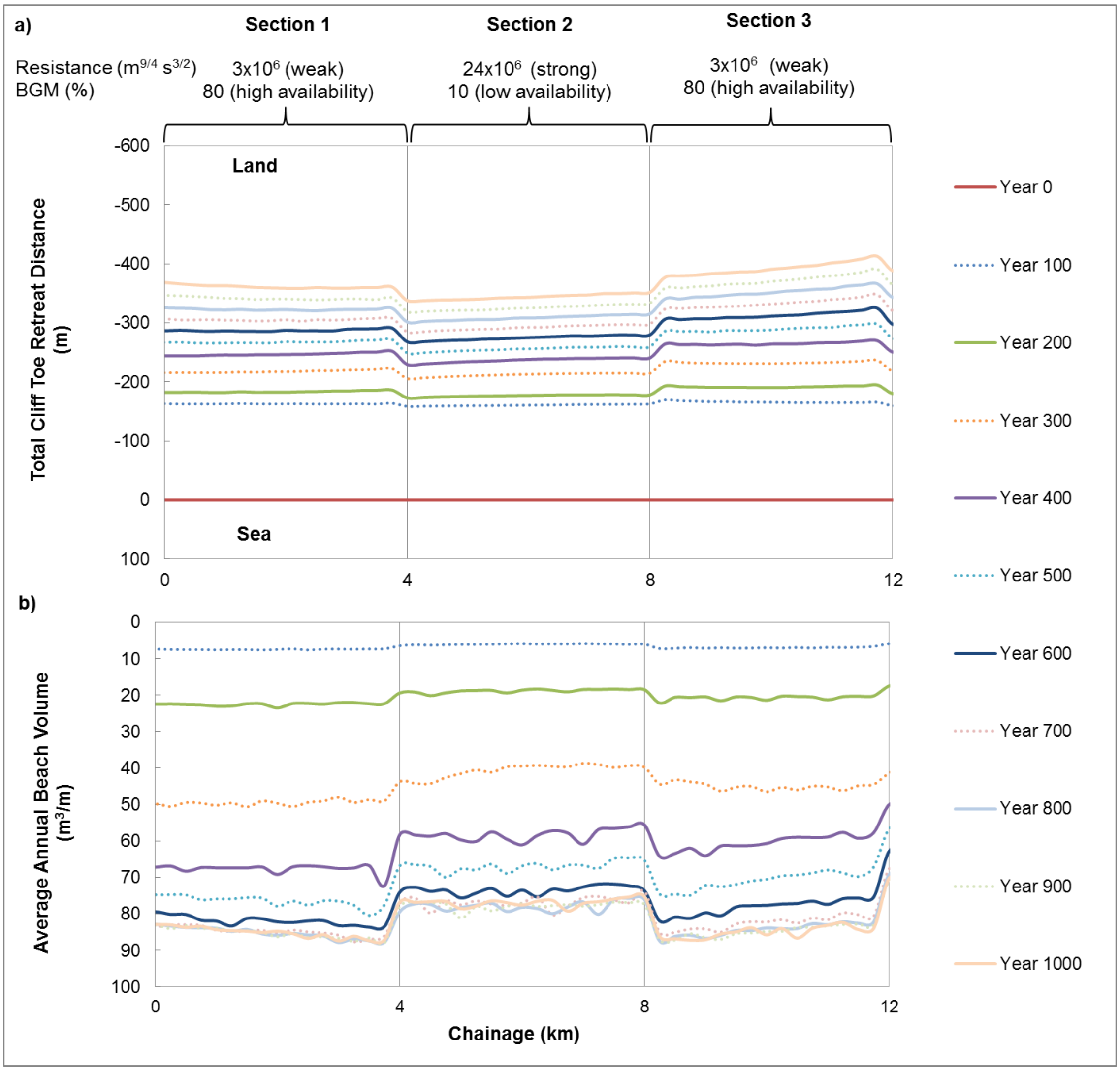


Figure 5-11: a) Cliff toe position with central section of increased resistance but low beach grade material, b) Corresponding average annual beach volumes

Simulations 3 to 5 show that longshore variations in resistance are a more dominant control on coastal planshape evolution than BGM; this can be attributed to two key factors:

- Resistance is fixed in space while the effect of BGM diffuses along the frontage by longshore sediment transport;
- BGM has an indirect effect on the erosion rate through the protective nature of fronting beach volumes, while resistance (*M*) is a direct control as would be expected from the SCAPE description of erosion (Equation 4-18) presented in Section 4.3.1.

5.2.2.3 Coastal evolution under high and low sediment availability

Longshore changes in resistance have been identified as an important control on coastal planshape evolution. The question then arises as to how and why some coasts of variable resistance appear to retreat at a uniform rate and maintain a smooth coastal planshape while others exhibit heterogeneous rates resulting in the formation of persistent headland and embayment features such as identified on the study frontage of the IoW.

The results of the earlier model simulations suggest that the change in response is governed by sediment availability. To test this, a final series of model simulations considered how variations in relative resistance along the shore influence coastal planshape and rates of retreat with low (10%) and high (80%) BGM availability. Proportions of BGM were based on the distinction made between Mode A and Mode B coasts by Figure 5-7. These could correspond to frontages comprising a high percentage of fine-grained material such as clay or mudstone, e.g. Santa Cruz, California, USA (Perg et al., 2003), and a high proportion of BGM such as sandstone or quaternary sediments, e.g. North Norfolk, UK (Clayton, 1988), respectively.

To understand whether heterogeneous coasts can reach dynamic equilibrium, Figure 5-12a shows the standard deviation between the average longshore rates of retreat for coasts exhibiting 2x and 8x changes in relative resistance under the two BGM scenarios. The results demonstrate how coasts with greater contrasting magnitudes of resistance and/or lower sediment availability exhibit greater variations in longshore rates of retreat and do not reach steady state by the end of the simulation. This highlights the important interplay between resistive strength and the availability of sediment on how headlands can remain persistent features or grow over time under different combinations of each. In contrast, with high sediment availability, negligible changes in longshore rates of retreat are apparent by the end of the simulation, regardless of variations in relative resistance.

The results are supported by Figure 5-12b, which shows a near linear increase in coastal offsets (taken from the final year of the model simulation) with increasing relative resistance and 10% BGM. The conditions correspond to Mode A cliff behaviour (Walkden and Hall, 2011); resistance remains an important control on the erosive potential and the subsequent coastal evolution through two key behaviours:

- Longshore transport rates are limited by the rate that mobile sediment is produced and the shoreline retreats at a rate governed by its resistive properties, hence retaining its shape (Valvo et al, 2006).
- The recession rate is regulated by adjustment of the foreshore slopes, which is governed by material resistance.

In contrast, with high sediment availability Figure 5-12b shows how the influence of longshore variations in resistance on coastal offsets is limited and decays asymptotically with 80% BGM. This corresponds to Mode B behaviour; larger protective beach volumes can develop in the weaker embayments, which combined with wave energy divergence reduce rates of retreat whilst the headlands experience higher rates of retreat owing to lower fronting beach volumes and wave energy focussing.

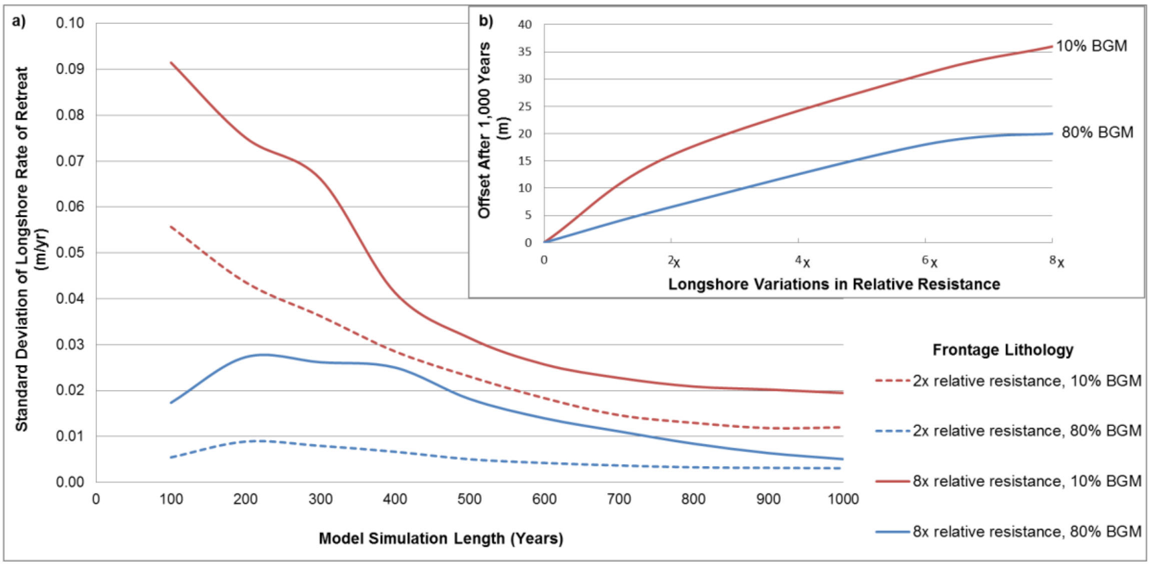


Figure 5-12: Comparing the effect of longshore variations in relative resistance under high and low sediment availability, a) standard deviation of average longshore rates of retreat over time, b) coastal offsets

5.2.3 Discussion of longshore investigations

Table 5-6 summarises the three questions posed at the start of the paper and associated model simulations. The results are addressed with reference to these questions in the following sections.

Table 5-6: Summary of model simulations and longshore set-up

Geomorphic Question	Model Simulation	Cliff Lithology Set-Up
1) Can cliff lithology be used to distinguish between high and low sediment coasts and how does their behaviour vary?	1	0 to 80% Homogenous BGM $3x10^6$ $M^{9/4}$ $S^{3/2}$ Homogenous Resistance 12km Homogenous Coastline
	2	0 to 80% Homogenous BGM $24x10^6$ $M^{9/4}$ $S^{3/2}$ Homogenous Resistance 12km Homogenous Coastline
2) How do longshore variations in cliff lithology influence coastal planshape evolution?	3	**Section 1** 10% BGM; **Section 2** 80% BGM; **Section 3** 10% BGM 12km Coastline, Homogenous Resistance ($3x10^6$ $M^{9/4}$ $S^{3/2}$)
	4	**Section 1** $3x10^6$ $M^{9/4}$ $S^{3/2}$ Resistance; **Section 2** $24x10^6$ $M^{9/4}$ $S^{3/2}$ Resistance; **Section 3** $3x10^6$ $M^{9/4}$ $S^{3/2}$ Resistance 12km Coastline, Homogenous BGM (20%)
	5	**Section 1** $3x10^6$ $M^{9/4}$ $S^{3/2}$ Resistance 80% BGM; **Section 2** $24x10^6$ $M^{9/4}$ $S^{3/2}$ Resistance 10% BGM; **Section 3** $3x10^6$ $M^{9/4}$ $S^{3/2}$ Resistance 80% BGM 12km Coastline
3) By what means can coasts of variable longshore lithology reach dynamic equilibrium?	6	**Section 1** $3x10^6$ $M^{9/4}$ $S^{3/2}$ Resistance 80% BGM; **Section 2** $6x10^6$ $M^{9/4}$ $S^{3/2}$ Resistance 10% BGM; **Section 3** $3x10^6$ $M^{9/4}$ $S^{3/2}$ Resistance 80% BGM 12km Coastline, Homogenous BGM (10 and 80%)
	7	**Section 1** $3x10^6$ $M^{9/4}$ $S^{3/2}$ Resistance 80% BGM; **Section 2** $24x10^6$ $M^{9/4}$ $S^{3/2}$ Resistance 10% BGM; **Section 3** $3x10^6$ $M^{9/4}$ $S^{3/2}$ Resistance 80% BGM 12km Coastline, Homogenous BGM (10 and 80%)

5.2.3.1 Can cliff lithology be used to distinguish between high and low sediment coasts and how does their behaviour vary?

Simulations 1 and 2 showed that the transition between Mode A (rock strength limited) and Mode B (transport limited) coasts (as previously defined on Sections 2.3.3.3 and 5.2.2.1) is determined by the balance between sediment inputs and sediment outputs. With increasing availability of sediment (either through higher proportions of BGM or weaker cliff lithologies) large fronting beach volumes can develop and protect the cliff toe from basal marine erosion. From Figure 5-7b a threshold beach volume of 40 m^3/m was identified, below which rates of cliff toe retreat increase as a result of exposure to prevailing coastal conditions. This is higher than the thresholds proposed by Lee (2008) and Walkden and Dickson (2008) as a result of the different prevailing conditions.

A proportion of 10% BGM available from an eroding cliff of low material resistance was found to be insufficient to maintain the threshold fronting beach volume throughout the 1,000 year simulation. These conditions therefore correspond to Mode A; the threshold beach volume cannot be maintained and recession is regulated by the resistive properties of the cliff and its effect on the emergent shore profile slope. In contrast, with 20% BGM and above fronting beaches can develop more rapidly and be maintained at volumes larger than the threshold over the simulation period. This corresponds to Mode B in which the cliff toe retreat rate is controlled by the fronting beach volume and the process of longshore sediment transport. These feedbacks are summarised in the conceptual model presented in Figure 5-13.

In this study, the distinction between the two modes of shoreline behaviour has been determined based on homogenous variations in cliff lithology. However, a range of additional factors may also influence the development of such conditions, including:

- The length of the sediment cell, which will determine the scale over which sediment must be distributed;
- Additional sources of BGM such as offshore or fluvial inputs;
- The height of the eroding cliffs, which will control the volume of sediment available.

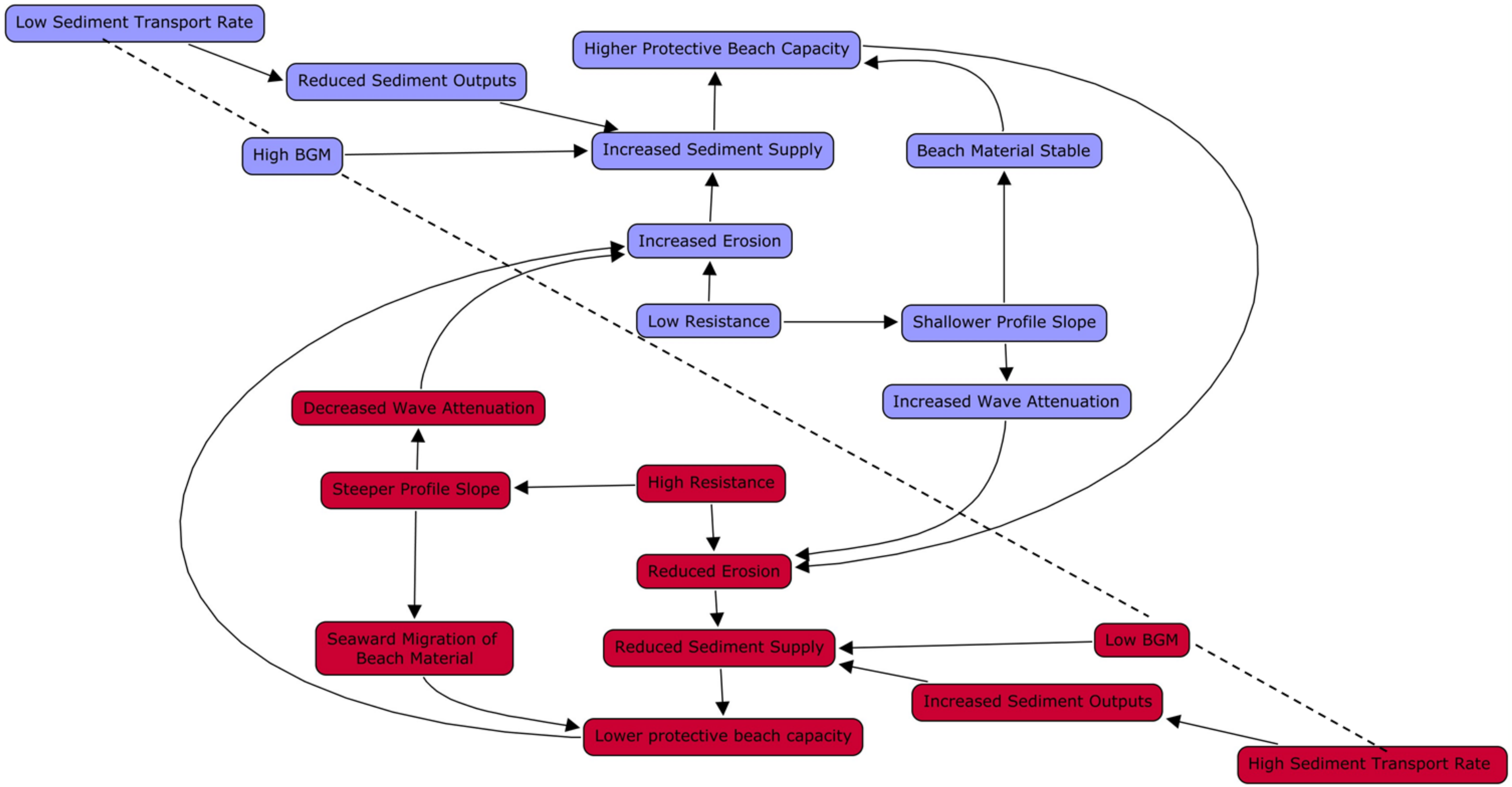


Figure 5-13: Conceptual model of Mode A (shaded in red) and Mode B (blue) interactions

5.2.3.2 How do longshore variations in cliff lithology influence coastal planshape evolution?

Simulation 3 demonstrated how subtle undulations in the coastal planshape can develop as a result of longshore variations in BGM; with slight protrusions forming at sediment rich sections (Figure 5-9). However, longshore variations in resistance (Simulation 4) were found to have a more significant effect on coastal planshape evolution and illustrated feedbacks between the erosive potential of each longshore section and the emergent coastal planshape on the development of protective fronting beach volumes with longshore sediment transport (Figure 5-10 and Figure 5-11).

The results are in contrast to those of a similar study by Valvo et al (2006), whose application of the CEM model showed BGM to be the more dominant control on coastal planshape evolution. For example, along an idealised, 30 km linear frontage they found offsets of up to 300m forming between 7.5 km heterogeneous sections of 0 % and 95 % BGM with homogenous resistance (with retreat rates reaching steady state after approximately 60 years). Furthermore, in a study of the effect of contrasting, variations in lithology their results showed indentations forming in sections of low (50 %) BGM despite sections being of four times greater resistance than adjacent, sediment rich sections with 95 % BGM.

Additional SCAPE simulations replicating the set-up of Valvo et al (2006), in terms of the variations in frontage length, heterogeneous sections, proportions of beach grade material showed that this contrast in results was not a result of variations in model set-up. The discrepancies are therefore related to the assumptions made in the model development, namely the different descriptions of the erosion rate and variations in coastal environments considered. For example, in the model of Valvo et al. (2006) an exponential dependence of the weathering rate (*W*, m/yr) on sediment thickness is described as outlined in Equation 4-13.

In contrast, in SCAPE the erosion of each layer (d_z) at every time-step is based on the results of Kamphuis (1987) and Skafel (1995) for glacial till cliffs. The resulting description of the erosion rate covers a broader range of parameters including the prevailing coastal conditions, material resistance, the distribution of erosion, the slope of the emerging shore platform and the tidal range. These differences between the weathering/erosion rate in the CEM and SCAPE models provide an explanation for the different significance of BGM on long term coastal evolution.

Finally, the simulations of Valvo et al (2006) enabled an equilibrium beach volume to develop by specifying a weathering rate greater than the overall retreat of the frontage and a constant shoreface profile was assumed. Therefore the results are more appropriate for assessing the relationship between vertical lowering of rock and surface erosion rates in sandy coastlines. In contrast, the SCAPE simulations have considered the effect of material resistance on soft cliff shore profiles across a range of sediment environments. The results highlight the importance of understanding changes in shore profiles slope, both temporally and spatially, thus supporting the application of the SCAPE model.

5.2.4 By what means can coasts of variable longshore lithology reach dynamic equilibrium?

Finally, to understand if coasts with longshore variations in resistance can reach dynamic equilibrium, simulations 6 and 7 considered the effect of changes in relative resistance on Mode A and Mode B coasts (based on the proportion of BGM available). The results showed how with an increasing magnitude of relative resistance and/or low sediment availability, coastlines exhibit heterogeneous rates of retreat that do not reach steady state by the end of the 1,000 year simulation, hence how headland and embayment features can persist through time.

While these results related to the evolution of an idealised, linear frontage, confidence in the key geomorphic findings can be gained by comparing the results with real cases. Referring back to the study frontage of the IoW on which the prevailing conditions of this study were based; as introduced in Chapter 3 the frontage yields a low percentage of BGM and the fronting beaches are of insufficient volume to influence rates of cliff toe retreat (Stuiver, 2013). Therefore, the evolution of a series of discrete headlands along the frontage is believed to be controlled by the development and elevation of dissipative fronting shore platforms which is in turn controlled by the varying resistance of materials along the frontage (Stuiver, 2013). As a result, parallels may be drawn between this frontage and the simulation findings, further highlighting the importance of variations in material resistance on the development of persistent headland features on low sediment coastlines.

In a contrasting high sediment scenario, the results demonstrated how coasts may reach uniform rates of retreat (steady state) by the end of the simulation period despite longshore variations in resistance. Fronting beach volumes develop more rapidly (as shown in Figure 5-7b) and become the more dominant control on rates of cliff toe retreat. These results are in agreement with the exploratory model results of Limber and Murray (In Review-ab) as introduced in Section 2.2.3.3. The model similarly demonstrated how as sediment availability increases, offsets between headland and embayment features decrease and longshore rates of retreat reach steady state more rapidly owing to the balance between wave energy focussing at the more resistant headlands and wave energy divergence combined with the dissipative effect of fronting beaches at weaker embayments. Through simulation of longer geomorphic timescales (~15,000 years) they also demonstrated how headland features may become transient features of the landscape under high sediment availability. This was supported by site comparisons for Montara Beach, California USA where headlands are observed to be retreating at a higher rate than adjacent bays (Hapke and Reid, 2007).

Finally, Limber and Murray (In Review-ab) showed how sediment availability is also influenced by a range of additional factors. For example increasing headland width lengthens the shoreline therefore increasing sediment availability while increasing embayment width requires greater volumes of sediment to fill pocket beaches effectively reducing sediment availability. The agreement in results supports the underlying assumptions of the simpler analytical model of Limber and Murray (In Review-ab) while Q3D SCAPE enables more detailed quantification of the cliff system which is more appropriate for understanding specific sites.

5.3 Identification and development of model refinements

Based on the application and assessment of the current versions of the SCAPE model, this section identifies suitable model refinements and describes methods for their inclusion.

5.3.1 Identification of refinements

Application of the 2D model to the study frontage has highlighted the control exerted by more resistant rock layers on the emergent vertical shore profile shape, with distinctive ledge features identifiable within bathymetric data of the study frontage. However, these effects could not be accurately replicated within the current 2D SCAPE model owing to the use of a single material resistance value to characterise the entire profile. This issue links back to that previously highlighted in Section 4.1.6; modelling inherently involves simplification of the system under question.

Based on the coastal planshape evolution of the study frontage, it is hypothesised that layers of increased resistance experience reduced rates of erosion owing to their lower erosive potential and that, upon submersion, they will continue to influence rates of retreat through attenuation of wave energy. Therefore the treatment of variable cliff lithology on geomorphic processes and shore retreat is a key consideration. In particular, it is important to understand the possible effects of vertical heterogeneity, because natural cliffs are commonly composed of variable layers of interbedded stratigraphy (such as the Isle of Wight). Moreover, as sea-level rises the resistance of the material being most influenced by marine processes may change and this may alter rates of retreat over time.

Application of the Q3D model has enabled the effect of longshore interactions to be considered through its inclusion of a one-line model. Owing to the complexity of the IoW study frontage, which includes a variable coastal planshape and cliff lithology, the model was applied to understand three key geomorphic questions relating to large-scale, long-term changes along an idealised, linear frontage.

5.0 Application and Assessment of Selected Soft Cliff Model

The Q3D model revealed the transition between Mode A (rock strength limited erosion) and Mode B (transport limited erosion) shoreline behaviour. This can be defined through the relative sediment inputs to outputs and therefore characterised by changes in cliff lithology (erosive potential of the cliff and the availability of Beach Grade Material, BGM). When no other sources of sediment are available, cliffs of less than 10% BGM were defined as Mode A, dictated by changes in shore profile slope as opposed to longshore sediment transport. The study frontage of the Isle of Wight can be defined as an example of such a coast, based on its low inputs of BGM from the eroding cliffs and the negligible effect of fronting beach volumes on rates of cliff toe erosion using the results of Stuiver (2013).

Based on the above findings it is proposed that the remainder of this thesis focusses on the refinement of the 2D SCAPE model to further understand the role of varying rock strength in the vertical plane for low sediment coasts. This is particularly important given that:

- Soft rock coasts commonly comprise of lithologies with a low proportion of Beach Grade Material, BGM (e.g. clay and mudstone);
- The presence of hard engineering structures can reduce downdrift beach volumes (Brown, 2008); and,
- The lithology of natural cliffs frequently varies both longshore and vertically.

It is envisaged that through application of the refined model the following key questions can be investigated:

1) What influence does heterogeneous material resistance in the vertical have on cliff geomorphology and retreat rates considering layers of varying degrees of resistance, width, position and interactions with sea-level rise?
2) Can model validation for the study frontage be improved by a varied description of material resistance and how does this correspond to field conditions?
3) Considering the application of the SCAPE model as a coastal engineering tool, what are the implications of changing climatic and environmental conditions on future rates of retreat along the study frontage?

5.3.2 Implementation of refinements

This section outlines the resultant methodology used to modify 2D SCAPE.

5.3.2.1 Vertical variations in material resistance

In the original SCAPE model, material resistance (*M*,) is represented as a single calibration parameter that is homogenous in the vertical plane (as demonstrated in Appendix B1). To modify this, *M* is considered as a variable in the vertical direction but is assumed constant in the horizontal. This has been achieved by assigning a material resistance value for each horizontal discretisation of the cliff (determined by the cliff total height divided by the width of each horizontal discretisation, d_z), as demonstrated in Figure 5-14. This enables the consideration of multiple layers of varying resistance up the shore platform and cliff face. Further details of the development of the code associated with this modification can be found in Appendix B2 and B3.

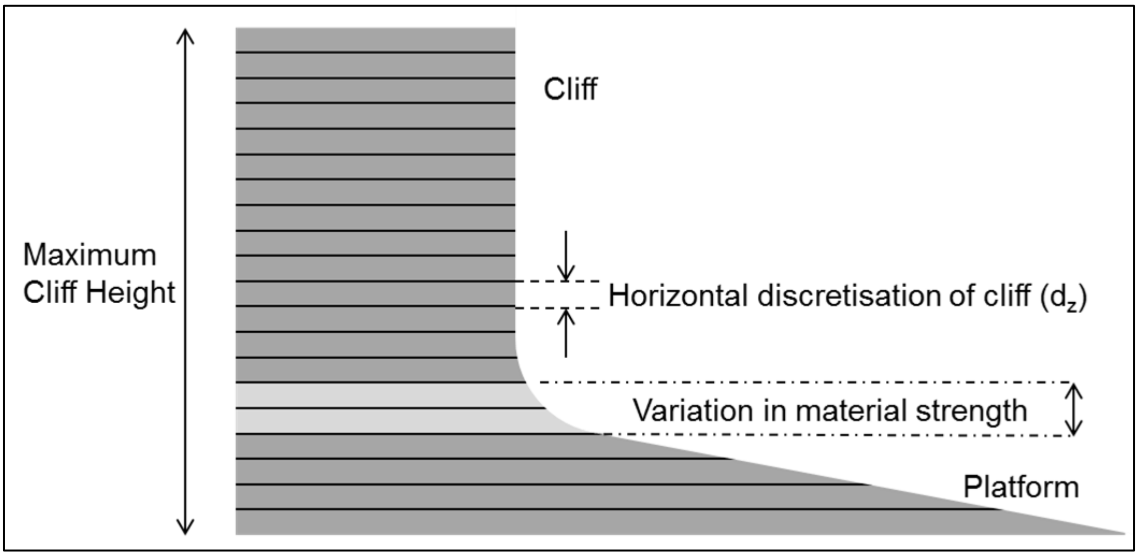


Figure 5-14: Diagram representing variation in material resistance for each horizontal discretisation of the SCAPE cliff

M has been kept as a hybrid calibration parameter, solely relating to the erosive potential and the hydrodynamic climate (units, $m^{9/4}\ s^{3/2}$). However, as previously demonstrated, *M* can be likened back to field conditions considering the visual appraisal of coherence. Furthermore, the relative resistance of the anomalous layers in proportion to that of the remainder of the cliff can also be considered.

5.3.2.2 Erosion shape function refinements

Finally, to help explore the effect of varying *M* and in alignment with reduced complexity modelling, the erosion shape function (f_1) used in Equation 4-18 was smoothed. As previously noted in Section 4.3 and Appendix A, the erosion shape function was originally based on an interpolated distribution Skafel's (1995) physical model results. A series of modifications were made to the shape of the function to determine its impact on shore profile shape. Modifications involved shifting the 'peak' of the erosion shape function, as demonstrated by Figure 5-15.

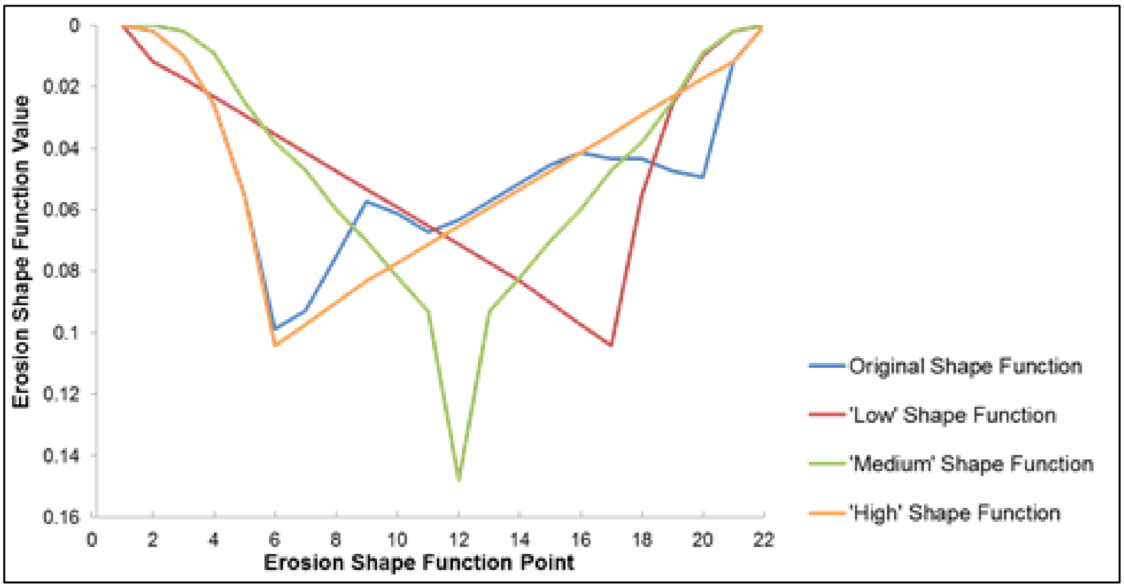


Figure 5-15: Original and tested erosion shape function distributions

Sensitivity testing of the modified erosion shape functions showed negligible difference in equilibrium retreat rates and shore profile geomorphology. This is demonstrated by Figure 5-16 which shows the final equilibrium profile shape in each case considering its evolution from an initial vertical cliff over a 10,000 year period. Based on these results the 'high' erosion shape function was chosen, which is a smoothed version of the original shape function used by Walkden and Hall (2005).

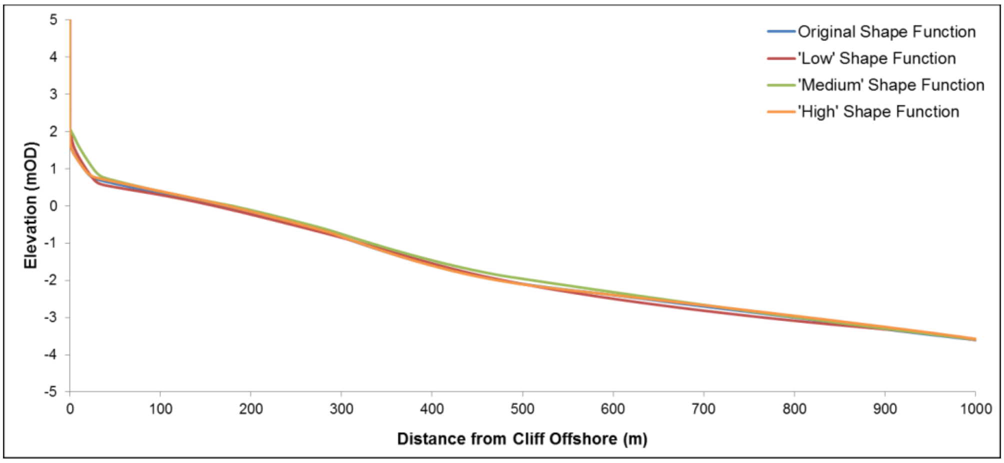


Figure 5-16: Comparison of final output profiles considering a range of erosion shape function distributions

5.4 Application and assessment of selected soft cliff model: closing comments

This chapter has applied the current 2D and Q3D SCAPE models to further evaluate its performance drawing insight from the study frontage of the IoW. 2D results highlighted the need to understand the effect of vertical variations in material resistance. Q3D results further highlighted the importance of material resistance as a control on shoreline behaviour for coasts of low sediment availability. Based on this, it was concluded that longshore interactions may be considered negligible for low sediment coasts as coastal behaviour is dominated by variations in foreshore slopes (Mode A behaviour) as defined by (Walkden and Hall, 2011). Therefore a focus on the 2D model for the remainder of this thesis was proposed. This has completed objective two of this research: *to assess the limitations of existing cliff retreat models*.

In response to objective three: *to improve the model capability drawing on real world observations*, the remainder of this chapter has identified and described a series of modifications to the 2D model to describe heterogeneous cliffs of variable material resistance in the vertical direction. While material resistance may also be subject to change as the cliff retreats landward, it was kept as a constant in the horizontal. However, it can be speculated that interactions between sea-level rise and material resistance (that will be tested later) will produce comparable results.

5.0 Application and Assessment of Selected Soft Cliff Model

The refined model will now be applied to answer the series of geomorphic questions previously introduced, as summarised below.

Table 5-7: Overview of refined model simulations

Chapter	Model	Geomorphic Question
6.0	**Refined Soft Cliff Model Application and Assessment, Part 1: Behaviour and Sensitivity Analysis**	1) What influence does heterogeneous material resistance in the vertical have on cliff geomorphology and retreat rates considering layers of varying degrees of resistance, width, position and interactions with sea-level rise?
7.0:	**Refined Soft Cliff Model Application and Assessment, Part 2: Study Frontage Application**	2) Can model validation for the study frontage be improved by a varied description of material resistance and how does this correspond to field conditions? 3) Considering the application of the SCAPE model as a coastal engineering tool, what are the implications of changing climatic and environmental conditions on future rates of retreat along the study frontage?

6. Refined Soft Cliff Model Application and Assessment, Part 1: Behaviour and Sensitivity Analysis

This Chapter applies the refined 2D SCAPE model to further understand some key geomorphic relationships relating to cliffs of variable lithology in the vertical. This will contribute towards objectives three and four of this research; *to improve model capability*; and, *to understand how the impacts of environmental and climatic change will influence shore profile geomorphology and rates of cliff toe retreat*. The chapter layout is as follows:

- Section 6.1 describes the set-up of the variable lithology model;
- Section 6.2 provides a sensitivity analysis of heterogeneous cliffs comprising of variable lithology;
- Section 6.3 discusses the results; and
- Section 6.4 concludes this chapter.

6.1 Introduction and refined model set-up

Based on the first geomorphic question outlined in Table 5-7, this chapter will address the impact of the following scenarios on shore profile morphology and cliff toe retreat:

a) A single layer of more resistant rock;
b) A single layer of less resistant rock;
c) Multiple layers of variable resistance.

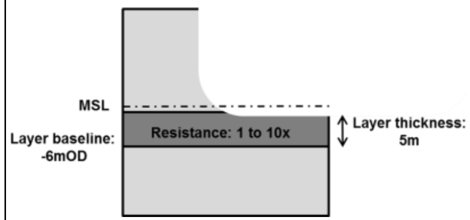
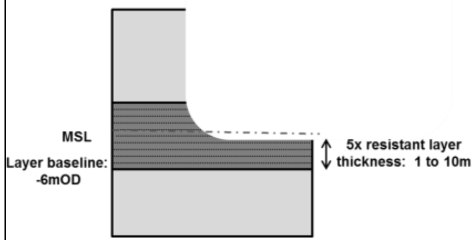
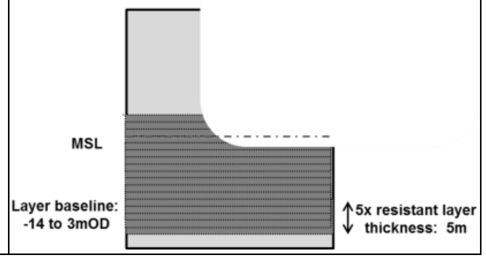
Consistent with Section 4.3.2, the same prevailing (wave and tide) conditions have been used. However, for the purpose of this research some of the additional inputs have been adjusted as outlined in Table 6-1. In particular, considering the focus of this research on quantifying the impacts of variable material resistance under low sediment availability, no fronting beach has been included in the simulations.

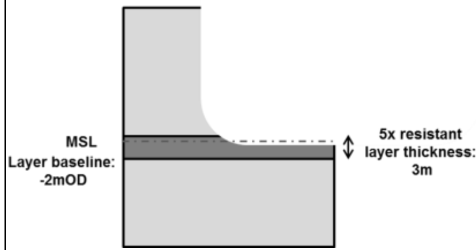
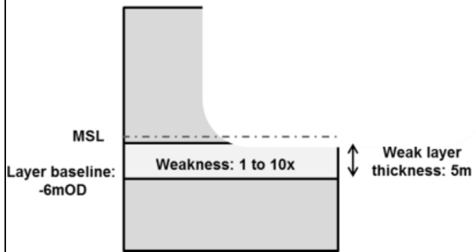
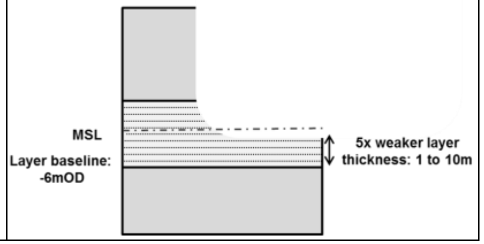
Table 6-1: Summary of refined model input parameters

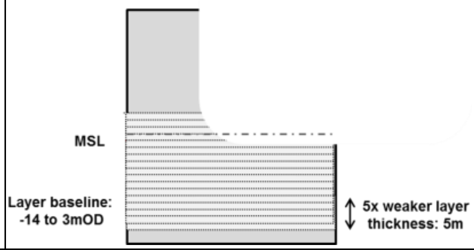
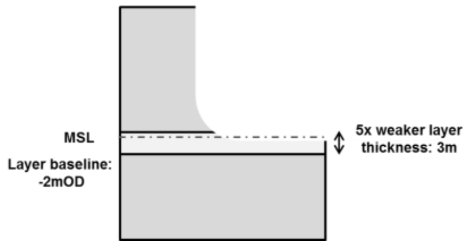
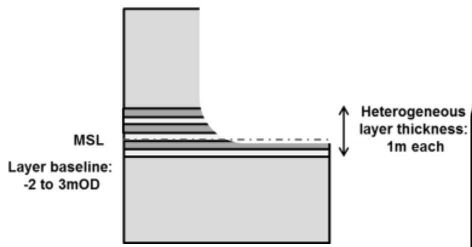
Purpose & preliminary inputs	Units	Value range
Profile evolution:		
• Wave Height	m	Variable with time: 0 to 4.86 (0.93 mean)
• Wave Period	s	Variable with time: 1.8 to 9.7 (4.18 mean)
• Run-up Limit	m	1.75
Cross-shore distribution of erosion:		
• Mean Sea Level	m OD	0
• Tidal Amplitude	m	Variable with time (1.17 mean)
• Beach Volume	m^3/m	0
• Rate of Sea-Level Rise	mm/yr	0
Calibration variable:		
• Material Resistance	$M^{9/4}$ $S^{3/2}$	$2x10^6$

As previously described in Section 4.3.2.1 (Figure 4-16), an equilibrium profile emerges from an initial vertical plunging cliff. In this research, an equilibrium cliff profile has been extracted after 10,000 years of simulation and used as a starting profile for a series of sensitivity analyses to assess the impact of a varying material resistance over a further 5,000 year simulation period. For these runs, all input conditions remained constant with those stated in Table 6-1 unless otherwise stated. This includes the material resistance of the cliff face, with the exception of the anomalous layer introduced to assess its effect; the characteristics of which are summarised in Table 6-2 for the various simulations.

Table 6-2: Summary of refined model sensitivity analysis set-up

Section	Simulation	Anomalous Layer Properties			Sea-level rise (mm/yr)	Visualisation
		Resistance ($m^{9/4}s^{3/2}$)	Thickness (m)	Baseline (m OD)		
6.2.1 Resistant Layer Effects	1.1 Layer Resistance	$2x10^6$ to $2x10^7$	5	-6	N/A	
	1.2 Layer Thickness	10 $x10^6$	1 to 10	-6	N/A	
	1.3 Layer Position	10 $x10^6$	5	-14 to +5	N/A	

Section	Simulation	Anomalous Layer Properties			Sea-level rise (mm/yr)	Visualisation
		Resistance ($m^{9/4}s^{3/2}$)	Thickness (m)	Baseline (m OD)		
	1.4 Sea-level Rise	10×10^6	3	-2	0 to 5	
6.2.2 Weak Layer Effects	2.1 Layer Weakness	2×10^6 to 2×10^5	5	-6	N/A	
	2.2 Layer Thickness	4×10^5	1 to 10	-6	N/A	

Section	Simulation	Anomalous Layer Properties			Sea-level rise (mm/yr)	Visualisation
		Resistance ($m^{9/4}s^{3/2}$)	Thickness (m)	Baseline (m OD)		
	2.3 Layer Position	$4x10^5$	5	-14 to +5	N/A	
	2.4 Sea-level Rise	$4x10^5$ to $10x10^6$	3	-2	0 to 5	
6.2.3 Multiple Layer Effects	3.1 Sea-level Rise Sensitivity	$2x10^6$ to $2x10^7$	1	-2 to +3	0 to 5	

6.2 Sensitivity analysis of heterogeneous cliffs of variable resistance

This section presents the results of the model sensitivity analysis, which was conducted to illustrate the effects of vertical variations in material resistance. Section 6.2.1 examines the influence of a single more resistant layer on shore profile geomorphology and recession rates; Section 6.2.2 explores the role of a single less resistant (weaker) layer; and Section 6.2.3 considers multiple alternating layers of differing resistance.

6.2.1 Resistant layer effects

The simplest case considers the effect of a single layer of more resistant material situated within the cliff profile. It can be expected that this layer will experience reduced rates of erosion but how will this effect vary with the magnitude of relative resistance, the thickness and location of the layer and as it interacts with sea-level rise?

6.2.1.1 Layer resistance

In simulation 1.1 (Table 6-2), a layer of more resistant material was introduced into the cliff profile, outcropping at -6 to -1 m OD (Ordnance Datum). A layer thickness of 5m was selected to ensure its effect would be readily detected within the profile (the effect of layer thickness is considered in the following section) and the layer position was based on the limit of the distribution of erosion calculated in SCAPE for a homogenous profile. Figure 6-1a compares the final profiles (following the 5,000 year simulation) for layers of various increased relative resistance (3x, 5x and 10x) with a baseline for homogenous rock. For context, the magnitudes of resistance can be compared using the classification of coherence of soft rocks developed by Soares (1993) previously introduced (Section 3.3). To reiterate, it correlates the compressive strength of rock (MPa) to four categories of coherence:

1. Coherent, >20 MPa
2. Intermediately coherent, 10 to 20 MPa
3. Less coherent, 5 to 10 MPa

4. Non-coherent, <5 MPa

Therefore, a 3x more resistant layer could correspond to a less coherent cliff (e.g. silt) with a more resistant layer of intermediate coherence (e.g. Shale), while a 5x more resistant layer may correspond to silt cliff with a more coherent layer (e.g. sandstone), respectively.

The effect of a resistant layer is evident in the shore profile shape for all degrees of resistance and is marked by raising and steepening of the profile in this area as indicated on Figure 6-1a. The trend of increasing shore profile slope with increased material resistance is consistent with previous model results and field observations for homogenous cliffs that the platform gradient increases with resistance (Trenhaile and Layzell, 1981, Walkden and Hall, 2005). The shore platform slopes gently from the upper boundary of the resistant layer to the cliff toe, whose position is substantially unaffected by the presence of a more resistant layer. This is further demonstrated by Figure 6-1b, which shows the non-dimensional rates of cliff toe retreat considering the rate the heterogeneous cliff as a fraction of that of the homogenous cliff. This provides a dimensionless comparison of the trends in cliff toe retreat rate over time under each scenario modelled, which is of most relevance considering the focus of this section on geomorphic understanding.

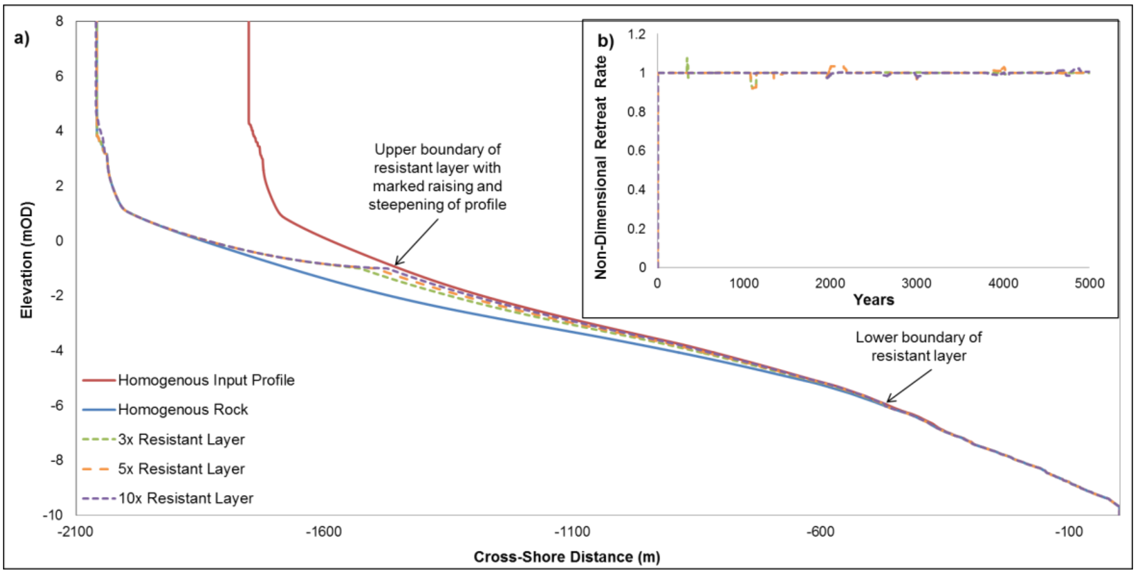


Figure 6-1: a) Output shore profile after 5,000 years with introduction of a more resistant layer of material of varying resistance, b) Cliff toe retreat rate as a proportion of that for a homogenous cliff

When the simulation is run for a longer period of time the influence of the hard layer on the softer platform above was observed to propagate upwards through time. After 5ka the effect reached an elevation of around 0 m relative to MSL (from -1 m), after 10ka the effect reached the cliff toe, and from then on the cliff toe retreat rate begins to fall. The long period of time between the resistant layer being encountered and the response of the cliff retreat may seem counterintuitive: at a real site we might well expect that local amplification of wave breaking caused by a resistant layer of bedrock should slow influence the rate of cliff retreat more quickly. This effect is discussed further in Section 6.3.

6.2.1.2 Resistant layer thickness and position

The above has demonstrated how a more resistant layer influences shore platform geomorphology but not necessarily rates of cliff toe retreat when situated below MSL. To investigate the effect of thickness of the resistant layer, a series of analyses were run in which the thickness of a band of 5x relatively more resistant material was increased in steps of 1 m from a constant base elevation of -6 m OD (Table 6-2).

The results showed that when the resistant layer thickness exceeds 5 m (upper limit at -1 m OD), a marked change in the cliff toe position and a reduction in retreat rates occur. However, above a resistant layer thickness of 9m (upper limit at +3 m OD), the effect of further increases in layer thickness are not apparent. This is demonstrated by again considering the non-dimensional rate of cliff toe retreat by the end of the model simulation, as outlined in Figure 6-2. This would be expected given the vertical extent of marine processes modelled in SCAPE and, in terms of marine processes, the results suggest that the position of the layer relative to Mean Sea Level (MSL) may be more important than its thickness in determining its influence on recession rate. Despite this, it is recognised that changes in material resistance above this upper limit will affect geotechnical processes in the cliff face. However, within SCAPE the cliff top is simply assumed to shear as vertical every ten recession events, based on the mesoscale assumption that cliff top recession is primarily determined by feedbacks between the cliff toe and shore platform . Therefore, it has not been possible to consider the potential effect of layers of variable resistance on geotechnical processes within the current refined SCAPE model. This is further supported by the focus of this thesis of cliff toe processes, based on the key link the feature provides between the terrestrial and marine system as demonstrated by Figure 2-3.

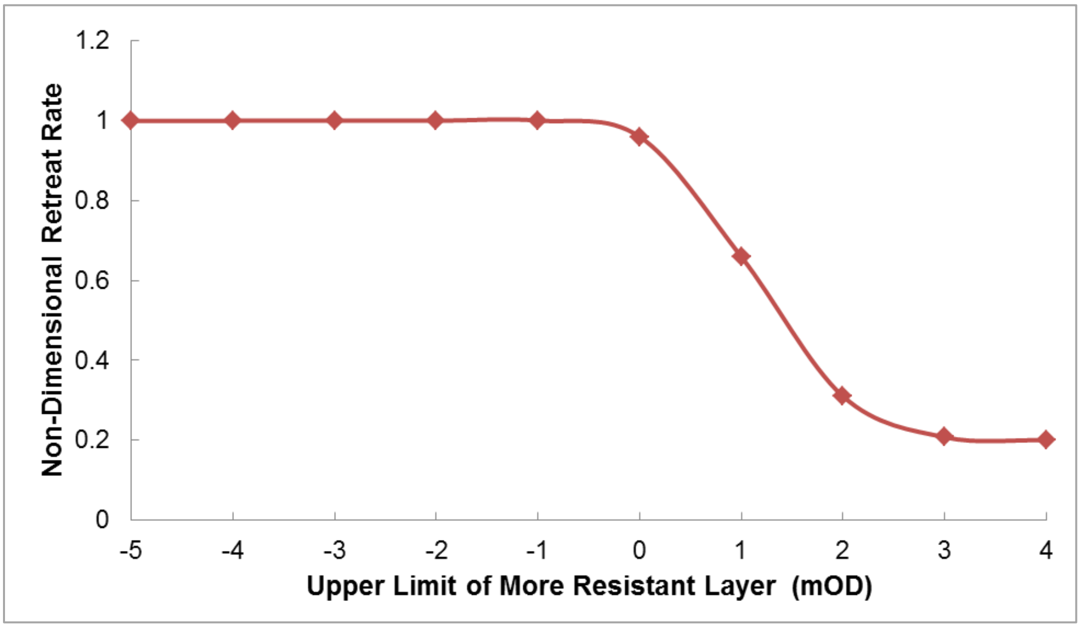


Figure 6-2: Cliff toe retreat rate as a proportion of that of a homogenous cliff with varying upper limit of a more resistant layer and a constant lower limit of -6 m OD

In light of the above, simulation 1.3 investigated a range of resistant layer locations moving in 1m increments up the cliff face (-14 to +5 m OD; Table 6-2). In agreement with the findings of layer thickness, the presence of this resistant layer did not begin to influence the cliff toe position until the upper limit of its extent rose above -1 m OD (which also corresponds to -1 m below mean sea level given the conditions used in this study). This can be attributed to the resistant layer not significantly affecting the shore profile geomorphology below this point, and therefore having limited effect on the processes of wave attenuation and in turn cliff toe recession. Above -1 m OD the resistant layer continued to influence the cliff toe position until the upper limit was above +3 m OD, again in agreement with the boundaries determined for layer thickness (but in this case with a constant layer thickness of 5 m).

Figure 6-3a outlines the final output profiles within these limits. The more resistant layer acts as a natural form of coastal protection, slowing erosion rates through its lower erosive potential combined with the effect of the emergent ledge feature attenuating wave energy reaching the cliff toe as further shown by Figure 6-3b. Overall, the limits within which the resistant layer influences cliff toe retreat support the findings on the effect of the layer thickness above: resistant layer position in the vertical plane is important with respect to marine erosional processes.

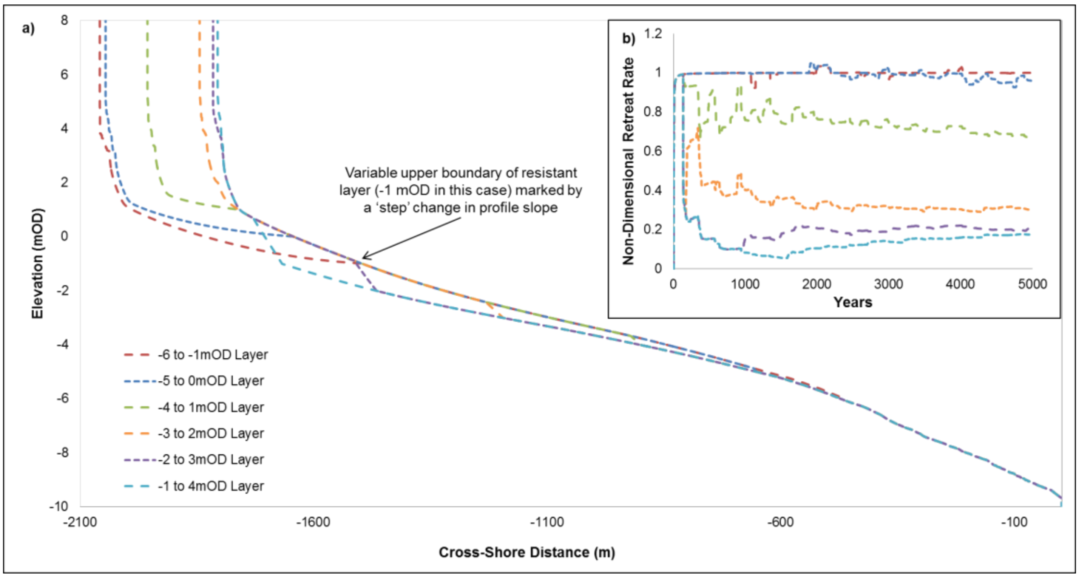


Figure 6-3: a) Output shore profile with varying position of resistant layer, b) Cliff toe retreat rate as a proportion of that for a homogenous cliff

6.2.1.3 Resistant layer and sea-level rise

Climate change is accelerating rates of sea-level rise (SLR) through thermal expansion of the oceans and melting of land-based ice. Tide gauge records indicate that global sea-level has risen at a mean rate of 1.7 (1.5 to 1.9) mm/yr between 1900 and 2010 and 3.2 (2.8 to 3.6) mm/yr between 1993 and 2010 (IPPC, 2013). Understanding and quantifying shore profile response to such changes is a key challenge facing coastal geomorphologists (Dubois, 2002). Walkden and Dickson (2008) applied the 2D SCAPE model to assess the response of soft rock shores fronted by low volume beaches to different rates of sea-level rise. They demonstrated how profiles steepen with accelerated rates of rise and presented an expression to predict future rates of cliff recession based on historic recession and historic and future sea-level rise. To investigate how vertical variations in resistance interact with sea-level rise, simulation 1.4 studied the effect of a 3 m thick resistant layer (baseline at -2 m OD) subjected to different rates of sea-level rise.

Figure 6-4a shows the final output profiles for rates of sea-level rise of 0, 1, 2, 3, 4 and 5 mm/yr (these rates do not represent specific projections but cover a range of trends noted by IPCC (2013). As with previous modelling of homogenous cliffs, the output profiles demonstrate; a) that the junction between the shore platform and cliff toe rises with sea level; b) the profile steepens as retreat can equalise across all elevations, and c) increased landward retreat with sea-level rise (Ashton et al., 2011, Trenhaile, 2010, Walkden and Dickson, 2008). Also, the more resistant layer remains as a relict feature within the shore profile following inundation in all scenarios. The final cross-shore position of the resistant layer moves seaward with increasing rates of sea-level rise as it is exposed to erosive processes for shorter time periods.

Figure 6-4b shows the associated non-dimensionalised cliff toe retreat rates. With no sea-level rise the resistant layer remains positioned about mean sea level and the retreat rate stabilises over time. An increase in the rate of sea-level rise increases recession rates as the greater water depths enable larger waves to attack the cliff toe. Furthermore, the resistant layer becomes submerged below low tide (for example after approximately 1,000 years with a 1mm/yr sea-level rise). Consequently, retreat rates for sea-level rise scenarios take longer to reach dynamic equilibrium owing to the overlying weaker material becoming involved in the erosion process. In a contrasting scenario not reported here, it was shown that a more resistant layer situated further up the cliff profile would result in a decline in rates of retreat when the rising sea reached that level.

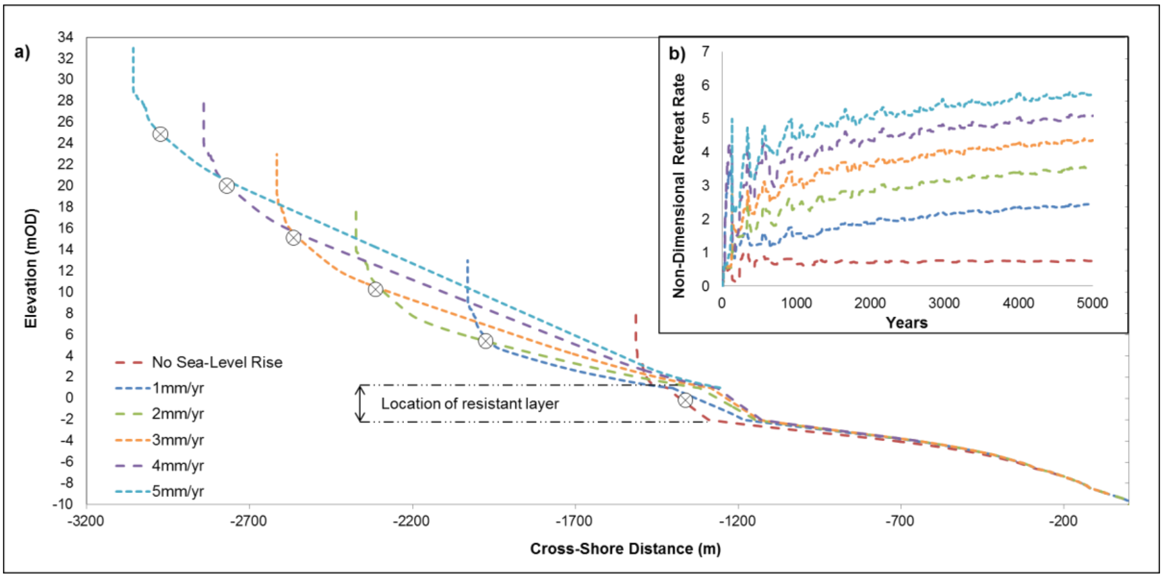


Figure 6-4: a) Comparative output shore profiles after 5,000 years with resistant layer and sea level rise (markers indicating MSL), b) Cliff toe retreat rate as a proportion of that for a homogenous cliff with static sea-level

6.2.2 Weaker layer effects

In terms of slope stability, a cliff is recognised to be only as strong as its weakest horizon (Isle of Wight Council, 2000). Therefore, in a contrasting simple case, how does a single layer of less resistant material influence shore platform geomorphology and rates of cliff toe retreat?

6.2.2.1 Layer weakness

Mirroring simulation 1.1, the sensitivity of the recession rate to a 5 m layer of less resistant material was investigated with a baseline of -6 m OD (simulation 2.1, Table 6-2). Figure 6-5a compares the final 5,000 year emergent profiles with the baseline for homogenous rock. The introduction of weaker layers results in a shallower profile slope overlain by a progressively lower and steeper cliff toe. This is a reversal of the trends in shore platform geomorphology found for a more resistant layer, which resulted in a raising and steepening of the shore profile at the location of the resistant layer, overlain by a wider, shallower section. Furthermore, whereas resistant rock situated at this location had little impact on the cliff toe position, the introduction of a weaker layer had a significant effect on the cliff toe position and retreat rate (Figure 6-5b). For example, a fivefold increase in the resistant layer had negligible influence on the equilibrium recession rate of the cliff toe (Figure 6-1b), whereas a fivefold decrease resulted in a 130% increase in the recession rate by the end of the simulation. However, a 'lag' in the influence of the weaker layer on the non-dimensional retreat rate (>500 years) is apparent. This is attributed to the submerged position of this layer and the subsequent time it takes the shore profile to adjust, with progressively shallower shore profile slopes and lower cliff toes with the presence of weaker material.

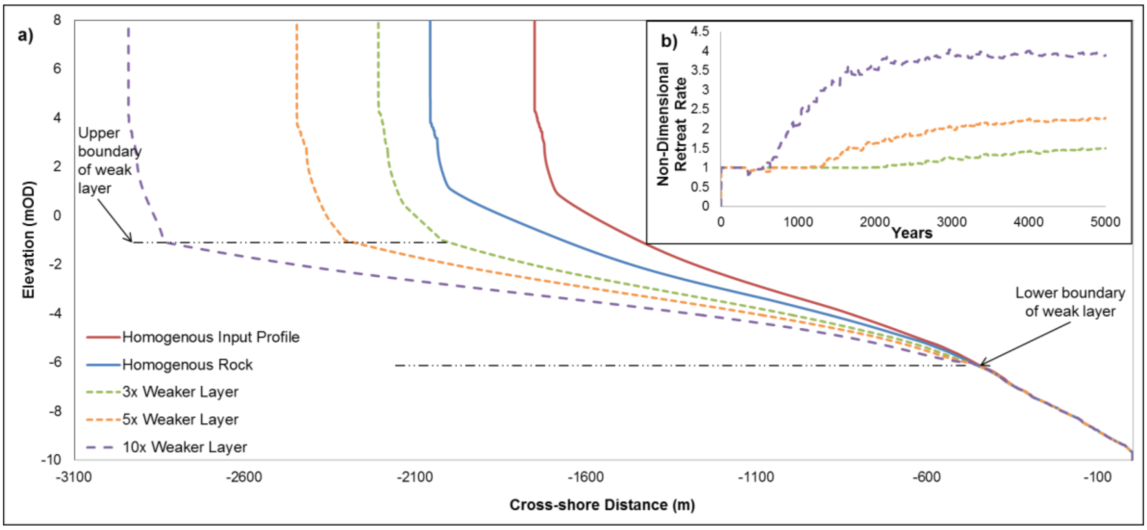


Figure 6-5: a) Output shore profile after 5,000 years with introduction of a less resistant layer of material, b) Cliff toe retreat rate as a proportion of that for a homogenous cliff

6.2.2.2 Weaker layer position

The vertical limit of a weaker layer on rates of cliff toe retreat was next explored. Figure 6-6a and b shows the 5,000 year profiles for a 5 m layer of weaker rock located at different elevations in the cliff face and the associated retreat rates of the cliff toe, respectively. Again, a range of locations were investigated but it is only when the upper limit of the weaker layer reached approximately -2 m OD (and -2 m relative to mean sea level given the conditions used in this study) that it began to influence the cliff toe position. This influence continued until the upper limit was above +2 m OD, again demonstrating the importance of the anomalous layer position. In comparison to the effect of resistant layer position, while the results show the same affected 4m range, the distribution with respect to mean sea level varies (-1 m OD and +3 m OD for a more resistant layer). This variation can be attributed to the contrasting effect the anomalous layers have on shore profile geomorphology; weaker layers lower the cliff toe and therefore it is more susceptible to marine processes at a lower boundary.

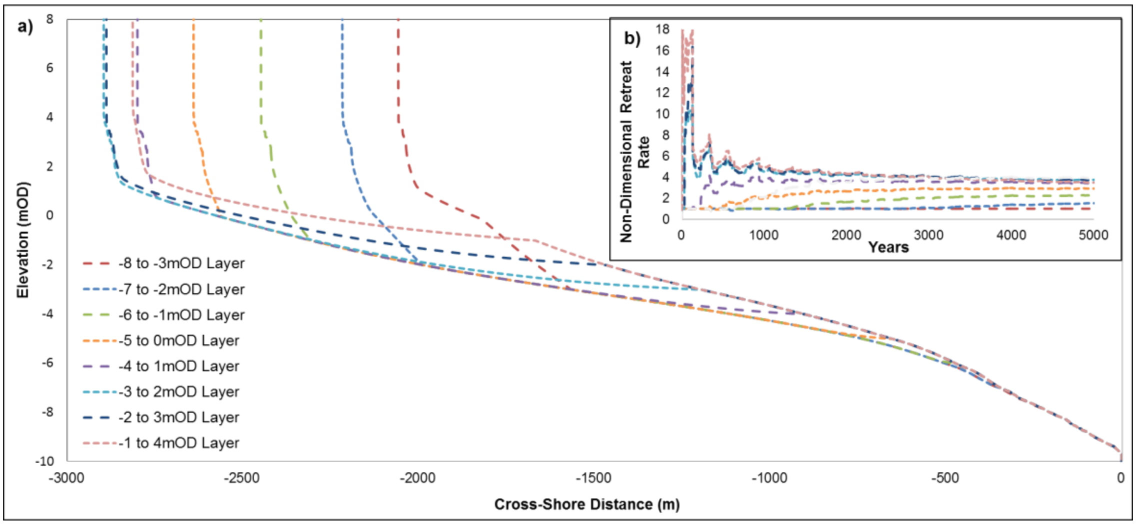


Figure 6-6: a) Output shore profile after 5,000 years with varying position of weak layer, b) Cliff toe retreat rate as a proportion of that for a homogenous cliff

6.2.2.3 Weaker layer and sea-level rise

Figure 6-7a shows the final profiles associated with a weaker layer subjected to sea-level rise (simulation 2.3, Table 6-2). Similar trends to those observed in Section 6.2.1 (resistant layer and sea-level rise) can be noted, with a rising and steepening of the cliff toe and an increase in the non-dimensional retreat rate (Figure 6-7b) with sea-level rise, and the presence of the anomalous layer remaining apparent in the shore platform geomorphology even following inundation.

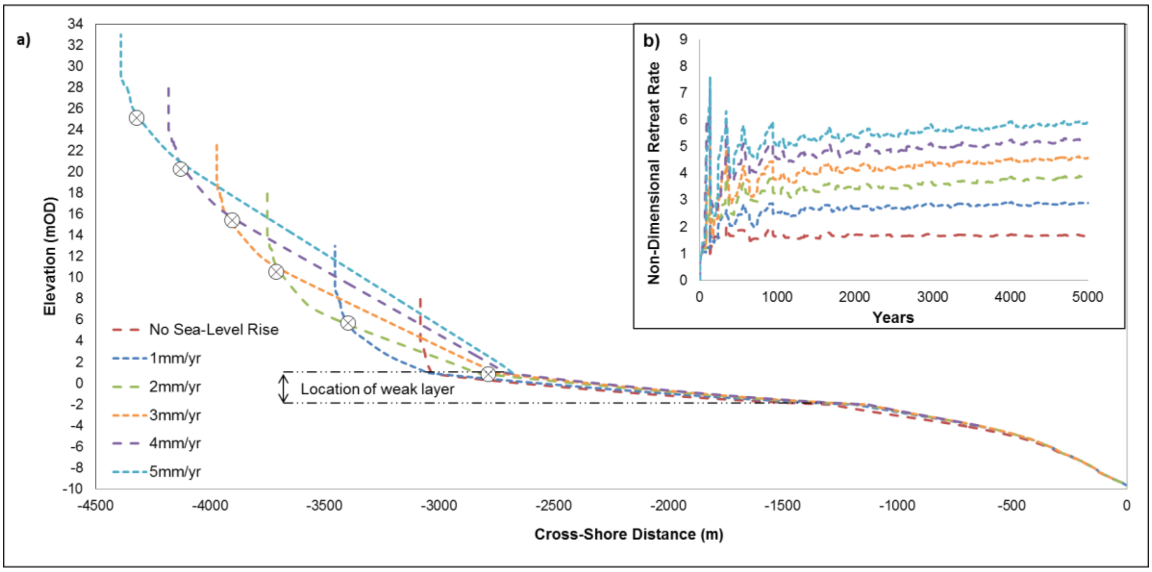


Figure 6-7: a) Comparative output shore profiles after 5,000 years with weaker layer and sea-level rise (markers indicating MSL), b) Cliff toe retreat rate as a proportion of that for a homogenous cliff with static sea-level

Comparing the effect of a 5x relatively more resistant layer (Figure 6-4b) with that of a 5x relatively less resistant layer (Figure 6-7b) the different sensitivities of the non-dimensional cliff toe retreat rate to accelerated sea-level rise are apparent. For a rate of sea-level rise of 1 mm/yr with the anomalous layers in the same location, a significant difference in the non-dimensional rates of retreat between the stronger and weaker layer is still apparent by the end of the model simulation despite the material resistance of the overlying cliff having the same properties in each run. In contrast, for a 5 mm/yr sea-level rise there is negligible difference between the non-dimensional rates of retreat by the end of the simulation. This indicates that heterogeneous cliff characteristics are more influential under slower rates of sea-level rise as the layer is exposed to marine erosion for a longer period. The layer thickness will also influence exposure duration, and hence the recession rate.

6.2.3 Multiple layers of variable resistance and interactions with sea-level rise

Simulation 3.1 aimed to mimic natural cliffs of interbedded stratigraphy, such as alternating layers of more resistant sandstone and less resistant mudstone.

Alternating 1m layers of material either 2x weaker or 2x stronger (than the material resistance of the homogenous cliff) were introduced up the cliff face. The lower boundary position ranged from -2 to +3 m OD as indicated in on Figure 6-8a, which also outlines the final profiles for various rates of sea-level rise. With a static sea-level, the influence of the anomalous material resistance on shore profile shape is visible until approximately +2 m OD, which corresponds to the boundaries of erosive sensitivity previously identified. As sea-level rises, the influence of the anomalous layers of material resistance up the cliff profile becomes apparent. This confirms that the outcropping of layers in relation to mean sea level is a key control on recession rates.

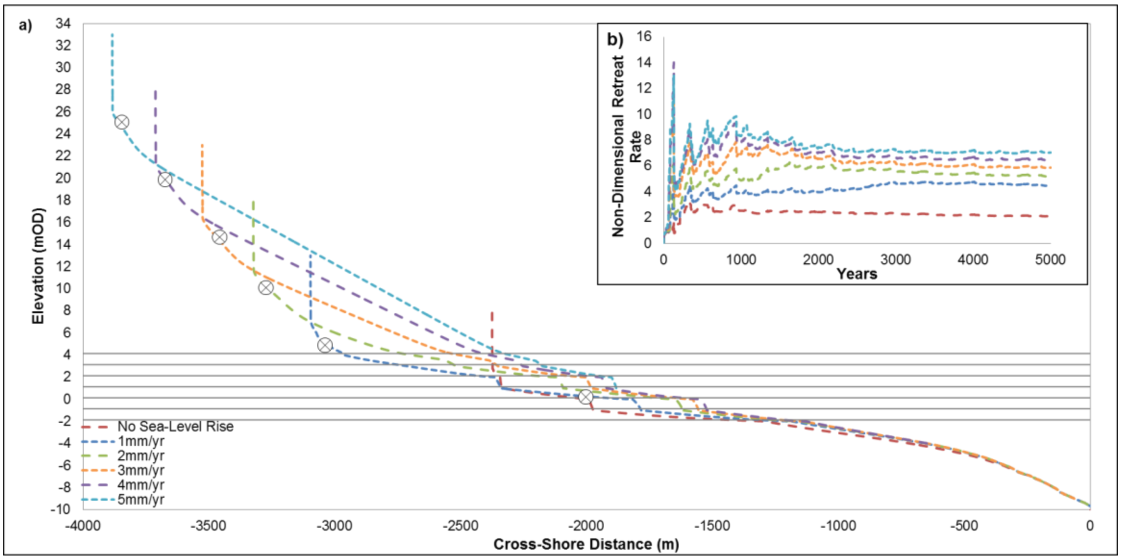


Figure 6-8: a) Emergent shore profiles after 5,000 years considering alternating layers of variable material resistance (as denoted by the 1m horizontal markers beginning with a weak layer at -2 m OD, markers indicate MSL), b) Cliff toe retreat rate as a proportion of that for a homogenous cliff with static sea-level

Figure 6-8b shows the associated non-dimensional cliff toe recession rates. Subtle fluctuations in the future rates of retreat of the cliff toe can be attributed to the vertical changes in material resistance and interactions with sea-level rise. For example, 1mm/yr sea-level rise corresponds to a change in material resistance (with respect to mean sea level) within the heterogeneous 1m layers every 1,000 years. This is reflected in the non-dimensional retreat rate; between years 1,000-2,000 a resistant layer is present; however, between years 2,000 to 3,000 a weaker layer is present and a rise in the retreat rate is apparent. The effect reduces with faster rates of sea-level rise, owing to the limited period of time that a given mean sea level has to interact with the anomalous layers. However, this also depends on the thickness of the layers encountered.

6.3 Discussion of results for cliffs of variable resistance

This chapter has applied a modified version of the 2D SCAPE model to further our understanding of coasts comprised of horizontal layers of variable resistance. The intention was not to model specific sites at this stage but to quantify the effects of variable material resistance on both shore platform geomorphology and rates of cliff toe retreat. The key findings with reference to their implications for real sites and their limitations will now be discussed.

6.3.1 Responses of the shore platform and cliff toe

The simulations have demonstrated how shore profile shape and cliff recession rate respond to the outcropping of a rock layer of different resistance. The finding that weaker (/ more resistant) layers lead to more (/ less) rapid retreat is intuitive, given the description of the erosion rate presented in Equation 1. More surprising is the asymmetry of the response of the cliff erosion rate to changes in layer resistance, and the difference in the timeframe of the response. This is highlighted by Figure 6-9, which shows the retreat rates as a proportion of that for a homogenous cliff versus the relative strength (Equation 6-1) of anomalous layers situated at -6 to -1 m OD and relative to MSL:

$$Relative\ Strength\ (n) = \frac{M_{layer}}{Mref}$$

Equation 6-1

where M_{layer} is the material resistance of the anomalous layer and M_{ref} is the reference material resistance ($2x10^6\ M^{9/4}S^{3/2}$ in this case).

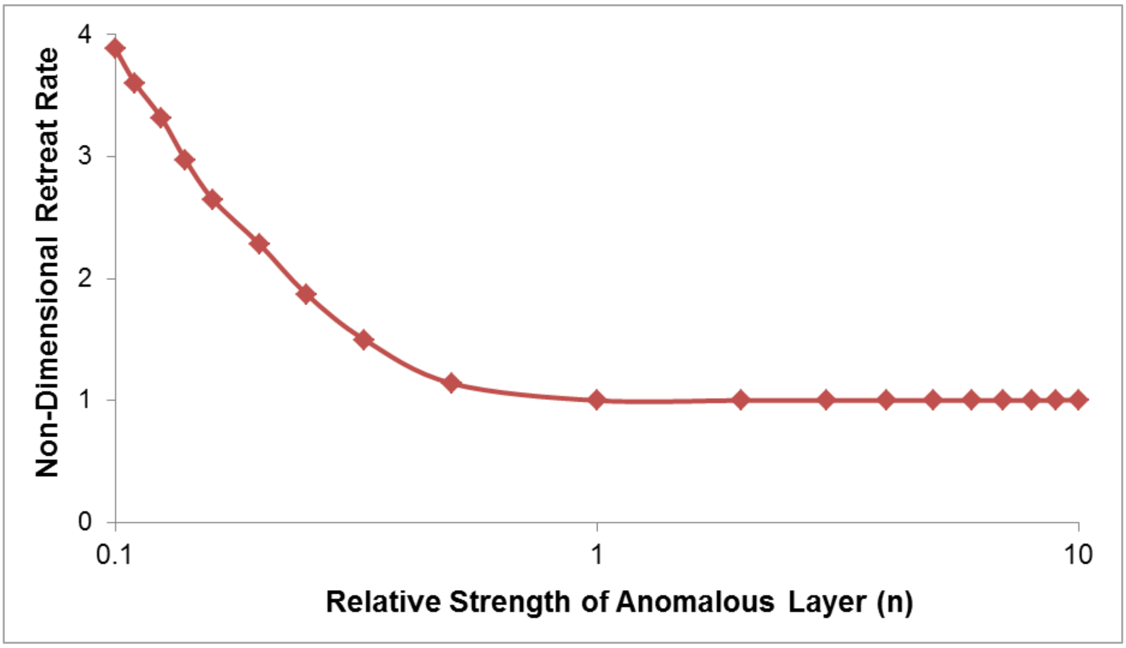


Figure 6-9: Non-dimensional cliff toe retreat rate versus varying relative resistance of a single anomalous layer

In these simulations the appearance of a weaker layer affected cliff recession rates much earlier than a more resistant layer, which took many millennia to be expressed at the cliff face (>10ka). The varying timeframes reveal quite different magnitudes of feedback governing the profile reshaping in each case (as summarised in Figure 6-10). Weaker layers trigger a cascade of response across the upper shore platform, whereby:

1. Increased retreat of the weaker layer steepens the section immediately above it;
2. Following Equation 4-9, steepening induces greater retreat despite the overlying sections higher resistive strength;
3. The process of steepening and increased erosion continues up the shore profile. The rate of removal of material necessary to reshape the profile is amplified by the process of localised steepening.

In contrast, the removal of material necessary to allow the reshaping of the platform above a more resistant layer is damped by profile flattening. The slope immediately above the more resistant layer becomes shallower because it is anchored to the outcrop, and therefore its retreat slows. This in turn reduces the slope of the layer above it. The effect passes up the profile, but is governed by a lessening of slopes, steadily decreasing the effectiveness of the erosive potential of the incident waves. In both cases the reshaping is controlled by negative feedback acting to re-establish a dynamic equilibrium, but the feedback factor is very different between the two.

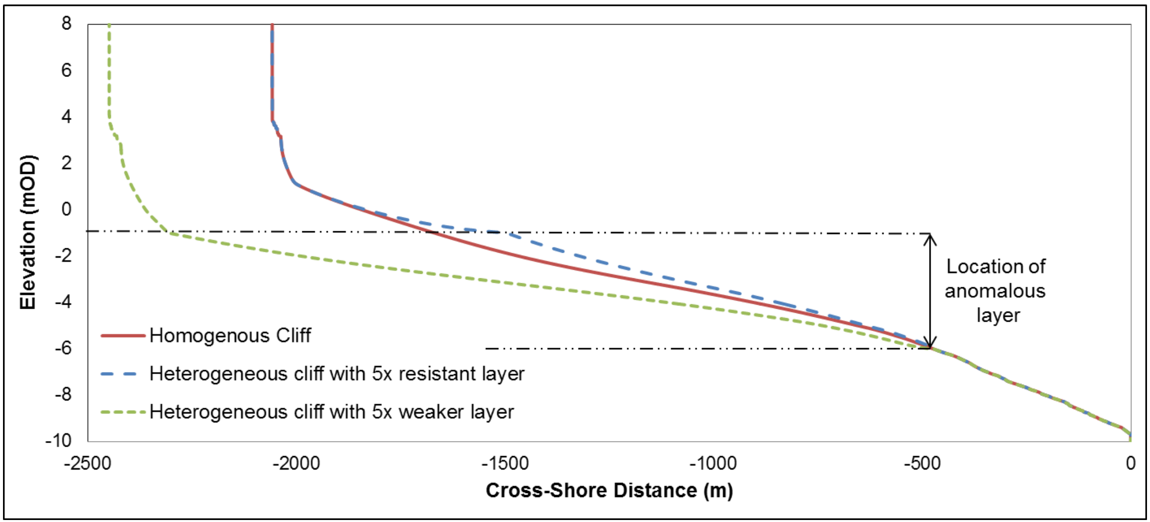


Figure 6-10: Comparison of final 5,000 year output profiles for homogenous and heterogeneous cliff (the latter considering a single variable resistance layer situated at -6 to -1 m OD)

The contrasting effect of stronger/weaker layers on shore profile slope and cliff toe elevation can also explain the differing boundary elevations for which such layers were found to influence rates of cliff toe retreat. The outcropping of lithologies in relation to MSL is paramount (-1 to +3 m for a more resistant layer and -2 to +2 m for a weaker layer). However, this range may well vary depending on the prevailing coastal conditions used. The findings are supported by the simulations of the effects of sea-level rise; multiple layers of variable rock strength in the cliff face only influence the profile shape and rate of cliff toe retreat when encountered by MSL.

6.3.2 Coastal management implications

Previous studies have recognised how sea-level rise may influence future rates of cliff toe retreat and are frequently used as a basis for coastal management (Bray and Hooke, 1997, Sunamura, 1988a, Walkden and Dickson, 2008). This study highlights the need to understand potential changes in in-situ cliff conditions, particularly variations in material resistance in the vertical direction. Application of the refined SCAPE model has demonstrated the importance of the position of anomalous layers about MSL and hence how interactions may change with sea-level rise over time. As stated above, the outcropping of weaker layers is paramount; inducing significant changes in shore profile geomorphology and rates of cliff toe retreat. However, the rate of sea-level rise will affect the duration of exposure of such layers, such that thicker layers or slower rates of sea-level rise may give rise to the greatest rates of cliff toe retreat over a longer period of time.

6.3.3 Study limitations

The results presented in this chapter were generated using the modified version of the 2D SCAPE model. As with all numerical models, the results represent an abstraction of reality and many of the processes within the coastal cliff system have been simplified in accordance with the usual principles of mesoscale, reduced complexity modelling. The key limitations are discussed below.

This study has characterised material strength solely in terms of the erosive potential of the rock. The effects of discontinuities which may be susceptible to quarrying by wave impact and air compression at or close to the water surface (Trenhaile, 2009) were not accounted for. Material strength within SCAPE is described by a hybrid calibration parameter based on Kamphuis (1987), Equation 4-9. Therefore, no explicit correlations between modelled material strength and the compressive strength of specific soft cliff lithologies can be made. However, given the intended generic application of this study relative changes in resistance have been considered sufficient.

In these tests, a model of homogenous material resistance was initially run for 10,000 years to dynamic equilibrium. The output profile was then extracted and used as an input within the heterogeneous model to understand the effect of material resistance over a further 5,000 years. This timescale was considered appropriate to understand the geomorphic evolution of the cliff through further model testing over timescales greater than 10,000 years that showed negligible difference in key trends. Non-dimensional retreat rates were specified considering the relevance of this research to geomorphic understanding as opposed to specific retreat predictions.

Variations in material strength have been limited to horizontally bedded layers within this study. No attempt has been made to consider layers of varying dip/strike, which may significantly change the dominant erosional processes being experienced beyond those within SCAPE. For example, where discontinuities dip seaward they can become the foundation of large scale landslides (Emery and Kuhn, 1982).

Bearing in mind the mesoscale SCAPE assumption that cliff top processes are predominantly driven by feedback mechanisms between the cliff toe and shore platform, the results of this study are most applicable to simple cliff behavioural units which are driven by basal marine erosion (Lee and Clark, 2002). SCAPE does not consider how variations in material strength may influence sub-aerial processes, which have been recognised to have an important effect on mass movement in a range of field and modelling studies including Jenkins et al (2011) and Castedo et al (2012), respectively.

SCAPE is a deterministic model, which assumes that the only climatic influence on cliff recession is via the shoreline. It does not take into consideration the influence of other climatic controls such as rainfall which can influence cliff top stability through prevailing conditions and sea-level rise (Dawson et al., 2009). As a result, the focus of this study has been on shore platform geomorphology, rates of cliff toe retreat and interactions with sea-level rise.

6.4 Refined soft cliff model application and assessment, part 1: closing comments

This study has applied the refined 2D SCAPE model to enable an understanding of the effect of vertically variable material resistance on coasts with low mobile sediment volumes. The importance of material resistance as a control on shore profile morphology and rates of cliff toe retreat has been confirmed. The results have shown that:

1. It is the outcropping of anomalous layers near to mean sea level (approximately +/- 2 m) which is a key control on cliff toe recession

rates owing to the integrated erosive potential of the tide, wave action and profile inundation.

2. A weaker layer results in an asymmetric decrease in the equilibrium slope and hence increase the rate of cliff toe retreat in comparison with the introduction of a more resistant layer of the same magnitude, thickness and location.
3. The rate of sea-level rise and anomalous layer thickness control the duration of exposure of such layers.

It is envisaged that the results of this study bring to the attention of coastal managers the important implications of extrapolating historic rates of retreat to obtain future predictions. While methods to account for the impact of accelerated rates of sea-level rise have received considerable attention, this study highlights the need to understand the interplay between the shoreline behaviour (based on sediment availability) and in-situ cliff conditions.

The following chapter will move on to consider validation of the refined model by application to the study frontage of variable lithology.

7. Refined Soft Cliff Model Application and Assessment, Part 2: Study Frontage Application

Addressing objective four of this research: *to understand how the impacts of environmental and climatic change will influence shore profile geomorphology and rates of cliff toe retreat*, this chapter applies the refined model to the study frontage, the layout is as follows:

- Section 7.1 outlines the validation process for the refined model across the study frontage;
- Section 7.2 assesses the future impacts of environmental and climatic change using the refined study frontage models;
- Section 7.3 discusses the refined model results, their implications for the study frontage and the model limitations; and,
- Section 7.4 concludes the chapter.

7.1 Refined model validation

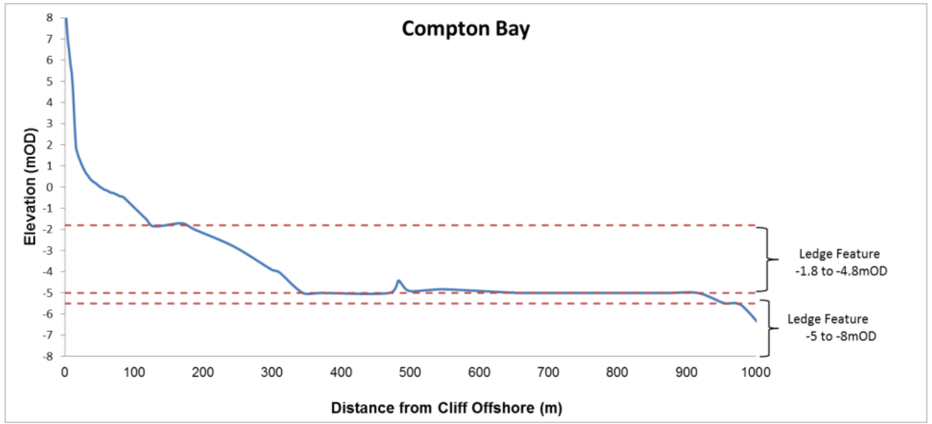
The following section discusses the refined model set-up and results for the seven selected sites along the Isle of Wight (IoW) study frontage. The results will enable evaluation of the refined model results against measured data for the frontage.

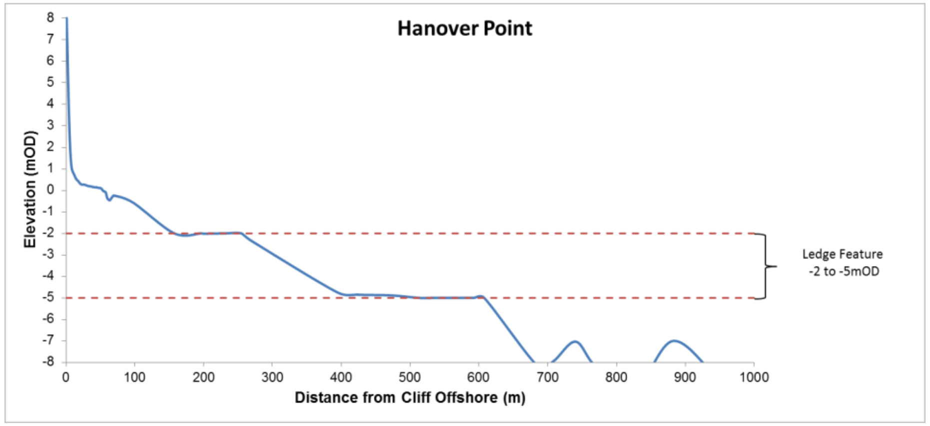
7.1.1 Refined model set-up and validation

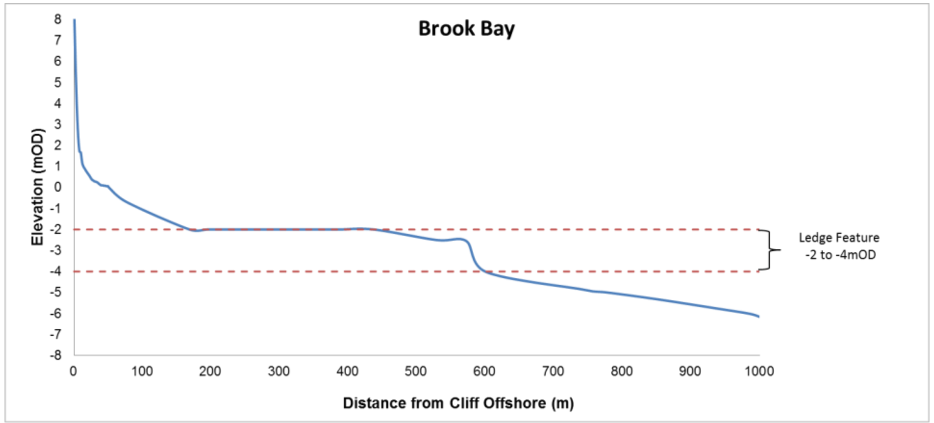
The input parameters outlined in Table 5-1 and Table 5-2 have been adopted for each refined model. However, the material resistance parameter has been varied in the vertical direction to consider a heterogeneous cliff consisting of a series of horizontal layers of variable resistance. The locations and associated values for layers of variable material resistance have been determined through a staged process:

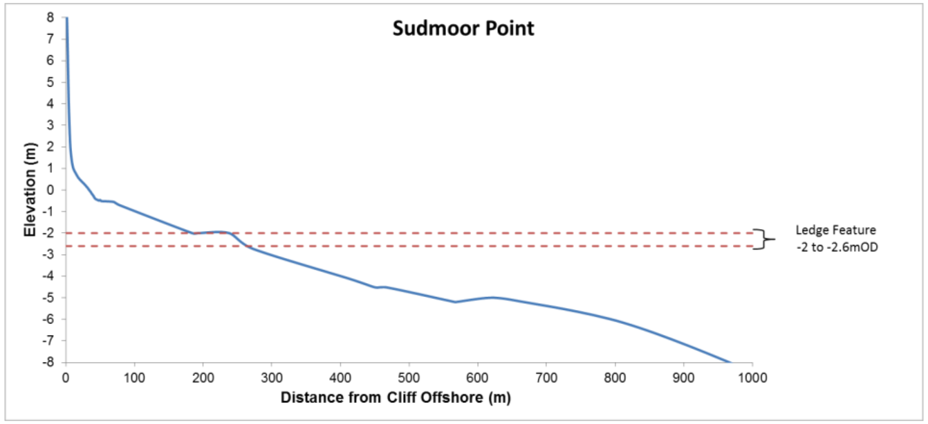
1. Measured bathymetric and shore profile data have been used to identify the location of ledge features which correspond to layers of increased material resistance.
2. The increased relative resistance of such layers in comparison with the original calibrated material resistance value (determined for the entire cliff in section 5.1.2) has been determined through an iterative process based on the output profile shape (evolving over 10,000 years from an initial vertical cliff).

Figure 7-1 provides a summary of stage 1, identifying the locations of more resistant ledge features within the actual measured profiles.


Compton Bay
Elevation (mOD)
Distance from Cliff Offshore (m)
Ledge Feature
-1.8 to -4.8mOD
Ledge Feature
-5 to -8mOD


Hanover Point
Elevation (mOD)
Distance from Cliff Offshore (m)
Ledge Feature
-2 to -5mOD


Brook Bay
Elevation (mOD)
Distance from Cliff Offshore (m)
Ledge Feature
-2 to -4mOD


Sudmoor Point
Elevation (m)
Distance from Cliff Offshore (m)
Ledge Feature
-2 to -2.6mOD

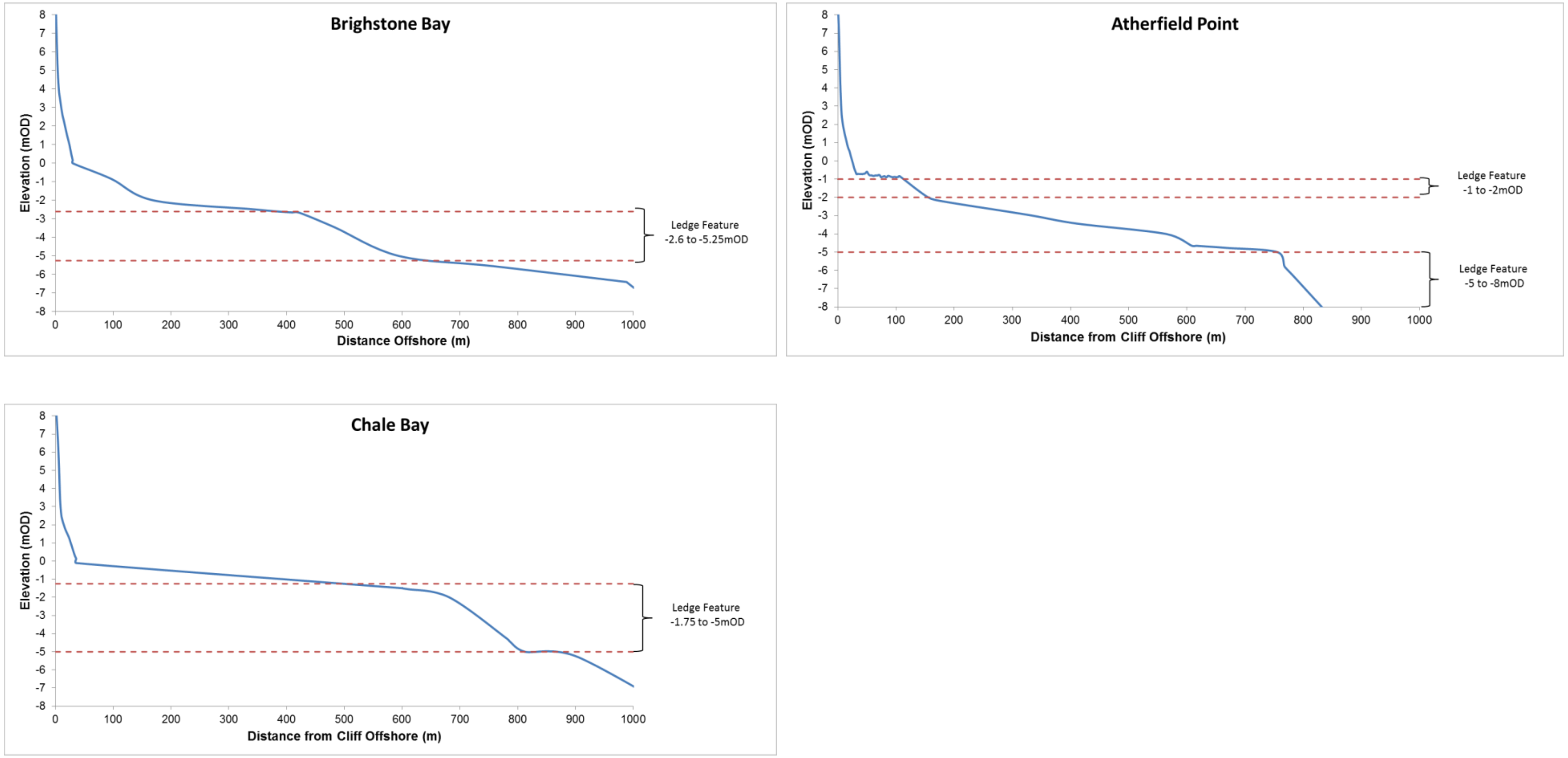


Figure 7-1: Identification of more resistant ledge features using measured shore profile data

7.0 Refined Soft Cliff Model Application and Assessment, Part 2: Study Frontage Application

The material resistance at each site was modified to reflect the more resistant ledge features identified in the present day. For example, Figure 7-2 provides an overview of the process of determining an appropriate resistance value (stage 2) for the profile at Brook Bay. As highlighted in Figure 7-1 a more resistant layer has been identified within the shore profile at -2 to -4 m OD. To replicate this feature, more resistant material resistance values (relative to the original material resistance calibration parameter determined for a homogenous cliff, Section 5.1.2) were trialled. The profile was again allowed to emerge over 10,000 years considering interactions with historic sea-level rise (SLR). Figure 7-2 shows the results for Brook Bay, further demonstrating how the profile rises and the slope steepens with increased relative resistance. A three times more resistant layer of rock was selected based on the closest fit to measure data as indicated.

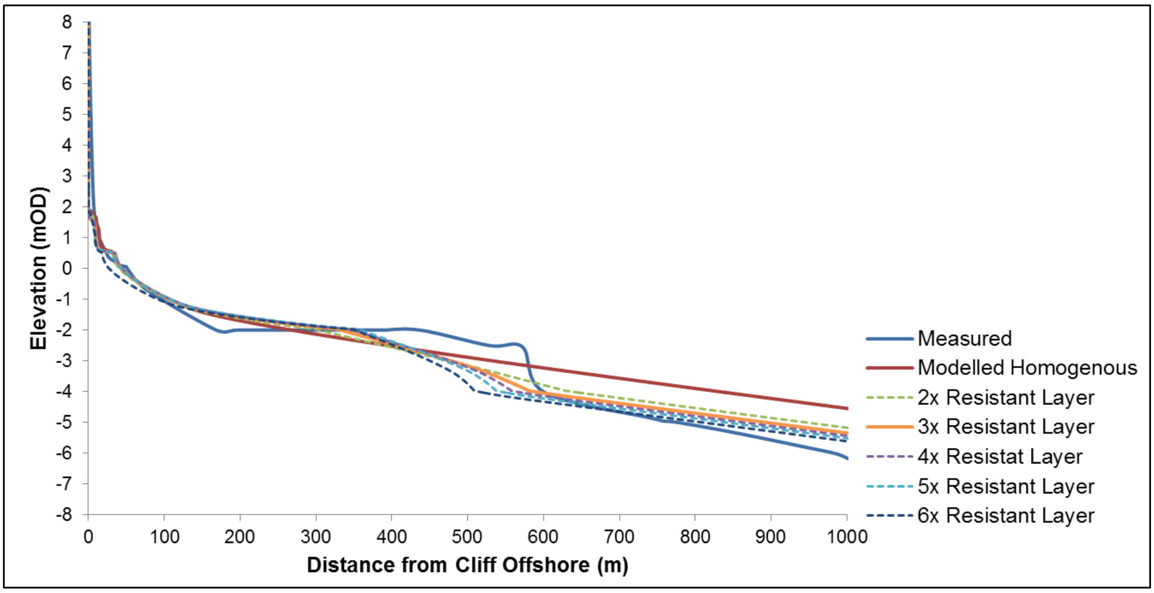
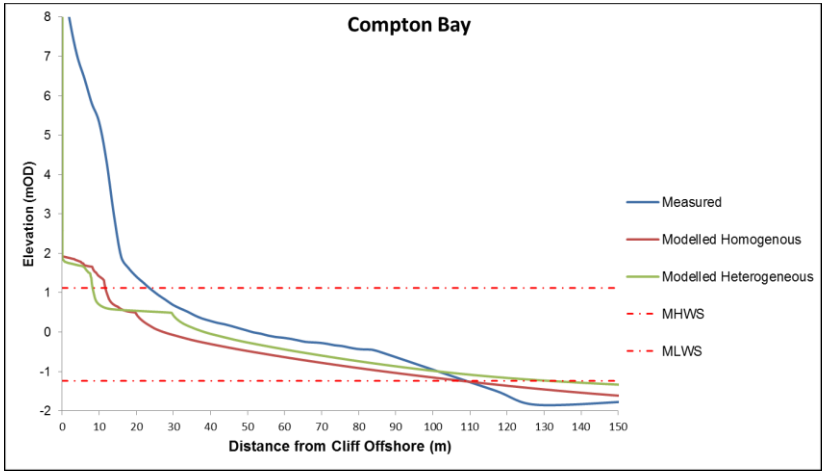
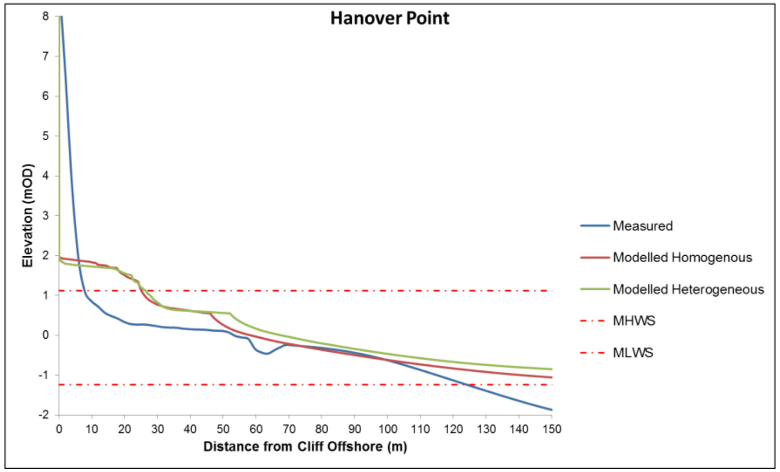
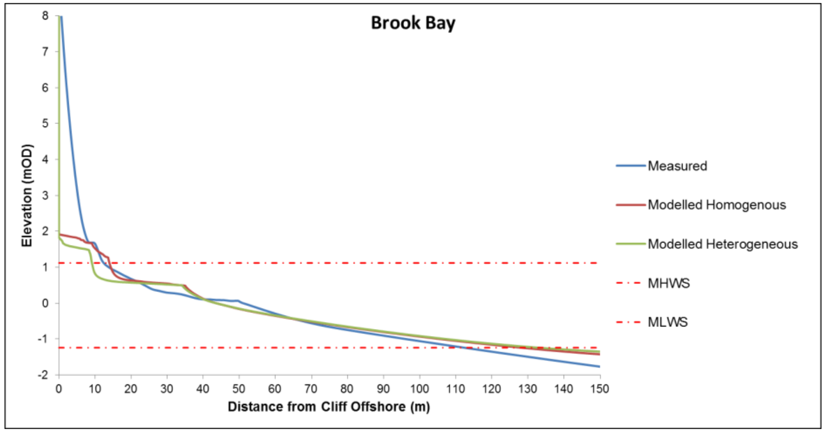


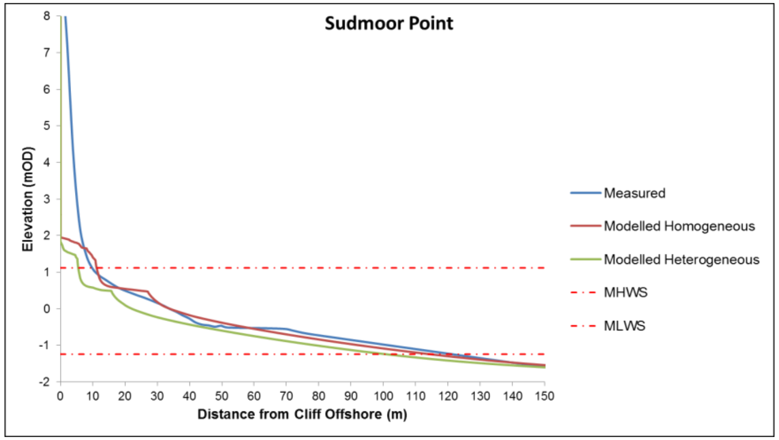
Figure 7-2: Calculating relative resistance of anomalous layer for Brook Bay

This iterative process of determining the relative resistance of the anomalous layers was repeated for each site. Figure 7-3 and Figure 7-4 provide a comparison of the measured, original modelled homogenous cliff and refined modelled heterogeneous cliff output shore and offshore profiles, respectively.


Compton Bay
Elevation (mOD)
8
7
6
5
4
3
2
1
0
-1
-2
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150
Distance from Cliff Offshore (m)
Measured
Modelled Homogenous
Modelled Heterogeneous
MHWS
MLWS


Hanover Point
Elevation (mOD)
8
7
6
5
4
3
2
1
0
-1
-2
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150
Distance from Cliff Offshore (m)
Measured
Modelled Homogenous
Modelled Heterogeneous
MHWS
MLWS


Brook Bay
Elevation (mOD)
8
7
6
5
4
3
2
1
0
-1
-2
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150
Distance from Cliff Offshore (m)
Measured
Modelled Homogenous
Modelled Heterogeneous
MHWS
MLWS


Sudmoor Point
Elevation (mOD)
8
7
6
5
4
3
2
1
0
-1
-2
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150
Distance from Cliff Offshore (m)
Measured
Modelled Homogeneous
Modelled Heterogeneous
MHWS
MLWS

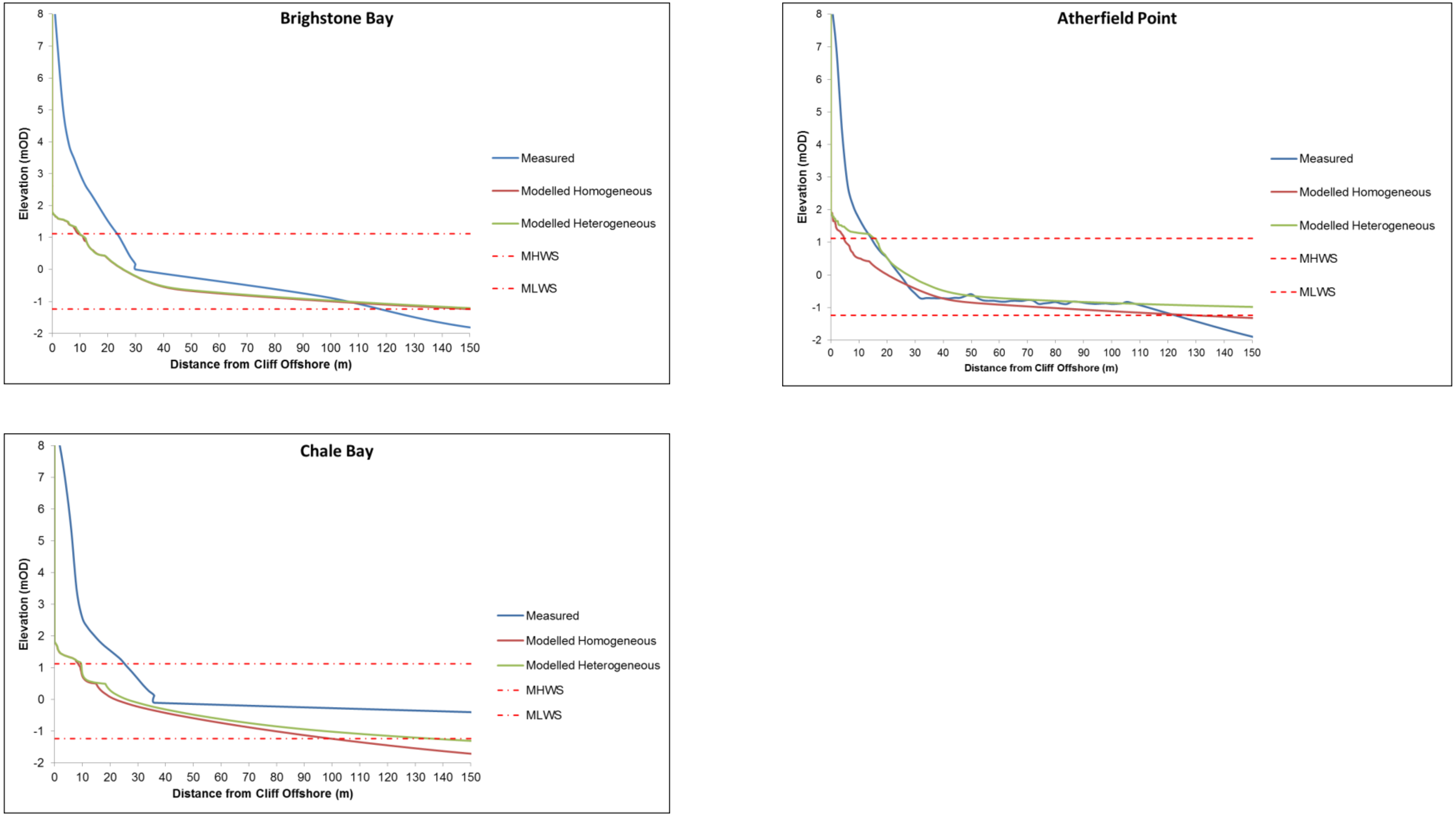
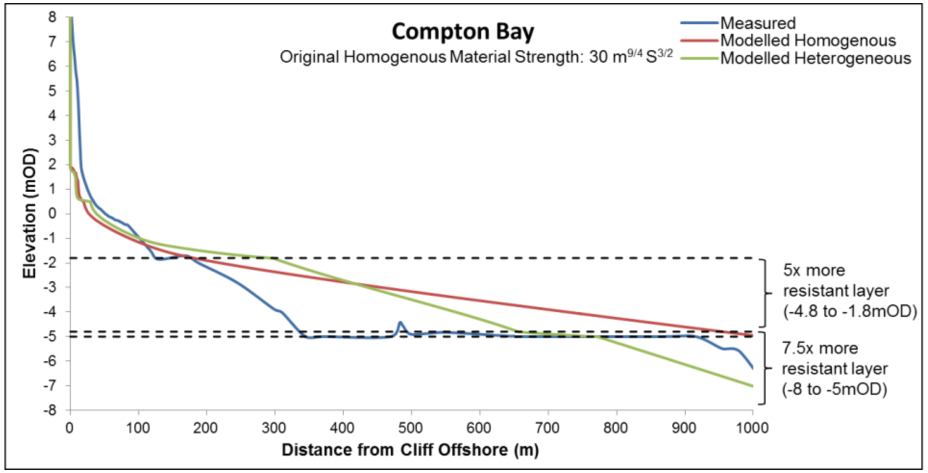
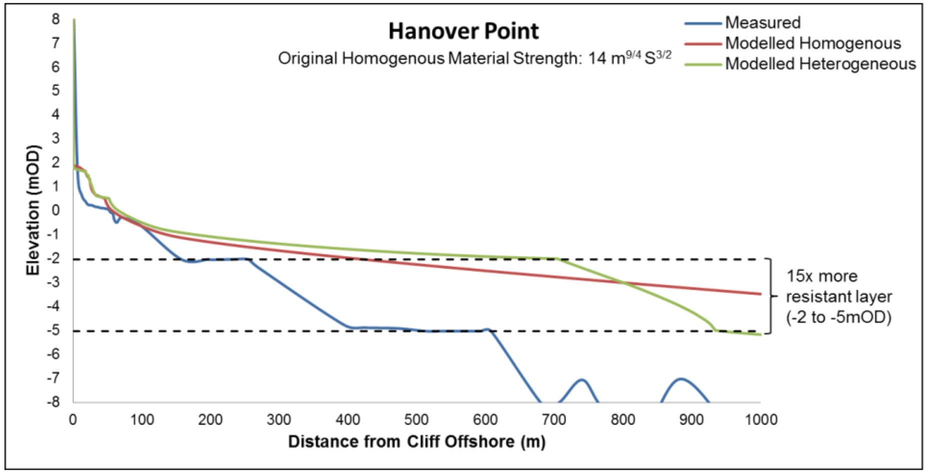
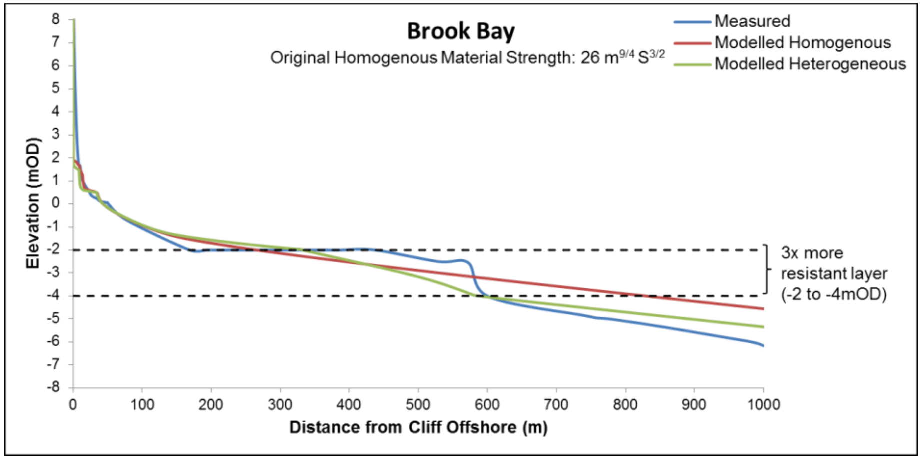
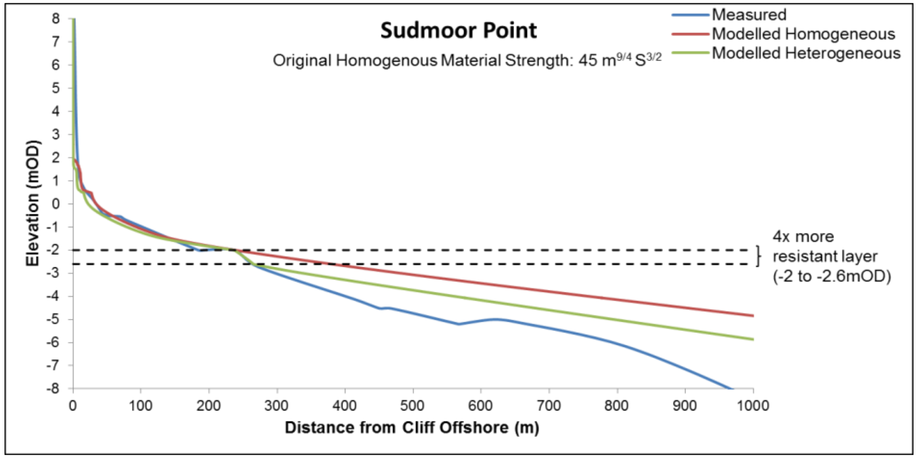


Figure 7-3: Refined model validation, measured data versus modelled homogenous and heterogeneous Shore Profiles


Compton Bay
Original Homogenous Material Strength: 30 m9/4 S3/2
Measured
Modelled Homogenous
Modelled Heterogeneous
5x more resistant layer (-4.8 to -1.8mOD)
7.5x more resistant layer (-8 to -5mOD)
Elevation (mOD)
Distance from Cliff Offshore (m)


Hanover Point
Original Homogenous Material Strength: 14 m9/4 S3/2
Measured
Modelled Homogenous
Modelled Heterogeneous
15x more resistant layer (-2 to -5mOD)
Elevation (mOD)
Distance from Cliff Offshore (m)


Brook Bay
Original Homogenous Material Strength: 26 m9/4 S3/2
Measured
Modelled Homogenous
Modelled Heterogeneous
3x more resistant layer (-2 to -4mOD)
Elevation (mOD)
Distance from Cliff Offshore (m)


Sudmoor Point
Original Homogenous Material Strength: 45 m9/4 S3/2
Measured
Modelled Homogeneous
Modelled Heterogeneous
4x more resistant layer (-2 to -2.6mOD)
Elevation (mOD)
Distance from Cliff Offshore (m)

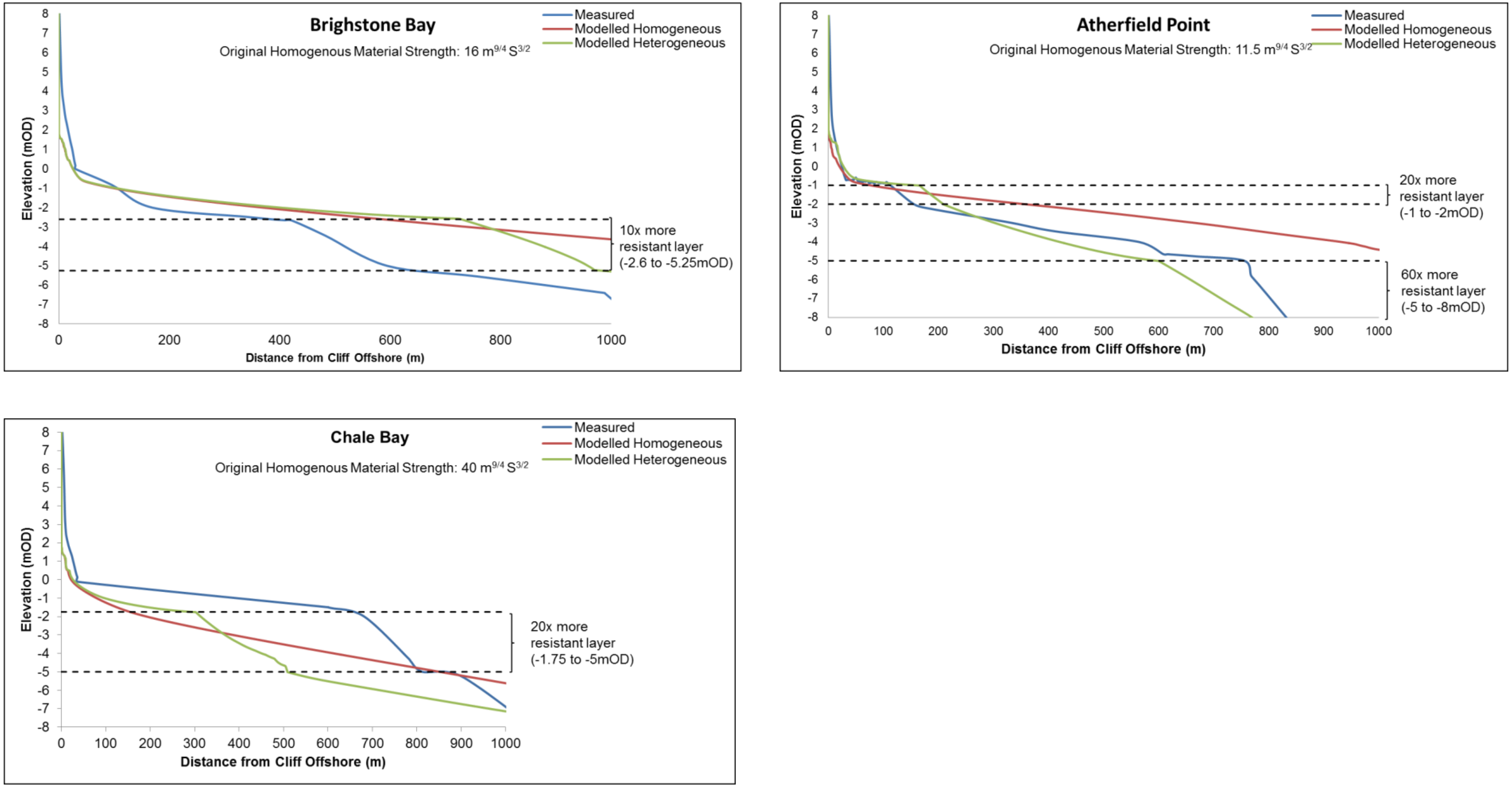


Figure 7-4: Refined model validation, measured data versus modelled homogenous and heterogeneous offshore profiles

Comparisons of modelled homogenous and heterogeneous shore profiles with measured data (Figure 7-3) show negligible difference in outputs. This is owing to the focus of variations in material resistance below MLWS, as highlighted by the Figure 7-4. The figures highlight how, dependent on the resolution, additional layers of variable material resistance may be identified up the shore profile. For example, at Compton Bay an additional layer at -2 to -0.5 m OD may be identified demonstrating potential for further model calibration.

As previously highlighted in Section 5.1.3, model validation against historic rates of cliff toe retreat cannot be undertaken as this is fixed by the calibration process with material resistance. Table 7-1 provides a comparison of the average vertical Root Mean Square Errors (RMSEs) of the modelled offshore profiles against measured data for both the original and refined model, repeating the process previously described in Section 5.1.3. The RMSEs of the shore profile have not been considered based on the negligible difference in modelled outputs demonstrated by Figure 7-2. The table demonstrates a reduction in vertical RMSEs at each site with application of the refined model (with the exception of Chale Bay). However, Figure 7-3 shows that, while the angles of the more resistant ledge features have been replicated, it has not always been possible to match this with their seaward projection. For example, at Brighstone Bay the modelled layer extends approximately 400 m further seaward than that measured. This is attributed to the limited consideration of variable layers within this study, limited to a maximum of two layers of increased resistance. This was selected to keep model simulations simple as it was recognised that with greater numbers and variations of layers, the greater the potential for errors introduced and the more difficulty in relating results back to field data. These limitations and the accuracy of these results in terms of comparisons to field data will be discussed in the model evaluation (Section 7.3). Despite this limitation, the refined models enable consideration of the effect of variable layers and associated changes in shore platform geomorphology for an actual site.

Table 7-1: Summary of root mean square errors for original homogenous versus refined heterogeneous model considering validation with measured offshore profile vertical elevation

Site	RMSE Original Model (m)	RMSE Refined Model (m)
Compton Bay	1.81	1.14
Hanover Point	3.84	3.67
Brook Bay	0.56	0.43
Sudmoor point	2.15	1.17
Brighstone Bay	1.95	1.68
Atherfield Point	3.20	1.12
Chale Bay	1.75	2.4
Average	2.22	1.65

7.1.2 Refined model recalibration

Figure 7-5 shows the non-dimensional cliff toe retreat rate expressed as a proportion of that calculated using the homogenous cliff models for each site. The results demonstrate how sea-level interacts with the layers of increased resistance, resulting in reduced rates of retreat. For example, Brook Bay has a single more resistant layer situated at -2 to -4 m OD (present day). With a historic rate of sea-level rise of 1.4 mm/yr, mean sea level (MSL) is aligned with the resistant layer at approximately year 7,000 of the simulation and is inundated by approximately year 8,500. Over this period the recession rate declines in comparison with that of the original homogenous cliff. On submersion of the layer the retreat rate begins to stabilise to a new equilibrium rate but does not return to that of the original homogenous cliff (which was initially calibrated against the measured historic rate of recession, Section 5.1.2), owing to the effects of the ledge feature on wave attenuation.

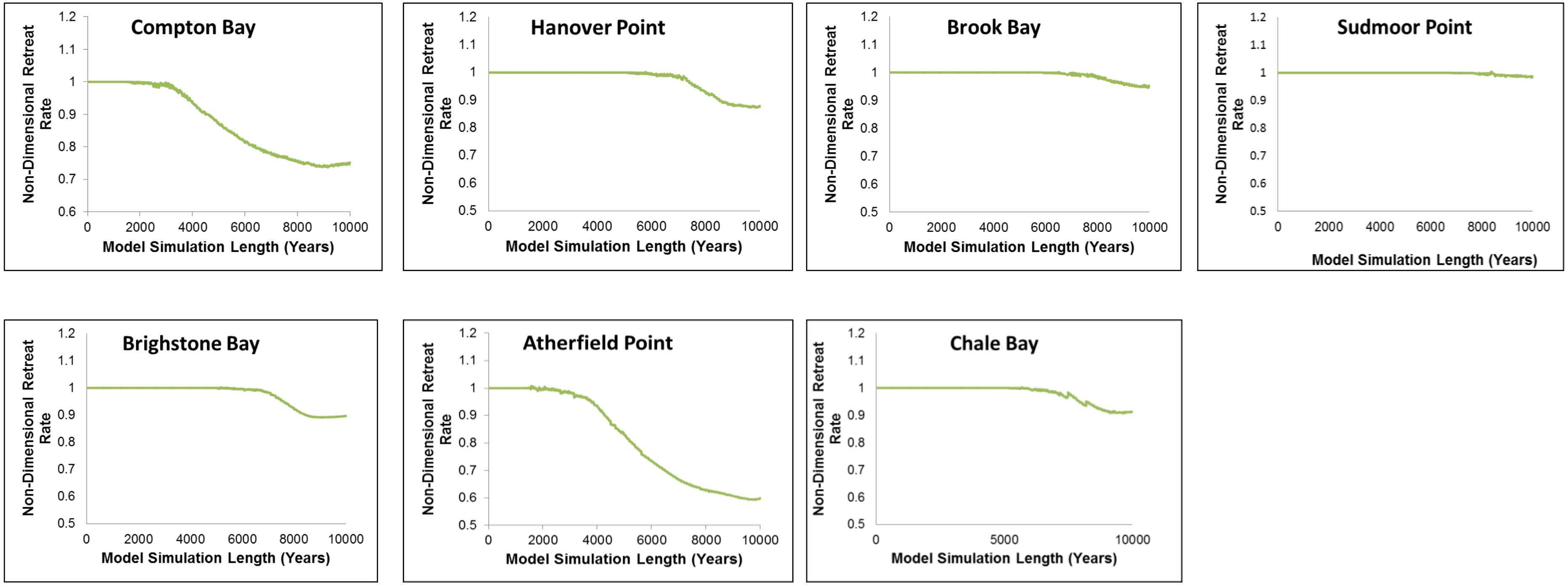


Figure 7-5: Cliff toe retreat rates as a proportion of that for the original homogenous cliff

The results highlight the importance of considering the effect of variable lithology on rates of cliff toe retreat. This is particularly important for sites exhibiting multiple resistant layers (i.e. Compton Bay and Atherfield Point), where a dramatic decline in the non-dimensional retreat rate in comparison with that of the homogenous cliff is calculated. The results also indicate a need to recalibrate the models against measured historic rates of retreat before future predictions can be considered. As it is the changes in relative resistance that induce changes in profile slope, the profiles have been recalibrated as a whole. For example, at Brook Bay:

- Section 5.1.2 determined a homogenous material resistance of 26×10^6 $m^{9/4} s^{3/2}$ to yield a historic rate of retreat of 0.52 m/yr (Table 5-3).
- In Section 7.1 a 3x more resistant layer (78×10^6 $m^{9/4} s^{3/2}$) at -2 to -4 m OD was introduced to create a heterogeneous cliff profile (Figure 7-3). However, this altered the retreat rate to 0.49 m/yr (Figure 7-5).
- Considering that it is relative changes in resistance (in comparison to the remainder of the cliff) that induce variations in profile slope, a 3x more resistant layer was maintained. However, the material resistance parameters were adjusted to 23.75×10^6 $m^{9/4} s^{3/2}$ for the majority of the cliff and 71.25×10^6 $m^{9/4} s^{3/2}$ for the anomalous layer; returning the retreat rate back to that originally measured at the site.

Table 7-2 provides a summary of the recalibration. The final output profiles and associated material resistance parameters will be used as input conditions to consider the future impacts of climatic and environmental change in the following section.

Table 7-2: Summary of model recalibration process

Profile	Measured Historic Rate of Retreat (m/yr)	Original, Homogenous Material Resistance ($m^{9/4} s^{3/2}$)	Refined, Heterogeneous Material resistance[23] ($m^{9/4} s^{3/2}$)	Adjusted Rate of Retreat (m/yr)
Compton Bay	0.49	30 $x10^6$	• $30x10^6$ • $20x10^6$ • $15x10^6$ • $14x10^6$	• 0.37 • 0.42 • 0.48 • 0.49
Hanover Point	0.71	14 $x10^6$	• $14x10^6$ • $11x10^6$ • $10.5x10^6$	• 0.68 • 0.70 • 0.71
Brook Bay	0.52	26 $x10^6$	• $26x10^6$ • $24x10^6$ • $23x10^6$ • $23.75x10^6$	• 0.49 • 0.51 • 0.53 • 0.52

[23] Note: used to determine the relative strength of anomalous layers

Profile	**Measured Historic Rate of Retreat (m/yr)**	**Original, Homogenous Material Resistance ($m^{9/4}\ s^{3/2}$)**	**Refined, Heterogeneous Material resistance[23] ($m^{9/4}\ s^{3/2}$)**	**Adjusted Rate of Retreat (m/yr)**
Sudmoor Point	0.41	45 x10^6	• 45x10^6 • 32x10^6 • 35x10^6 • 42x10^6 • 44x10^6	• 0.37 • 0.48 • 0.46 • 0.43 • 0.41
Brighstone Bay	0.68	16 x10^6	• 16x10^6 • 12x10^6 • 13.5 x10^6 • 12.75 x10^6	• 0.60 • 0.70 • 0.66 • 0.68
Atherfield Point	0.76	11.5 x10^6	• 11.5 x10^6 • 4 x10^6 • 3.5 x10^6 • 3.25 x10^6	• 0.45 • 0.69 • 0.74 • 0.76
Chale Bay	0.43	40 x10^6	• 40 x10^6 • 37 x10^6 • 34 x10^6 • 33 x10^6	• 0.39 • 0.41 • 0.42 • 0.43

7.2 Assessing the future impacts of environmental and climatic change

As stated in Chapter 1, there is a need to further understand the future impacts of environmental and climatic change to inform a range of coastal management practices. Considering the original development of the SCAPE model as a coastal engineering prediction tool, this section applies the refined study frontage models to a range of scenarios.

7.2.1 Model set-up and scenarios tested

The values of material resistance and associated final output profiles determined in Section 7.1 are used as model inputs, which correspond to the shore profile morphology and in-situ conditions in year 2008 (as the models were calibrated and validated against data for this year). The prevailing conditions for the study frontage described in Chapter 5 (Table 5-1 and Table 5-2) have remained the same with the exception of those modified to describe future climatic scenarios, as described below.

As SCAPE is a mesoscale prediction tool, this section focusses on predictions over the next 100 years. This is consistent with the UK's Shoreline Management Plans (SMPs). Predictions made with the refined model are compared to those presented in the second generation of the Isle of Wight SMP (Isle of Wight Council et al., 2010a) to inform future land-use planning for the study frontage.

Table 7-3 outlines the climatic/environmental scenarios tested and the associated parameter values. To further describe each scenario:

- **Scenario A** considers the rates of sea-level rise used within the current Isle of Wight SMP. The rates are in accordance with the national government guidance issued by Defra (2006) for south east England, describing an exponential increase in sea-levels over future epochs. This replaces the previous guidance of a linear allowance of 6.0 mm/yr.
- **Scenario B** uses the above sea-level rise projections combined with a 10% increase in the wave climate described in Table 5-1. Despite some

speculation that the wave climate of the northern hemisphere may decrease (Hemer et al., 2013), the potential impacts of an increased wave climate have been included bearing in mind the interaction between wave activity with sea-level rise (Brooks and Spencer, 2012, Walkden and Hall, 2005). This scenario was not considered by the SMP but provides an opportunity to consider a 'worst case' estimate.

- **Scenario C** considers the climate projections used in A1 combined with a potential change in material resistance up the cliff face at each of the sites. In view of the difficulty in confidently prescribing an accurate material resistance value up the cliff face, which is outside of the model calibration, a 50% reduction in material resistance of the upper cliff face value has been applied at each site. This scenario may represent cases along the study frontage where either:
    - More coherent channel sandstones are eroded away;
    - Weaker formations not yet exposed in the cliff face outcrop as the cliff erodes landwards owing to the laterally discontinuous and complex nature of the cliffs.

Table 7-3: Summary of climate change scenarios considered for the study frontage

Climate Scenario	Description	Rate of Sea Level Rise for each Epoch (mm/yr)				Increase in Wave climate (%)	Changes in Cliff Lithology (%)
		2009-2025	2025-2055	2055-2085	2085-2105		
A	Defra (2006) sea-level rise projections	4.0	8.5	12.0	15.0	No change	No change
B	Defra (2006) sea-level rise projections and increased wave climate	4.0	8.5	12.0	15.0	10	No change
C	Defra (2006) sea-level rise projections combined with a reduction in material resistance up the cliff face	4.0	8.5	12.0	15.0	No change	50% reduction in cliff face resistance

7.2.2 Potential study frontage futures

This section presents the refined model predictions for each site under each scenario. The results are compared considering:

- The SMP methodology versus application of the refined SCAPE model;
- The effect of increased wave height;
- The effect of weaker exposed lithology.

Table 7-4 summarises the total erosion predicted at each site, under each climate scenario, compared with the Shoreline Management Plan. Appendix C provides more detailed tables for each site outlining the retreat rate for each epoch.

Table 7-4: Comparison of SMP and refined SCAPE model retreat predictions for a range of climate change scenarios

	Scenario	**Location**						
		Compton Bay	**Hanover Point**	**Brook Bay**	**Sudmoor Point**	**Brighstone Bay**	**Atherfield Point**	**Chale Bay**
SMP Predicted Total Erosion (m)	**A**	80	80	80	80	80	120	120
Refined SCAPE Model Predicted Total Erosion (m)	**A**	83	96	62	49	97	143	53
	B	95	107	69	56	110	174	56
	C	111	132	82	70	130	243	67

7.2.2.1 Comparison of prediction methods

The refined SCAPE model results can first be compared against those presented for the study frontage in the IoW SMP, which used the same sea-level rise scenarios as modelled with Scenario A (Defra, 2006). However, the SMP applied the Walkden and Dickson (2008) formula (as described in Section 4.1.4) based on its applicability for soft rock shores with low fronting beach volumes. Also, the SMP extrapolated two generalised predictions across the study frontage based on its division into two units; Compton Bay to Brighstone and Atherfield to Chale). In contrast, this study has considered representative sections for each of the frontage headlands and bays. Figure 7-6 compares the total retreat predicted by each method. As would be expected, application of the refined SCAPE model at a greater number of sites yields greater variability in total recession across the frontage. This is important considering the historic variability in retreat rates across the study frontage, as demonstrated by Stuiver (2010).

Overall, the refined model predicts higher rates of retreat at four of the seven sites (Compton Bay, Hanover Point, Brighstone Bay and Atherfield Point). The SCAPE model predicts significantly lower total retreat at Sudmoor Point and Chale Bay than that predicted in the SMP. The lower retreat at Sudmoor Point is acceptable given the historic rate of retreat determined at this profile (obtained from the results of Stuiver, 2010 as described in Section 5.1.2.1), which is associated with the presence of the more resistant Sudmoor Point Sandstone along this section of the frontage. However, the lower retreat predicted at Chale Bay is believed to be an anomalous result arising from model set-up as will be further discussed in Section 0.

Ignoring the result for Chale Bay, the refined model predicts an average overall increase in cliff retreat of 16% in comparison to the SMP results applying the Walkden and Dickson (2008) formula. Comparisons of the total retreat distance from the two methods also show an average standard deviation of 17.7 m across all predictions, as further outlined by Figure 7-6.

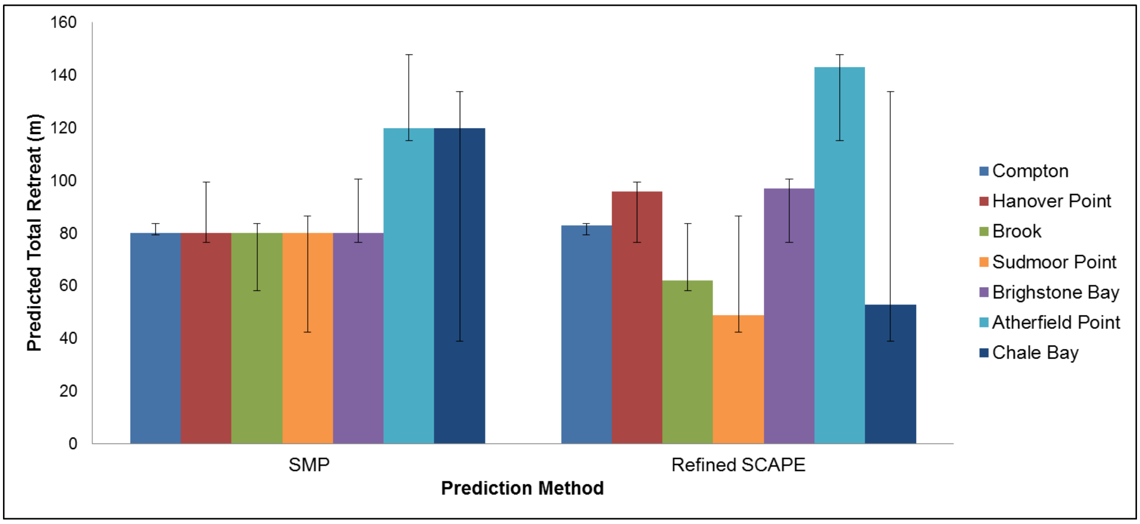


Figure 7-6: Comparison of SMP versus refined SCAPE model total predicted retreat across the study frontage and associated standard deviations

7.2.2.2 Effect of increased wave climate

Scenario B considered the combined effect of sea-level rise with a 10% increase in wave climate. Figure 7-7 compares the variation in total predicted retreat by the refined model under this scenario in comparison to only sea-level rise (scenario A). The results yield a 12% increase in retreat with a standard deviation of 8m and show how an increase in wave energy can also have an important effect on rates of cliff retreat. As demonstrated in Section 5.2 this is particularly important for low sediment coasts where fronting beaches provide limited protection to the cliff toe from basal marine erosion.

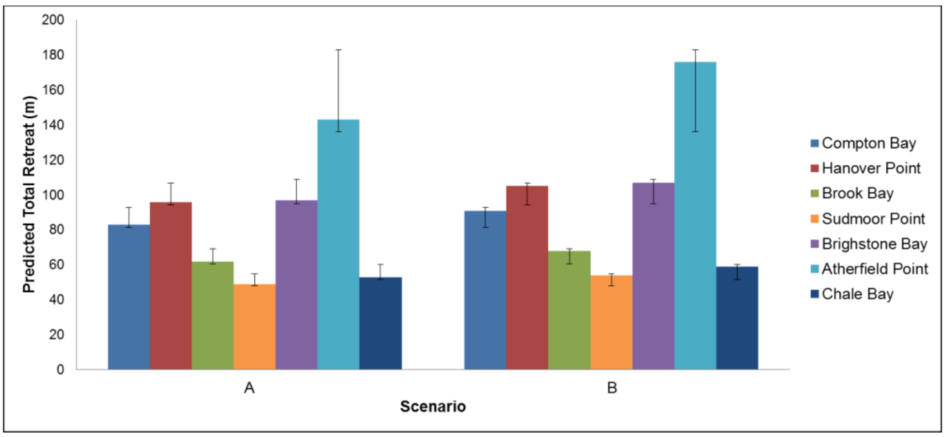


Figure 7-7: Comparison of scenario A Versus scenario B total predicted retreat across the study frontage and associated standard deviations

7.2.2.3 Effect of weaker exposed lithology

To understand the potential impacts of marine processes interacting with exposed, weaker layers of lithology, Scenario C has considered the effect of a 50% reduction in cliff face material resistance with sea-level rise Scenario A. Figure 7-8 shows the results in comparison with scenario A (sea-level rise only with no change in overlying material resistance). The results show an average 40% increase in the total retreat distance (average standard deviation 25m). While this is a hypothetical scenario, it demonstrates the significant impact that weaker exposures would have on rates of retreat. Bearing in mind the variable lithology of the study frontage and its laterally discontinuous nature, such a scenario is feasible and likely to occur with future sea-level rise and erosion processes.

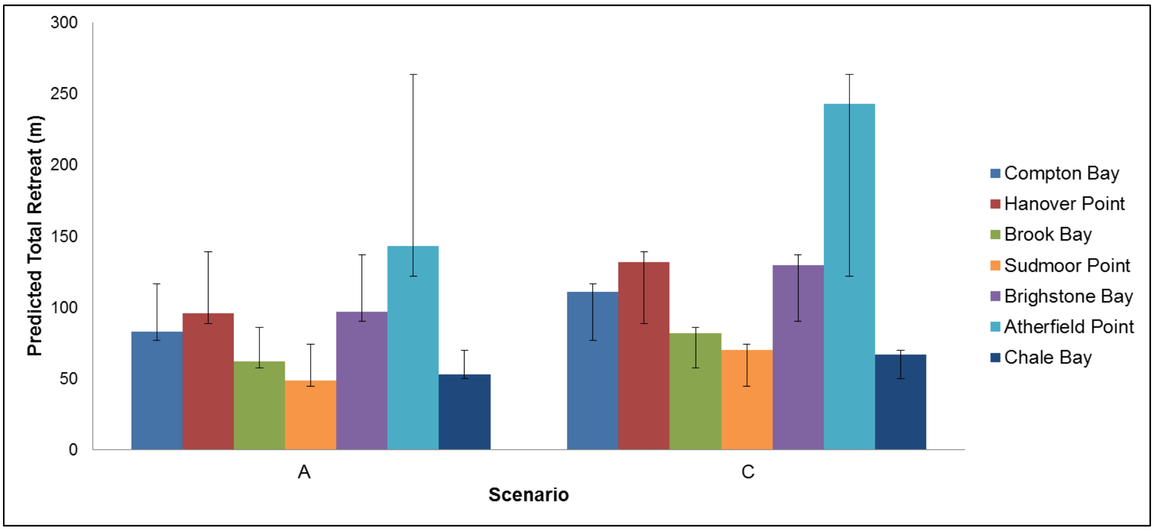


Figure 7-8: Comparison of scenario A versus scenario C total predicted retreat across the study frontage and associated standard deviations

The results highlight the importance of exercising caution when applying historic rates of retreat to frontages of variable lithology as past conditions may not remain representative of the future, particularly as a result of interactions with sea-level rise.

7.3 Discussion of refined model results for study frontage

This chapter has applied the refined model of variable resistance to the study frontage. The remainder of this chapter discusses the model set-up in comparison with field observations, the geomorphic and coastal management implications of the results, the limitations of the model and areas for further improvement.

7.3.1.1 Comparison of modelled versus measured shore profiles

Section 7.1 outlined a method to determine the location and relative resistance of variable layers based on measured bathymetric data and historic rates of retreat. Prescription of variable resistance in the vertical resulted in improved representation of the shore platform in comparison with the application of the original homogenous model (as demonstrated through root mean square errors with measured data in each case).

This improved fit could not simply be achieved through input of measured shore profiles as, with homogenous material resistance, the profile would always tend to smooth over time. Furthermore, the impacts of variable resistance on rates of cliff toe retreat with sea-level rise interactions can only be determined with the refined model. This was highlighted through the non-dimensional retreat rates in proportion to that of the original homogenous cliffs.

Despite the improved capabilities of the refined model Figure 7-3 showed that, while the angles of the more resistant ledge features have been replicated, it has not always been possible to accurately match this with their measured seaward extent. This can be attributed to the limited consideration of a maximum of two relatively *more* resistant layers within each 2D profile, while the remainder of the cliff (above and below the resistant layer(s)) has been kept at the same resistance value. Given the geological mapping of the study frontage (Figure 5-5:), there is potential for more complex combinations of variable material resistance at each site, including the presence of relatively less resistant layers. However, for the purpose of this study, simulations have been limited to the inclusion of relatively more resistant layers which can be more confidently identified in the bathymetric data and simulated through the calibration process (based on the output with shore profile slope). Furthermore, this limited breakdown of the cliff profile aids comparisons with field data.

7.3.1.2 Comparison of modelled versus measured material resistance

Earlier simulations using the original, homogenous SCAPE Model (Chapter 5) demonstrated a qualitative link between the calibrated material resistance parameters and field data. Table 7-5 compares the refined resistance parameters with field observations, distinguishing between the cliff and shore platform lithology. It is therefore possible to determine whether the link between modelled and measured material resistance is maintained, which is important considering the application of SCAPE as a coastal engineering tool.

Taking an example from Hanover Point; the cliff face is predominantly composed of variegated Marl. On the coherence scale of Soares (1993), this material was rated as being of low coherence (5 to 10MPa). The associated material resistance parameter used in the refined model to reflect this was 10.5×10^{6} $m^{9/4}$ $s^{3/2}$. In contrast, the shore platform at Hanover Point is composed of channel sandstone with high coherence (>20MPa) and the modelled material resistance parameter was 210×10^{6} $m^{9/4}$ $s^{3/2}$. This demonstrates that the qualitative relationship between field observations of coherence and material resistance is maintained (as previously determined in Section 5.1.4).

One exception to this trend is the 20x more resistant layer (in comparison to the remainder of the cliff) modelled at Chale Bay. A material resistance value of 660×10^{6} $m^{9/4}$ $s^{3/2}$ was prescribed in an attempt to replicate measured data for this location. However, this value was significantly higher than those used at the other sites along the study frontage (maximum material resistance of 210×10^{6} $m^{9/4}$ $s^{3/2}$) and is believed to have caused unrealistically low rates of retreat at this location. The refined model set-up at this location appears is insufficient to accurately represent this section of the coastline. The model requires further refinement with inclusion of an additional layer of overlying weaker material and lower contrasts in relative resistance.

Table 7-5: Comparison of cliff face and shore platform material resistance (measured versus modelled) along the study frontage

Location	Cliff Face Characteristics			Shore Platform Characteristics		
	Lithology	**Measured Coherence (Coherent (1) to non-coherent (4))**	**Modelled Material Resistance ($m^{9/4} s^{3/2}$)**	**Lithology**	**Measured Coherence (Coherent (1) to non-coherent (4))**	**Modelled Material Resistance of anomalous Layer(s) ($m^{9/4} s^{3/2}$)**
Compton Bay	Variegated Wessex Marl interbedded with Compton Bay Sandstone	3	14×10^6	Channel Sandstone and interbedded Marl	1 to 2	70×10^6 and 105×10^6
Hanover Point	Variegated Wessex Marl interbedded with Compton Bay Sandstone	3	10.5×10^6	Channel Sandstone and partially interbedded Marl	1	210×10^6
Brook Bay	Variegated Wessex	2	23.75×10^6	Marl	1 to 2	71.25×10^6

Location	Cliff Face Characteristics			Shore Platform Characteristics		
	Lithology	**Measured Coherence (Coherent (1) to non-coherent (4))**	**Modelled Material Resistance ($m^{9/4} s^{3/2}$)**	**Lithology**	**Measured Coherence (Coherent (1) to non-coherent (4))**	**Modelled Material Resistance of anomalous Layer(s) ($m^{9/4} s^{3/2}$)**
	Marl					
Sudmoor Point	Variegated Wessex Marl interbedded with Sudmoor Point Sandstone	2	44×10^6	Sudmoor Point Sandstone and Marl	1 to 2	180×10^6
Brighstone Bay	Wessex Marl and interbedded Sandstone	2	12.75×10^6	Marl	2	127.5×10^6
Atherfield Point	Atherfield Clay	3 to 4	3.25×10^6	Perna Beds	1 to 2	65×10^6 and 195×10^6

Location	**Cliff Face Characteristics**			**Shore Platform Characteristics**		
	Lithology	**Measured Coherence (Coherent (1) to non-coherent (4))**	**Modelled Material Resistance ($m^{9/4} s^{3/2}$)**	**Lithology**	**Measured Coherence (Coherent (1) to non-coherent (4))**	**Modelled Material Resistance of anomalous Layer(s) ($m^{9/4} s^{3/2}$)**
Chale Bay	Atherfield Clay, sandstone beds and ferruginous sands	3	33×10^6	Sandstone Beds	1	660×10^6

Overall, the difficulty in making quantitative links between modelled and measured variations in material resistance can be recognised, owing to the hybrid nature of the SCAPE material resistance term (as previously highlighted in Section 5.1.2.1). In particular, confidently determining changes in material resistance up the cliff face is a challenge (as material resistance cannot be calibrated against changes in shore profile slope in this instance). This issue could be overcome in later refinements to the SCAPE model through making the material resistance parameter independent of calibration. Material resistance could be based on the UCS (Uniaxial Compressive Strength, KPa) of the rock mass along with a separate calibration parameter used to represent the other hydrodynamic constants ($m^{13/4}s^{7/2}$/kg). The advantages of this approach were recently demonstrated by Castedo (2012) for a range of sites along the Holderness coast, UK.

7.3.2 Geomorphic understanding of the study frontage and future evolution

The IoW Study frontage consists of a series of bays intersected by three discrete headlands. The location of the headlands is controlled by the presence of more resistant layers within the intertidal zone, which experience reduced rates of erosion, leading to the formation of ledge features that act to attenuate wave energy as argued by Stuiver (2013). This is supported by the application of the refined model in this study, within which the representative headland profiles typically express the highest material resistance values within the anomalous layers (as summarised in Table 7-5 with the exception of Chale Bay).

The refined model results can also provide insight into the future evolution of the coastline. In particular, is there evidence for headland/bay growth/decline over time? Figure 7-9 compares total retreat distances along the study frontage by 2105 for the range of climatic and environmental change scenarios tested. The results demonstrate that the coastline has not yet reached a steady state, with variations in total retreat clearly identifiable along the frontage. In view of the low fronting beach volumes, this variation is governed by changes in material resistance in both the vertical and longshore directions. The results are supported by the geological mapping of Stuiver (2013) in Figure 5-5: , the findings of Chapter 5 for low sediment (Mode A) coastlines and the refined model set-up (Section 7.1).

The headland at Sudmoor Point appears to be 'growing', as indicated by the lower modelled rates of retreat in comparison with the adjacent bays of Brook and Brighstone. The headlands of Hanover Point and Atherfield Point appear to be declining in comparison to adjacent bays. This implies that the headlands may become transient features of the landscape over time and that (supporting the results of Chapter 6) it is the elevation of these more resistant layers in comparison with the remainder of the frontage that has influenced their formation. However, taking into consideration the variable dip and strike of variable layers along the study frontage, it is plausible that following interaction with and inundation by rising sea-levels the location of headlands may vary in the longshore direction over geomorphic timescales.

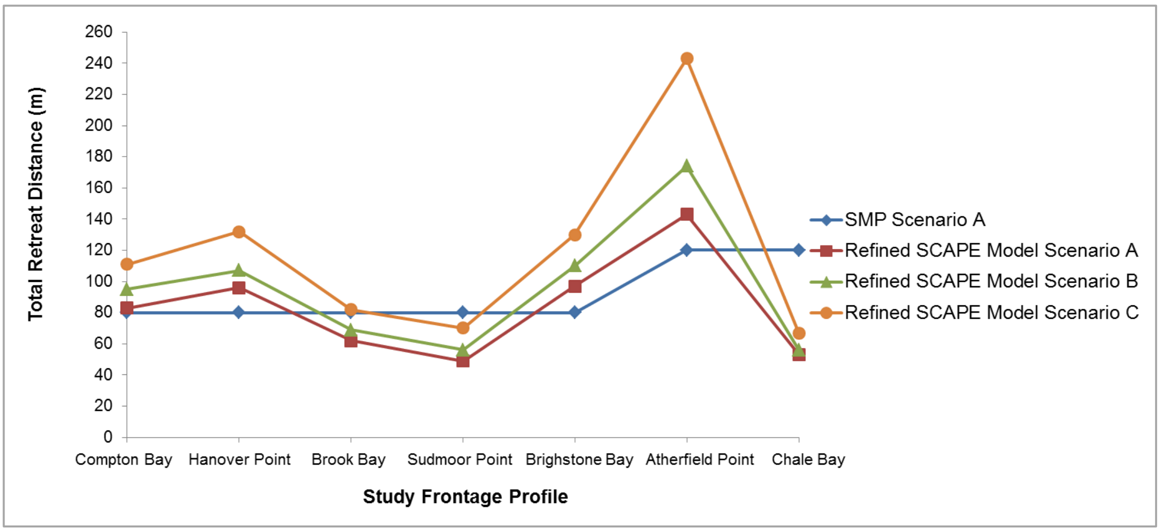


Figure 7-9: Comparison of total retreat along the study frontage

The results highlight the important potential variability in future rates of retreat for sites of variable lithology as a result of changing in-situ and climatic conditions. However, one key limitation of the application of the refined SCAPE model to the study frontage must be noted; the set-up of the 2D models involves calibration with known historic rates of retreat. These rates are, to a degree, locked into the future predictions and highlight the importance of an accurate understanding of past rates in making predictions. Further discussion of the future evolution of the study frontage is provided in Appendix C which includes a discussion of the implications of the results for coastal management.

7.3.3 Study Limitations

This chapter has described the application of the refined model to the study frontage to; a) further confirm the trends for layers of variable material strength in the vertical identified in Chapter 6; and, b) apply the refined model as a coastal engineering tool. The remainder of this section discusses the study limitations which have not yet been addressed above.

7.3.3.1 Scenarios tested

Section 7.2 applied the refined study frontage models to understand the future impacts of environmental and climatic change on the cliff system and utilise the refined model as a prediction tool. A range of scenarios were tested. Scenario A modelled the sea-level rise projections of Defra (2006), which were also used within the IoW SMP with the Walkden and Dickson (2008) formula. It can be noted that this sea-level rise projection exceeds more recent projections such as those of the UK Climate Projections, UKCP (2009) as summarised in Table 7-6, which yields an average rate of 3.9 mm/yr and 5.6 mm/yr under the low and high emissions scenarios, respectively. Therefore, the results presented with the refined SCAPE model can be recognised as highly conservative, presenting a ‘worst case’ prediction. However, for the purpose of this study, no additional sea-level rise scenarios were applied as Scenario A enabled direct comparisons with the IoW SMPs predictions. Furthermore, the revised Intergovernmental Panel on Climate Change (IPCC) projections due for publication 2013/2014 were not yet available. Overall, the results highlighted the variability that arises through application of different prediction methods, which will be further exacerbated depending on the climate change scenario used.

Table 7-6: Mean sea-level estimates for London (cm) with respect to 1990 levels (UKCP, 2009)

Year	Emissions Scenario		
	High	Medium	Low
2000	3.5	3	2.5
2010	7.3	6.2	5.3
2020	11.5	9.7	8.2
2030	16	13.5	11.4
2040	20.8	17.5	14.8
2050	25.8	21.8	18.4
2060	31.4	26.3	22.2
2070	37.2	31.2	26.3
2080	43.3	36.3	30.5
2090	49.7	41.6	35
2095	53.1	44.4	37.3

Scenario B combined sea-level rise Scenario A with a 10% increase in wave height. The increase was applied across all wave height data exclusively; no changes to wave period were made. As noted by Dickson et al (2007) this approach may result in an unrealistic step change in retreat rates. This could be refined in future studies by applying a linear increase over time. However, for the purpose of these demonstrative comparisons the method applied was considered sufficient.

Scenario C considered the potential for weaker outcropping lithologies to be exposed within the cliff face with sea-level rise. Owing to the issues related to confidently prescribing varying material resistance up the cliff face, a 50% reduction in resistance from that of the cliff face was applied at each site. As previously discussed, more accurate descriptions of variable lithology would require separation of the material resistance parameter from calibration and UCS testing of the range of geological formations along the study frontage. No data is currently available for the latter.

As highlighted in Chapter 2, a further range of climatic and environmental factors may influence the cliff recession process. For example seasonal changes in precipitation will influence slope stability and may result in changes in the magnitude and frequency of mass movement events. However, such factors were not modelled in this study owing to the focus on cliff toe processes and the limited role of the cliff top within the SCAPE model.

7.3.3.2 Study frontage representation

Section 7.3 has discussed the future evolution of the study frontage. The variations in retreat rates indicated that two out of the three headlands appear to be in decline. However, only one representative profile of each site was modelled and caution must be exercised when extrapolating results across the entire headland/bay in question.

The refined SCAPE model only considers variations in material resistance as horizontal layers. However, Stuiver (2013) has highlighted variations in the dip/strike of lithological layers along the study frontage. Such changes will influence the location of more resistant layers across each headland/bay which will in turn result in varying interactions with mean sea level. This may ultimately result in subtle longshore movement of headlands across the study frontage as sea level rises, as demonstrated in Figure 7-10. However, to accurately model this situation more detailed geological mapping of the study frontage is required combined with application of a modified quasi-3D model to consider how variations in lithology in both the vertical and longshore directions may influence coastal planshape over time.

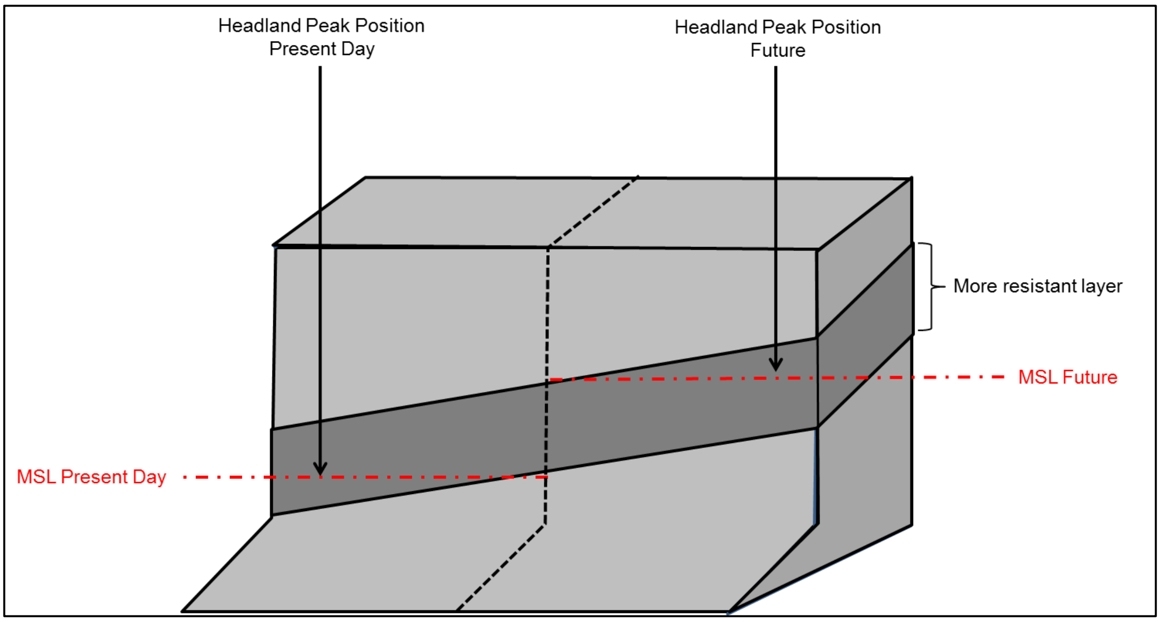


Figure 7-10: Diagram outlining the potential for headland location to shift over time due to interactions between a layer of increased resistance and sea-level rise

7.4 Refined soft cliff model application and assessment Part 2: closing comments

This chapter has applied the refined SCAPE model to seven sites along a study frontage of variable lithology to validate it against measured data. Validation (Section 7.1) supports the trends identified in Chapter 6 that more resistant layers can form emergent ledge features within the shore platform which can be identified from measured bathymetry data.

Following recalibration (Section 7.1.2) the refined models were applied to understand the effects of a series of climatic and environmental change scenarios. The key conclusions of the results are:

- Application of the refined SCAPE model at a greater number of sites than considered within the SMP has demonstrated the heterogeneous nature of the frontage and how extrapolation of results in the longshore may lead to over/under prediction of retreat.
- The refined SCAPE model shows the potential for an average 16% increase in total rates of retreat at 4 out of 7 of the sites modelled. This

demonstrates the advantages of process-based models which, in this case, can consider how the inundation of more resistant layers by sea-level rise and shore platform lowering can affect rates of cliff toe retreat.

- There is significant variability in the results depending on the climatic and environmental scenario modelled. This emphasises the need to reduce uncertainty in future climate change projections and to further understand in-situ cliff conditions.
- There is a potential for headland and embayment migration resulting from the variations in lithology in both the longshore and vertical combined with sea-level rise interactions over geomorphic timescales.

In summary, this chapter has demonstrated a practical application of the refined SCAPE model to a site exhibiting both vertical and longshore variations in material resistance.

8. Conclusions and Further Research

This Chapter provides a synthesis of the key findings of the thesis and presents the conclusions and knowledge contributions in relation to the aims and objectives originally presented in Chapter 1. Recommendations for further research are provided at the end of the chapter.

8.1 Conclusions and knowledge contributions

The overriding aim of this research was; *to develop an improved, more integrated model of the soft cliff system to enhance our understanding of the effects of changing environmental and climatic factors*. It was envisaged that the development of such a model could provide further insight into the recession process and ultimately be used as a refined prediction tool.

To achieve this aim, the first objective was; *to take a systems view of the coastal cliff system.* Chapter 2 subsequently identified a broad range of sub-systems influencing the cliff system; geotechnical, geological and hydrogeological, sub-aerial, coastal and marine, meteorological and climatic and human. Considering the complex interactions and feedback mechanisms identified between the number of parameters and processes within each sub-system, the findings were synthesised in a systems based model (Figure 2-9) to provide a generalised, holistic understanding of the cliff system. To further simplify the model, a key 'pathway' between the coastal and terrestrial portions of the model was identified. As a result, material resistance was recognised as a key parameter, present within both the cliff face and shore platform with a key interface formed at the cliff toe.

The conclusion that cliff toe processes are an important control on meso-scale predictions of cliff erosion support previous findings. For example, kamphuis (1987) concluded that '...the controlling factor for actively eroding bluffs is related primarily to the foreshore erosion rate which in turn controls the recession of the cliff toe' based on the results of a study of cohesive bluff erosion rates. Similarly, Walkden and Hall (2005) assumed that the long term rate of recession of the cliff top is primarily dictated by that of the cliff toe based on the observation that a far higher proportion of incident wave energy is expended on the shore platform as opposed to the cliff face as demonstrated by Stephenson and Kirk (2000).

Considering the application of this research to the south west coast of the Isle of Wight (IoW), further justification for the focus on cliff toe processes can be provided. As recognised in Chapter 3, the study frontage is composed of a diverse geomorphology and a range of Cliff Behavioural Units (CBUs). However, it can be recognised that the frontage remains relatively linear with the exception of the three discrete headlands. These features have been correlated to the presence of more resistant layers within the shore platform within this thesis and Stuiver (2013), implying that mass movement processes are not a significant driver in the mesoscale.

The second objective of this thesis was; *to assess the limitations of existing cliff recession models*. A detailed evaluation of the range of existing cliff recession methods (extrapolation from historic data, structured use of expert judgement, empirical prediction methods, probabilistic simulation modelling and process-response simulation modelling) was carried out in Chapter 4. The merits of process-based modelling were recognised, primarily based on the methods ability to simulate a range of parameter and process interactions and changing conditions; both demonstrated as important elements through the systems based model and the review of cliff recession factors provided in Chapter 2.

Based on a review of available process-based models, SCAPE was selected for further application, evaluation and potential refinement within this study. Selection of an existing model as opposed to development of an entirely new model was chosen to avoid repetition with existing studies which have provided a well-documented foundation of geomorphic understanding (e.g. Kamphuis, 1987, Meadowcroft et al (1999), Walkden and Hall (2005), Valvo et al (2006), Trenhaile (2009, 2010) and Castedo et al (2012, 2013). Therefore, application of an existing model aimed to encourage further model development which was further facilitated by application to the study frontage of the IoW. The latter presented a more complex frontage than those previously modelled, for example the Naze, Essex and north Norfolk which are predominantly smooth coastal frontages composed of homogenous lithology and simple CBUs.

Application of the 2D model to the series of headlands and bays across the study frontage in Chapter 5 outlined the model set-up and calibration process with historic rates of cliff retreat. Model validation considering average vertical Root Mean Square Errors (RMSEs) through comparisons with corresponding measured shore profile data demonstrated a good match. Correlations were also made between the modelled calibration parameter and field observations of coherence (Figure 5-4), which could serve as a useful chart for future application of the model across the study frontage. However, model validation considering the average vertical RMSEs for the area further offshore, below MLWS recognised the importance of vertical variations in material resistance. This factor could not be quantitatively assessed with the original SCAPE model owing to its limited consideration of a single value of material resistance to characterise the entire cliff face, as presented in Carpenter et al (2012).

The significance of the material resistance parameter, particularly for low sediment coasts, as a control on cliff recession rates and coastal planshape evolution was further emphasised through sensitivity testing of quasi-3D model. The concepts of contrasting modes of shoreline behaviour (Mode A – rock strength limited erosion; and Mode B – transport limited erosion), originally introduced by Walkden and Hall (2011) were expanded on. The results provided a quantitative understanding of the role of material resistance and the supply of beach grade material from the eroding cliff on controlling the potential for the development and maintenance of protective fronting beach volumes; thus dictating the mode of shoreline response. Overall, when protective fronting beach volumes cannot be maintained, cliff retreat is primarily dictated by changes in the foreshore slopes as a result of the resistive strength of the cliff (Mode A). The feedbacks between these contrasting modes of shoreline behaviour were illustrated by Figure 5-13 and Carpenter et al (In Review) and used to provide an explanation for the process of headland and embayment persistence or decline with longshore variations in cliff lithology. This emerging concept is supported by recent research by Young et al (Young et al., 2014) and Limber and Murray (In Review-ab).

Based on these findings, objective three of this research was to; *improve the capability of the existing cliff recession model*. Considering the recognised importance of low sediment coastlines, the 2D model was refined to explore interactions between vertical changes in material resistance and prevailing coastal conditions, omitting longshore interactions by considering material resistance as a variable. While initial sensitivity testing of the key input parameters of the 2D SCAPE model (Figure 4-28) also highlighted wave height as an important prevailing condition (Figure 4-28), focus on the impacts of material resistance was maintained considering the variable lithology of the IoW study frontage.

The refined model was applied to address the final objective of this thesis; *to understand how the impacts of environmental and climatic change will influence shore profile geomorphology and rates of cliff toe retreat*. In response, the refined model was initially applied to idealised cliffs in Chapter 6 to quantitatively explore the impacts of vertical variations in material strength. The results demonstrated the importance of understanding stratification of the shore platform and cliff face and interactions with sea-level rise over time. The outcropping of variable layers about MSL was found to be a key control on cliff toe recession rates owing to the integrated erosive potential of the tide, wave action and the influence of the parameter on the equilibrium profile slope. Layers of increased material strength were found to induce steeper shore profile slopes and reduce rates of cliff toe retreat whilst weaker layers were found to induce shallower slopes and increased cliff recession. This relationship is supported by a range of previous field and modelling studies including; Trenhaile (2000, 2002), Walkden and Hall (2005), Moore et al (2009).

This highlights a need to understand changes in material resistance in the vertical and interactions with the rate of sea-level rise over time. In particular it is important to understand the relative resistance/weakness of the anomalous layer, its thickness and the rate of sea-level rise to understand the magnitude of erosion and duration of exposure. This concept is similarly supported by Stephenson and Naylor (2011) who found that erosion susceptibility was dependent on which geological layer was at the surface, as different layers provided variations in resistance, in their study of a limestone shore platform in Wales, UK. Chapter six also demonstrated how weaker layers can result in an asymmetric decrease in the equilibrium slope and hence increase the rate of cliff toe retreat over a much shorter timeframe to that of a more resistant layer of the same magnitude, thickness and location. The varying timeframes revealed different magnitudes of feedback between the two layers.

Finally, the refined model was re-applied to the study frontage in Chapter 7. The results presented a methodology to prescribe variable layers of increased resistance below MLWS using field data considering the location and slope of more resistant layers. However, as weaker layers have been found to have a more profound effect on shore platform geomorphology and rates of cliff toe retreat in the mesoscale, the limitations of this approach are recognised. The methodology was limited within this study owing to the material strength parameter remaining as a calibration term within the model and the associated calibration with emergent ledge features. Therefore, the potential to further modify the material strength parameter to UCS (similarly to Castedo, 2013) and re-apply the model to model shallow layers of relative weakness along the study frontage is highlighted, as will be elaborated upon within Section 8.2, further research.

The refined models results highlighted the variability in retreat rates across the study frontage and showed a 16% increase in predictions from those included in the IoW SMP under the same sea-level rise scenario. The results have important implications for coastal management studies extrapolating historic rates of retreat for cliffs of variable material resistance in both the longshore and vertical directions under the influence of sea-level rise. However, it was highlighted that the utilised projection of Defra (2006) presents a top end estimate, thus providing a conservative 'worst case' sea-level rise prediction.

In conclusion, this study has extended an existing soft cliff model to contribute towards a more integrated understanding of the soft cliff recession process. Owing to the models inclusion of material resistance as a calibration term, the refined model is more appropriate as a geomorphic tool that can consider relative changes in resistance. However, the model has provided a foundation for further development and enhanced our understanding of soft cliff systems and interactions with climate change. In summary, the key conclusions are:

- Material strength is an important control on shore platform geomorphology and rates of cliff toe retreat on low sediment coasts.
- Owing to the integrated erosive potential of the tide and wave action, the cliff system is most sensitive to the outcropping of variable layers about MSL.

- Weaker layers result in an asymmetric increase in rates of cliff toe retreat as they induce shallower platform gradients inducing excessive mining of the shore platform to take on a new equilibrium form.
- Extrapolations of historic rates of retreat are not appropriate for coasts of variable lithology and there is a need to understand the thickness of variable layers and the rate of sea-level rise to determine timescales of exposure.

8.2 Further research

Following on from this research, four potential areas for further research can be identified:

1) Comparison of the refined model results with alternative process-based models;
2) Application of the refined model to other sites with different geomorphic and forcing conditions;
3) Continued development of our understanding of the soft cliff system and the impacts of changing conditions on rates of retreat;
4) Further investigations of the processes influencing coastal planshape evolution along the Isle of Wight study frontage.

The justifications for further focus on these areas and the potential for further research are explored in more detail below.

8.2.1 Comparison of the refined model results with alternative process-based models

This research has provided a quantitative analysis of the impact of layers of variable material resistance in the vertical. As previously discussed in Section 8.1, the results support the previous findings. However, it is recognised that the results of this study will be limited to the SCAPE models description of erosion, which is based on the equation of Kamphuis (1987). Therefore, cross comparisons with modified versions of alternative process-based model could provide interesting opportunities to further understand the impacts of layers of variable material resistance. For example the model of Trenhaile (2009. 2010) considers three separate erosional processes (excess shear stress, abrasion and mechanical wave erosion) which may provide opportunities for further model sensitivity analysis.

8.2.2 Application of the refined model to other sites with different geomorphic and forcing conditions

The current study has applied the refined SCAPE model to a low sediment study frontage of soft cliff variable lithology on the south west coast of the IoW, UK. The frontage was selected on the basis of its more complex coastal planshape and geomorphology in comparison to previous applications of the model. The results demonstrated the importance of material resistance as an important control on shore platform geomorphology and rates of soft cliff recession. On this basis, it is speculated that application of the model to sites with different geomorphic and forcing conditions will identify further important relationships within the cliff system, further contributing towards the development of a more integrated model.

In terms of geomorphic forcing and considering the systems-based model presented in Figure 2-9, there is potential to apply the refined SCAPE model to different climatic extremes. For example, as recognised in Section 2.2.2, tropical or polar climates may induce a greater dominance of weathering processes such as chemical and freeze-thaw weathering respectively. Application of the refined model to such conditions would require additional code to numerically describe the appropriate weathering processes, extending the applicability of the refined model beyond temperate regions. Such modifications would present an opportunity to further enhance our process-based understanding of the cliff system e.g. how does the influence of variable lithology change in environments where sub-aerial processes dominate?

Considering the initial model sensitivity analysis of model parameters (Figure 4-28) variations in wave conditions were recognised as the most important prevailing condition within the cliff system. Therefore further investigation of the refined model with varying wave conditions would also form an interesting avenue for further investigation. For example, will increased wave height accelerate or retard the influence layers of variable resistance?

8.2.3 Continued understanding of the soft cliff system

The need to continue to develop our understanding of the soft cliff system is a top priority based on the findings of the review of the cliff system and associated model presented in Chapter 2. This identified a broad range of parameters, processes and feedback mechanisms which can influence cliff recession. The present study has focussed on cliff toe processes which form the interface between the marine and terrestrial environment and are a more dominant control for simple cliff behavioural units. However, it is recognised that for more complex cliff systems the role of geotechnical cliff top processes will become more dominant. A more advanced understanding of how the cliff top will respond to the impacts of climate change is required for a range of coastal management activities, as introduced in Chapter 1.

There are a vast range of opportunities for further research to investigate how changing climatic and environmental factors may influence rates of cliff top erosion. This includes (but is by no means limited to):

- How the presence of anomalous layers of material resistance up the cliff face will also influence cliff failure mechanisms through undercutting of more resistant layers and mass movements induced by the presence of weaker layers.
- How changes in rainfall patterns and pore water pressure can influence slope stability and the frequency and magnitude of mass movement events which ultimately dictate the cliff top position.

8.2.4 Further investigations of processes influencing coastal planshape evolution on the study frontage

The present study has drawn insight from the south west coast of the Isle of Wight. The selection of this site was justified in Chapter 3 and included the areas variable lithology, complex coastal planshape and natural character. However, the frontage has received limited attention in terms of coastal geomorphology and therefore provides a multitude of opportunities for further research.

Refinements to the quasi-3D (Q3D) model within this research were discounted on the basis that longshore interactions are negligible on low sediment coasts.

However, following on from refinement of the 2D SCAPE model, it is recognised that layers of variable lithology along the study frontage are not horizontal and express varying dip/strike. This presents an opportunity to update the Q3D model to consider both vertical and longshore variations in material resistance to further understand past and future interactions with sea-level rise. In particular, the refined model will enable the process of headland and bay evolution and the potential for longshore migration over time to be investigated.

The above combined with the variability in rates of retreat demonstrated by the application of a series of refined 2D models also presents an opportunity to apply a refined Q3D SCAPE model of the study frontage as a coastal engineering tool. This would enable further quantitative predictions of coastal change to be made that would provide an enhanced understanding of the entire coastlines response. Furthermore, there would be an opportunity to apply the revised IPCC (2013) climate change projections to inform the sustainable management of the frontage.

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9. Appendices

9.1 Appendix A: SCAPE numerical description of erosion

As noted in Section 4.1.6, the description of the erosion rate (E) was based upon the expression from Kamphuis (1987). Within SCAPE, this equates to:

$$\frac{\Delta y}{\Delta t} = \frac{F}{M} \tan\alpha$$

Equation 9-1

Where *y* is the retreat distance, Δt is the model timestep, M represents material resistance and some hydrodynamic constants, and *F* represents the erosive forces where:

$$F = H_b^{13/4} T^{3/2}$$

Equation 9-2

The erosive forces act under random waves in the absence of tidal variation and is assumed to vary with depth (P_z) in a manner described by a shape function ($f_1(p_z)$) with an area equal to 1, as demonstrated below:

$$\int f_1 p_z = 1$$

Equation 9-3

If *w* is the water level and *z* is the elevation then:

$$P_z = w - z$$

By inserting the shape function into Equation 9-1, this becomes:

$$\frac{\Delta y}{\Delta t} = \frac{F}{M} f_1(w - z) \tan\alpha$$

Equation 9-4

As previously noted, the platform slope (α) varies with elevation so:

$$\alpha = f_2(z)$$

Therefore:

$$\frac{\Delta y}{\Delta t} = \frac{F}{M} f_1(w-z)\tan(f_2(z))$$

Equation 9-5

Owing to the influence of the tide, the water level (*w*) is a function (f_3) of time (*t*):

$$\frac{\Delta y}{\Delta t} = H_b^{13/4} T^{3/2} M^{-1} f_1(f_3(t)-z)\tan(f_2(z))$$

Equation 9-6

To further elaborate on the three functions:

The Erosion Shape Function (f_1)

This function is derived from the physical model tests of Skafel (1995). The study conducted wave tank experiments in which pseudo-random waves shoaled and broke over a model shore composed of intact glacial till. The model was given a profile of $y=0.18x^{2/3}$ and two water depths were tested. This meant that the platform at the waterline was steeper in the deeper water tests, resulting in plunging waves, whilst the waves in the shallower water tests were classified as 'spilling'. The distributions of erosion rate that resulted from these experiments identified significant differences; plunging waves show larger erosion rates, particularly close to the still water line Figure 9-1a. However, neither was found to be appropriate for the erosion shape function because they are subject to the influence of the shore platform. As such, both distributions were divided by the local slope, as outlined in Figure 9-1b. Here, the distance from the still water line has been converted to water depth and normalised by the depth at which the waves began to break.

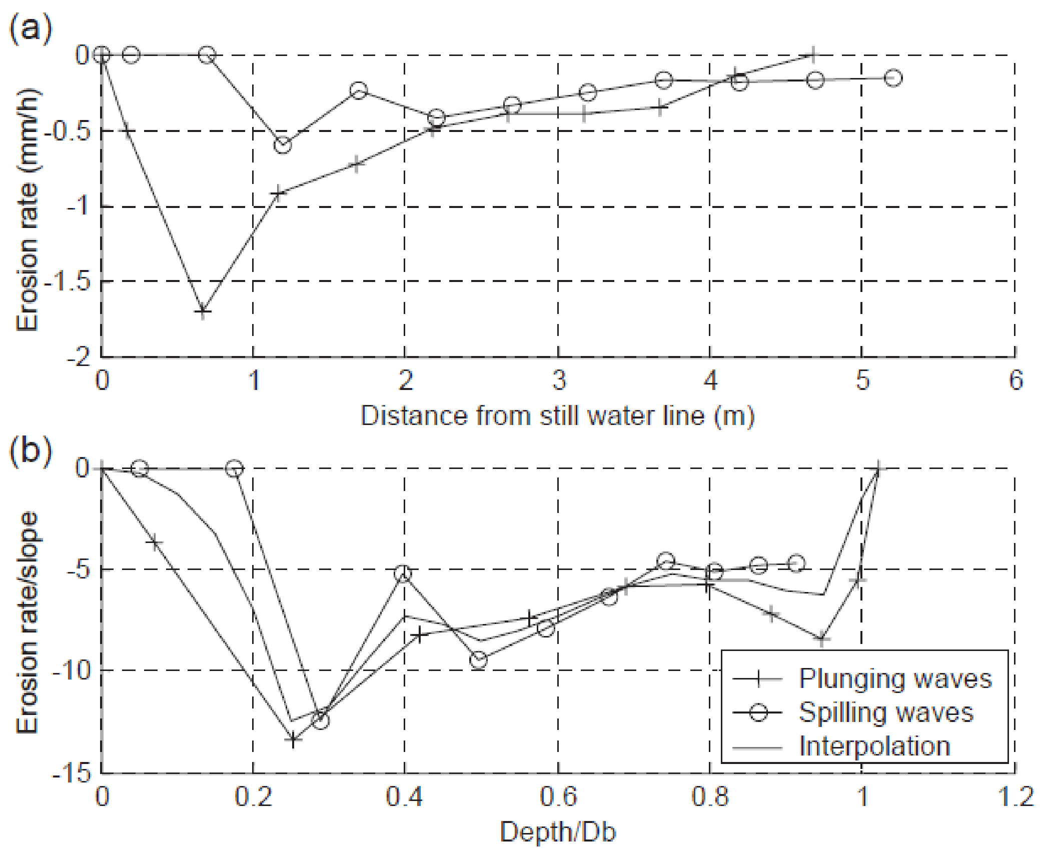

Figure 9-1: a) Distribution of erosion rate under breaking waves (data from Skafel (1995)), b) Variation of erosion rate/platform slope elevation

The resulting distributions are similar, and an interpolated distribution was produced to represent them both which was adopted as the shape function f_1. It is noted that the peak in this distribution does tend to amplify erosion at approximately D/D_b=0.25. However, Walkden & Hall (2005) note that this does not result in excessive mining at this level because of the tan α term in Equation 10-1.

The Profile Slope Function (f_2)

The profile slopes are calculated by the model at every timestep and therefore change throughout the simulation in response to the calculated erosion. The tangent in Equation 10-1 causes erosion to tend to infinity as α approaches vertical (90°). At the start of the modelling process, the cliffs are assumed to be vertical and in deep water with no platform. To prevent excessive erosion during this early stage, α is limited to a maximum slope of 50°.

The Tide Function (f_3)

The tide function is represented as a sinusoid, which oscillates about mean sea-level with a period of 12.46 hours. Realistic tidal amplitudes are read from an input file and sea level change is represented as a small shift in the elevations of the cliff elements at every timestep.

9.2 Appendix B: Modifications to SCAPE code

B1: Homogenous Material Resistance in original SCAPE model

As highlighted in Section 5.3.2.1, in the original SCAPE model, material resistance (M) is represented as a single, homogenous parameter in the vertical plane. The associated code from the main body of the SCAPE program is highlighted in the box below.

```
! Allocate arrays for resistance

allocate(resistance(nce,nsect),stat = alloc_error)

if(alloc_error /= 0)then

write(6,*)'*** Error : could not allocate space'

write(6,*)'*** Error : for Resistance'

stop

end if

! Settings

resistance(2) = 10600000

! The resistance is related to the time step so:

resistance = resistance / tstep_secs

!Deallocate Arrays

deallocate(cliffy,beachy,talus,upbeachy,lowbeachy,cliffheights,
&sect_erode_new,sect_erode,surface,& top_erode,bot_erode,cx_temp,np_cliff,
&sect_height,startprofile,startprofiles,resistance,resistance_null,angleosc, &
talus_width,ubvolume,lowbvolume,stormflag, ubrange, lbrange,
&stat=alloc_error)

if(alloc_error /= 0)then

write(6,*)'*** Unexpected deallocation error'

write(6,*)'*** for cliffy, beachy & cliffheights'

endif
```

Box B1: Code from the original, homogenous SCAPE model relating to material resistance

B2: Heterogeneous material resistance in refined SCAPE model

The SCAPE model was refined to consider M as a variable in the vertical direction but is assumed to remain constant in the horizontal. This was originally prescribed by developing am input file to be read in by the model, assigning an individual value of M for each horizontal discretisation of the cliff. The code associated with this initial modification is provided in the box below.

Open files outside the main loop

```
open(26,file='resistance_input.txt')

! Allocate & initialise arrays

allocate(cliffy(nce,nsect), & beachy(nce,nsect), & talus(nce,nsect), &
upbeachy(nce,nsect), & lowbeachy(nce,nsect), & cliffheights(nce), &
sect_erode(nce,nsect), & sect_erode_new(nce,nsect-1), &
surface(nce), & top_erode(nsect),bot_erode(nsect), & startprofile(nce),  &
startprofiles(nce,lacp), & resistance_null(nce), & resistance(nce,lacp), &
sect_height(nsect),np_cliff(nsect), & cx_temp(nce), & talus_width(nce), &
ubvolume(nsect), lowbvolume(nsect),& stormflag(nsect),angleosc(nsect), & stat
= alloc_error)

if(alloc_error /= 0)then

write(6,*)'*** Error : could not allocate space'

write(6,*)'*** Error : for cliffy, beachy, & cliffheights'

stop

end if

resistance_null=0

resistance=0

! Read Resistance as an Input File

if(nsect == 1)then

open(unit=20,file='resistance.txt',action='read') ! Only one section

do i=1,nce

read(20,*)resistance_null(i)

end do

else

open(unit=20,file='resistance1.txt',action='read') !

do i=1,nce
```

```
read(20,*)resistance(i,2)

end do

endif

close(20)

write(6,*)resistance

! deallocate arrays

deallocate(cliffy,beachy,talus,upbeachy,lowbeachy,cliffheights,  &
sect_erode_new,sect_erode,surface, &
top_erode,bot_erode,cx_temp,np_cliff, &
sect_height,startprofile,startprofiles,resistance,resistance_null,angleosc, &
talus_width,ubvolume,lowbvolume,stormflag, ubrange, lbrange, &
stat=alloc_error)

if(alloc_error /= 0)then

write(6,*)'*** Unexpected deallocation error'

write(6,*)'*** for cliffy, beachy & cliffheights'

endif
```

Box B2: Code from the refined SCAPE model prescribing variable material resistance as an input file

B3: Heterogeneous material resistance within refined SCAPE model with sea-level rise

Within SCAPE, sea-level rise is considered as a shifting frame of reference. Therefore, it was recognised that the in-situ properties of the cliff (e.g. vertical variations in material resistance) are actually adjusted with the rate of sea-level rise, as demonstrated by Figure 9-2. For example, a more resistant layer situated 1m below Mean Sea Level (MSL) in the present day, should be situated 2m below the ‘future’ mean sea level when considering a 1m rise. However, when material resistance is considered as an input file, the variable resistance layers were found to be adjusted up the cliff profile with the rate of sea-level rise; consequently the resistant layer remains situated 1m below the ‘future’ mean sea level.

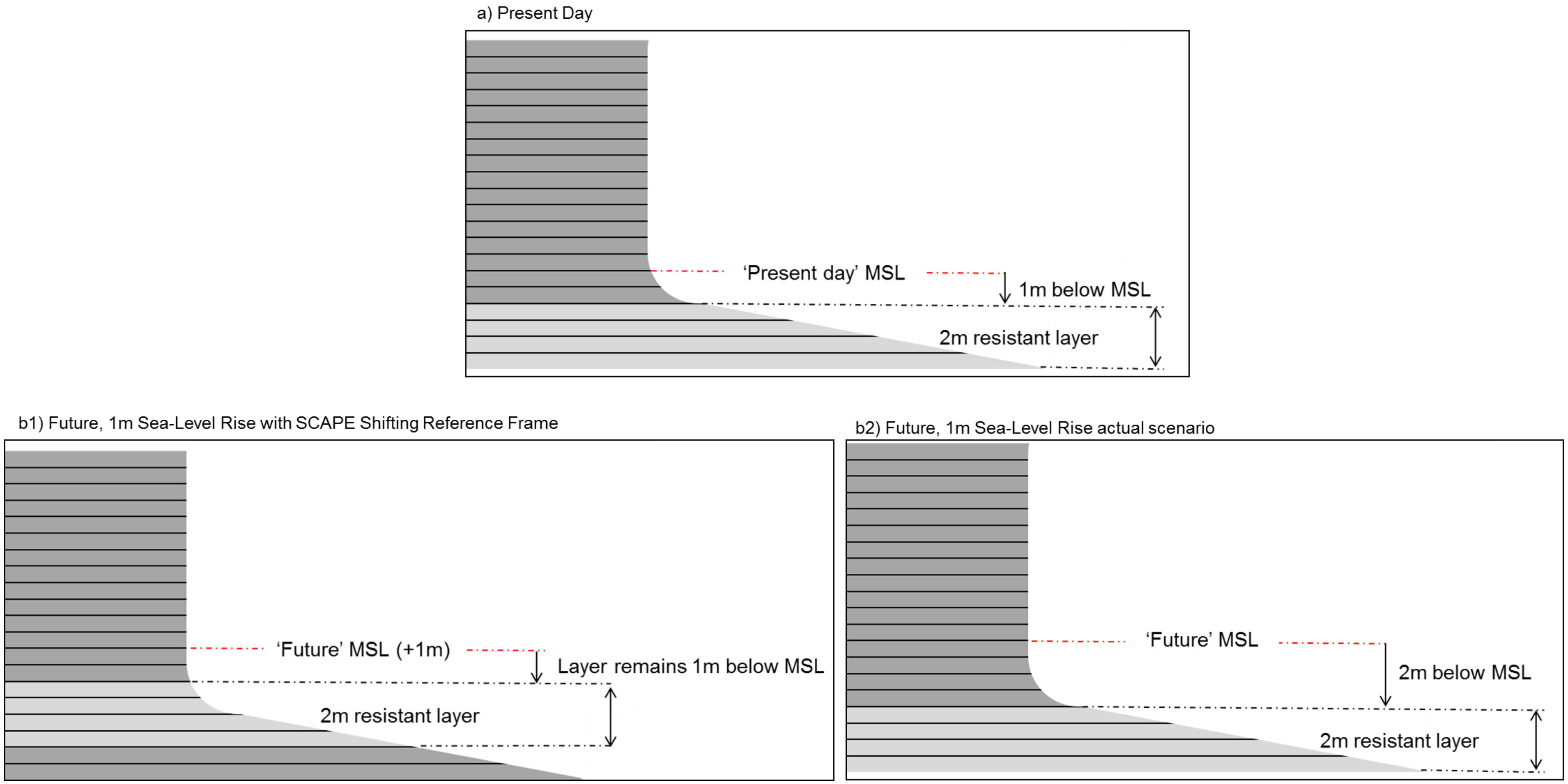

Figure 9-2: Diagram demonstrating how the original SCAPE shifting reference frame considers the location of a layer of variable resistance with 1m sea-level rise in comparison to reality

As a result, it was recognised that the impact of layers of variable resistance could not be accurately represented with sea-level rise under the model set-up described in B2. Therefore, additional modifications were made to alter the locations of the layers of variable resistance with the rate of sea-level rise. To achieve this, the resistance of each cliff element was prescribed in the model as a variable and additional code written to adjust the location of these cliff elements with respect to sea-level rise , as outlined in Box B3.

```
! Allocate & initialise arrays

allocate(cliffy(nce,nsect), & beachy(nce,nsect), & talus(nce,nsect), &
upbeachy(nce,nsect), & lowbeachy(nce,nsect), & cliffheights(nce), &
sect_erode(nce,nsect), & sect_erode_new(nce,nsect-1), &
surface(nce), & top_erode(nsect),bot_erode(nsect), & startprofile(nce),  &
startprofiles(nce,lacp), & resistance_null(nce), &  resistance(nce,lacp), &
sect_height(nsect),np_cliff(nsect), & cx_temp(nce), & talus_width(nce), &
ubvolume(nsect), lowbvolume(nsect),& stormflag(nsect),angleosc(nsect), & stat
= alloc_error)

if(alloc_error /= 0)then

write(6,*)'*** Error : could not allocate space'

write(6,*)'*** Error : for cliffy, beachy, & cliffheights'

stop

end if

resistance_null=0

resistance=0

! Set Resistance Values for Each Cliff Element

do i=0,1800                      ! Prescribe resistance value for cliff elements

resistance(i,2)=334.1501         ! 0 to 1,800

end do


do j=1801,2300                   ! Prescribe resistance value for cliff elements

resistance(j,2)=3341.501         ! 1801 to 2300 (10x more resistant layer)

end do


do k=2301,3200
```

```
resistance(k,2)=334.1501
end do
! Adjust resistance values of cliff elements with sea-level rise
do i=0,1800
resistance(i,2)= 334.1501
if (slr>0) then                 ! if there is sea-level rise
l=i-(year*(slr/10))             ! adjust the cliff elements which are resistant
resistance (l,2)= 334.1501      ! to compensate for SCAPE shifting reference
end if
end do

do j=1801,2300                  ! Repeat process for each resistant section
resistance(j,2)= 3341.501
if (slr>0) then
m=j-(year*(slr/10))
resistance(m,2)= 3341.501
end if
end do

do k=2301,3200
resistance(k,2)= 334.1501
if (slr>0) then
n=k-(year*(slr/10))
resistance(n,2)= 334.1501
end if
end do
! deallocate arrays
deallocate(cliffy,beachy,talus,upbeachy,lowbeachy,cliffheights,  &
sect_erode_new,sect_erode,surface, &
top_erode,bot_erode,cx_temp,np_cliff, &
sect_height,startprofile,startprofiles,resistance,resistance_null,angleosc, &
talus_width,ubvolume,lowbvolume,stormflag, ubrange, lbrange, &
```

```
stat=alloc_error)
if(alloc_error /= 0)then
write(6,*)'*** Unexpected deallocation error'
write(6,*)'*** for cliffy, beachy & cliffheights'
endif
```

Box B3: Code from the refined SCAPE model prescribing variable material resistance with sea level rise

Figure 9-3 demonstrates the contrast in results for the original and modified SCAPE shifting reference frame, both simulating a more resistant layer situated 2 to 4 m above ‘present day’ mean sea level. Considering a rate of sea-level rise of 1 mm/yr over 10,000 years the resistant layer should be apparent 8 to 6 m below ‘future’ mean sea level by the end of the model simulation. Figure 9-3a shows the final output profiles and Figure 9-3b the associated rate of cliff toe retreat for each model. The original reference frame shows that the resistant layer is not reflected in the cliff face or in the cliff toe retreat rate, as the layer has always remained 2m above mean sea level. In contrast, the modified reference frame shows the resistant layer is present in the cliff profile at -8 to -6 m OD with respect to the final mean sea level. The cliff toe retreat rate reflects interactions between mean sea level and the resistant layer with a decline in the rate after approximately year 2000. Upon submersion of the more resistant layer by sea-level rise (approximately year 4,000) the retreat rate begins to stabilise.

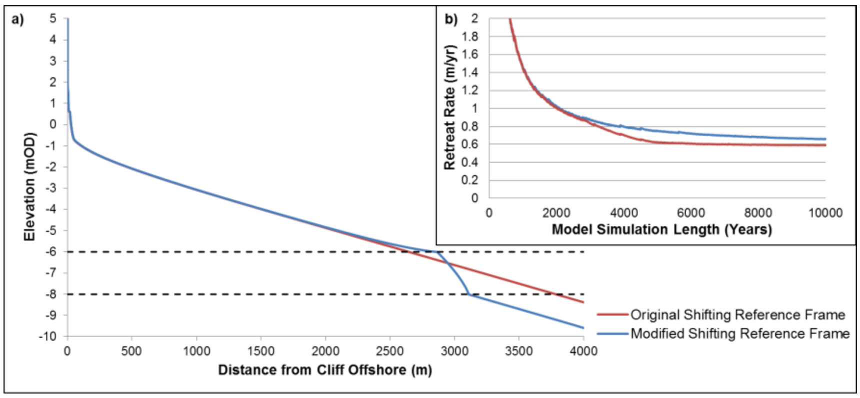

Figure 9-3: Comparison of results for the original SCAPE and modified SCAPE shifting frame of reference with a single layer of increased resistance, a) final output profile, b) associated rate of retreat

9.3 Appendix C: Refined model predictions of study frontage rates of retreat

This Appendix summarises the retreat rates and total retreat predicted at each site along the study frontage under a range of climatic and environmental scenarios. The results are discussed in terms of their implications for future coastal management of the study frontage.

C1: Modelled predicted retreat

Table 9-1: Summary of refined model predicted rates of retreat across the study frontage for a range of scenarios

Location	Scenario	Cliff Retreat Rate for Each Epoch (m/yr)				Total Erosion (m)
		2009-2025	2025-2055	2055-2085	2085-2105	
Compton Bay	A	0.84	0.85	0.88	0.89	83
	B	0.95	0.96	1.02	1.00	95
	C	1.08	1.13	1.19	1.15	111
Hanover Point	A	0.91	0.99	1.04	1.03	96
	B	1.03	1.08	1.17	1.16	107
	C	1.31	1.35	1.38	1.45	132
Brook Bay	A	0.65	0.63	0.61	0.73	62
	B	0.65	0.67	0.76	0.76	69
	C	0.82	0.83	0.87	0.87	82

Location	Scenario	Cliff Retreat Rate for Each Epoch (m/yr)				Total Erosion (m)
Sudmoor Point	A	0.51	0.50	0.49	0.56	49
	B	0.57	0.57	0.55	0.64	56
	C	0.68	0.70	0.71	0.82	70
Brighstone Bay	A	0.96	0.99	1.02	1.08	97
	B	1.09	1.11	1.15	1.23	110
	C	1.28	1.31	1.36	1.47	130
Atherfield Point	A	1.51	1.52	1.49	1.42	143
	B	1.80	1.84	1.83	1.76	174
	C	2.42	2.46	2.55	2.70	243
Chale Bay	A	0.55	0.53	0.51	0.64	53
	B	0.59	0.56	0.60	0.60	56
	C	0.67	0.66	0.72	0.72	67

C2: Implications for future coastal management

The study frontage is subject to a long term policy of No Active Intervention (NAI) across all epochs in the SMP. This was based on the need to:

- Maintain the landscape value of the area, including Area of Outstanding Natural Beauty (AONB) and Heritage coast designations;
- Support the aims of the geological designation of Steephill cove to Compton Chine Site of Special Scientific Interest (SSSI);

- Allow the nature conservation interests of the South Wight Maritime and Isle of Wight Downs Special Area of Conservation (SAC) to naturally adapt to the area.

The following erosion impacts were recognized by the SMP under the no active intervention policy:

- **General:**
    - The coastal footpath will require realignment;
    - Archaeological heritage sites may be lost;
    - Steepening and potential decline of the coastal gullies (chines) that interrupt the coastline if retreat of landward extents does not keep pace with cliff face erosion.
- **Epoch 1 (to 2025):**
    - The A3055 main road will be lost at Brook during this period followed by later adjacent sections and will require realignment or alternative inland routes;
    - Loss of sections of the A3055 will limit access to scattered properties and impact on the amenity use of the area (part of the 'round the island' tour).
- **Epochs two and three (to 2105):**
    - Several properties at risk including Atherfield Coastguard Cottages, Atherfield Holiday Centre's, Brighstone Holiday Centre, Chilton Chine and Brook Green.
    - Sea-level rise combined with shore platform lowering, coastal storms and increased winter rainfall will accelerate cliff retreat but increase sediment supply to downdrift beaches;
    - Relatively resistant headlands may become more pronounced with faster erosion in the bays between them.

However, application of the refined SCAPE has demonstrated the potential for an increase in total erosion. Therefore, comparing the total predicted retreat at each site presented within the SMP against the results for Scenario B (to consider a conservative 'worst case' scenario of sea-level rise and increased wave energy but not changes in lithology owing to the uncertainties associated with accurately prescribing a specific value at each site), the following changes can be identified.

At Compton Bay model results predict 15m more erosion than the SMP, with a total of 95 m threatening the Military Road (A3055) and resulting in the loss of Shippards Chine cap park. At Hanover Point model results express similar findings; the refined model predicts 27m more erosion than the SMP (total erosion of 107m).

The model results for Brook Bay exhibit higher rates of retreat for epoch 1 (as summarized in Appendix C), which will have implications for the longevity of the Military Road at this location. However, the model predicts slightly lower total erosion of 69 m by 2105.

Lower rates of retreat are predicted for each epoch than that predicted in the SMP for Sudmoor Point. This is a result of the lower historic rate of retreat measured at the site used in the refined model calibration owing to the presence of the more resistant Sudmoor Point Sandstone. In Contrast, higher rates of retreat across all epochs are predicted by the model for Brighstone Bay. Overall, 30 m more erosion is predicted over the next 100 years with the yielding a total erosion of 110 m at the site.

Atherfield Point also shows higher rates of erosion for all epochs resulting in a significantly higher loss of land by 2105 (174 m versus 120 m for refined model versus SMP predictions). This substantial increase in retreat may be due to the consideration of variable material resistance within the SCAPE model; upon inundation of more resistant layers retreat rates increase as weaker material is exposed to wave attack. The potential for higher rates of retreat may lead to premature loss of property at this location e.g. Atherfield Cottages.

Finally, Chale Bay expresses lower rates of retreat for all epochs than that predicted by the SMP but as previously discussed is believed to be an anomalous result.

9.4 Appendix D: Abstracts of Associated Publications

D1: Investigating the recession process of complex soft cliff coasts: An Isle of Wight case study (Carpenter, 2012)

Understanding future retreat rates of soft rock cliffs is important for a range of coastal management activities, particularly when considering the impacts of climate change. One key method is process-based numerical modelling. However, this technique is still in its early stages and consequently the process of cliff recession is typically over-simplified. This paper reviews the application of the SCAPE (Soft Cliff and Platform Erosion Model) to a varied geological frontage on the south west coast of the Isle of Wight. Evaluation of the 2D model has been undertaken through validation of the output model profiles compared with measured and field data observations. The results have identified the importance of vertical variations in rock strength within the cliff system, which has a strong influence on recession rates, cliff morphology and the development of emergent features. Evaluation of the model has also highlighted the importance of translating cliff base retreat into an appropriate cliff top position, which defines the extent of the erosion hazards, and hence is of more practical use (e.g., land-use planning). This requires more consideration of the role of terrestrial processes within the cliff recession process.

D2: Development of a process-based model of the effects of variable lithology: an Isle of Wight case study

Process-based numerical modelling of soft rock cliffs is an important tool for predicting future rates of retreat. This is particularly important considering the potential impacts in climatic and environmental change. However, many existing model are criticised for the generalised manner in which the soft cliff system and retreat process is described. One key issue is the assumption of uniform vertical lithology when most natural cliffs are composed of interbedded stratigraphy of varying strength and composition. In response, this paper describes modifications to the 2D SCAPE (Soft Cliff and Platform Erosion) model to explore the influence of horizontal layers of varying material strength along a study frontage on the south west coast of the Isle of Wight, UK. Model validation against measured shore and bathymetric profiles of the study frontage has demonstrated improved fit when the effects of more resistant layers within the profile are incorporated into the model. Such layers influence the geomorphology of the profile, forming emergent ledge features which experience reduced erosion and increased profile slope with increasing resistance. The outcropping of such layers with respect to mean sea level is recognised as a key control on rates of cliff toe recession owing to the integrated erosive potential of the tide. Therefore, model results have highlighted the importance of considering interactions between layers of variable material strength and sea-level rise. As a consequence, the results highlight the important implications for studies involving historical extrapolation of retreat rates for coasts of interbedded stratigraphies.

D3: Understanding the role of lithology on soft cliff planshape evolution under high and low sediment availability (Carpenter et al, In Review-a)

The quasi-3D SCAPE model has been used to address a series of key geomorphic questions relating 15 to large-scale, long-term coastal planshape evolution under low (Mode A) and high (Mode B) 16 sediment availability. These modes can be defined based on the long term trends in cliff retreat and 17 the maintenance of threshold beach volumes. The latter has been defined as 40 m3/m, which 18 requires >20 % availability of beach grade material from the eroding cliff to be maintained under the 19 conditions simulated. Below this threshold, the resistive properties of the rock and their effect on 20 the shoreline slopes become the more dominant control. Contrasting modes of shoreline behaviour 21 are particularly important when considering longshore variations in cliff lithology. For example, 22 SCAPE analysis has shown that, under Mode A, eight times relative changes in material resistance 23 across an idealised linear frontage result in long term heterogeneous rates of retreat and the 24 development of offsets in the coastal planshape. However, under Mode B, the same relative changes in material resistance do not result in the formation of significant offsets and retreat rates reach 26 steady state within 1,000 years. The results show how some coastlines can exhibit a persistent series 27 of headlands and embayments, while others remain smooth or display transient features over time, 28 despite longshore variations in resistance, owing to the balancing effects of wave energy, beach 29 volume and material resistance. Results are compared and contrasted to previous simulations and 30 site specific examples.

D4: Effects of varied lithology on soft cliff recession rates (Carpenter et al, In Review-b)

Understanding soft cliff systems is a significant challenge owing to the complex recession process, 15 high rates of retreat and the need to quantify the response to climate change (Brown et al., 2006, 16 Dubois, 2002, Lee and Clark, 2002). Geomorphic modelling is a key method of developing 17 understanding and a range of process-based models have been used to study the influence of 18 variable lithology on the plan-shape shoreline evolution. However, the influence of varied vertical 19 lithology has yet to be quantified. This paper describes modifications to the SCAPE (Soft Cliff and 20 Platform Erosion) model carried out to explore such interactions between vertical changes in 21 material strength and prevailing coastal conditions. Results of analyses demonstrate how the 22 introduction of a single more or less resistant layer changes the shore profile slope; with stronger 23 material forming steeper profiles, and weaker layers shallower and wider profiles. As expected, more resistant layers give rise to reduced rates of cliff-toe recession owing to their lower erosive 25 potential. However, this effect is strongly influenced by the position of such resistant layers relative 26 to mean sea level, where the erosive potential is greatest. Moreover, model simulations reveal that 27 layers of variable resistance give an asymmetric response. Therefore, a fivefold increase in the 28 relative resistance of a 5 m layer situated 6 m to 1 m below mean sea level has little influence on the 29 equilibrium profile form and hence recession rate (in comparison to that of a homogenous cliff), 30 whereas a fivefold decrease results in a 130% increase in retreat rates. This non-linear response can 31 be attributed to the relationship between material resistance and profile slope. The introduction of a 32 weaker layer gives a greater erosive potential and leads to the development of shallower profile 33 gradients. As a result, the cliff takes on a new equilibrium shape through the process of accelerated 34 erosion. The results have important implications for the management of coastal cliffs exhibiting 35 variable stratigraphy combined with the potential for future interactions with sea-level rise.