Modelling the dynamic interaction between hydrology, slope stability and wave run-up processes in the soft-sea cliffs at Covehithe, Suffolk, UK

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Declaration: the work presented in this thesis is my own_________________________

Abstract

Soft-rock coastal cliff retreat progresses by an intermittent and discontinuous series of slope mass movements, generally accepted to be concentrated during phases of strong wave attack or heavy rain. One of the fundamental limitations to improving understanding of these processes is a lack of accurate quantitative data on the hydrological and geotechnical behaviour of the cliff slope. In this study, high-resolution terrestrial surveys of coastal change over a fifteen year period have been analysed and combined with hydrological and geotechnical simulations of cliff behaviour under rainfall stress. The input parameters for the simulations have been established from site survey, cross-checked with data from a range of published literature. The numerical model has been applied to typical hydrological, climatic and geotechnical conditions at Covehithe, Suffolk.

In addition, analyses of water levels and beach elevations have subsequently been included using archive observation data, to further investigate the mechanisms governing the nature of change at the study site. Key findings include: (a.) high-resolution modelling of rainfall-infiltration processes combined with slope stability analysis provides a unique insight into the complex interaction between slope morphology and dynamic hydrology in soft sea cliffs. (b.) detailed analysis of daily factors of safety related to specific daily rainfalls is significant in reproducing failure conditions at the study site, and elucidates the complex interaction between cliff stratigraphy, cliff hydrology and rainfall. (c.) The results of the water level and beach elevation analyses show that marine processes are significant to the generation of cliff instability, consistent with the field observations and with the Sunamura (1983) model. These findings suggest that the instability of soft sea-cliffs results from complex and interacting controls that require an approach utilising a fully integrated transient hydrology and slope stability modelling. These results have significant implications for current coastal management practice.

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Contents

Title page 1

Abstract 2

Acknowledgements 3

Contents 4

List of figures 9

List of tables 14

Chapter 1 Introduction 16

1.1 The general significance of cliff erosion 16

1.1.1 The global importance of cliff erosion 16

1.1.2 Cliffed coastlines and retreat rates around the UK 17

1.1.3 Challenges to coastal governance in the UK 18

1.1.3.1 Rapid coastal retreat 20

1.1.3.2 Global environmental change 21

1.1.3.3 Uncertainty in predictions of retreat rates 22

1.2 Timescales for soft rock cliff erosion and controls on retreat rates 23

1.2.1 Soft-rock cliffs 23

1.2.2 Soft rock cliff failure processes and mechanisms 24

1.2.3 Timescales for soft rock cliff erosion 27

1.2.4 Controls on retreat rates 28

1.2.4.1 Primary factors 28

1.2.4.2 Secondary factors 29

1.2.5 Episodic cliff erosion: Triggering events and preparatory processes 31

1.2.5.1 The Sunamura (1983) model 31

1.2.5.2 Brunsden's concept of redundant events 32

1.2.5.3 The relationship between preparatory and triggering factors 33

1.2.5.4 Future scenarios after change in external forcing factors 33

1.3 Research needs for better understanding of soft cliff erosion 34

1.3.1 Recent research advances 34

1.3.2 The remaining gaps that need to be addressed 35

1.3.2.1 The non-conformance of soft sea-cliff retreat to common statistical methods 35

1.3.2.2 The incomplete understanding of the role of rainfall infiltration in the retreat of soft sea-cliffs 36

1.3.3 The specific role of modelling in meeting the research needs 37

1.4 Thesis Outline 38

Chapter 2 The Study Site: cliffs at Covehithe Suffolk 39

2.1 Background to the study area 39

2.1.1 Regional setting 39

2.1.2 The nature of rapidly eroding soft cliffs 40

2.1.2.1 Cliff morphology and height 40

2.1.2.2 The geological structure of typical soft cliffs in the region 41

2.1.3 Regional bathymetry 42

2.1.3.1 Southern North Sea 42

2.1.3.2 East Anglian coast 43

2.1.3.3 Offshore configuration of the Suffolk coast 44

2.1.3.4 Near shore configuration of the Suffolk coast 45

2.2 Sea level history 46

2.2.1 Long-term sea level changes (Holocene) 46

2.2.2 Sea level history of the last century 47

2.2.3 Current trends in sea level 48

2.3 Process environment 49

2.3.1 Rainfall 49

2.3.2 Tides 50

2.2.3 Waves 50

2.2.4 Sediment transport, sediment cells and sand bar dynamics 52

2.4 Extreme events 53

2.4.1 Development of extreme events in the North Sea 54

2.4.2 Impacts of extreme storms and storm surges 54

2.4.3 Storms, storm surges and climate change: future trends 54

2.5 The suitability of Covehithe for study 57

Chapter 3 Research design and methodology 59

3.1 Research Design 59

3.2 Methodology 62

3.2.1 Models that have been used to elucidate cliff retreat 62

3.2.1.1 Physically based computer modelling: recent advances 67

3.2.1.2 Soil hydraulic conductivity modelling 69

3.2.1.3 Slope stability modelling 74

3.2.1.4 Coupled hydrology-stability modelling 77

3.2.2 The history of retreat in the cliff line at Covehithe 79

3.2.3 The association between rainfall and cliff retreat 86

3.2.4 Terrestrial forcing of cliff retreat 86

3.2.4.1 Coupled hydrology and stability model parameterisation 89

3.2.4.2 Hydrological response to disturbing rainfall stress 106

3.2.4.2 FS response to disturbing rainfall stress 109

3.2.5 Marine forcing of cliff retreat 111

3.2.5.1 Introduction 111

3.2.5.2 Obtaining water level data 112

3.2.5.3 The record of water level at Lowestoft 113

3.2.5.4 The record of cliff base elevation at the study sites 113

3.2.5.5 The association between water level and cliff retreat 114

Chapter 4 Results 116

4.1 The history of retreat in the cliff line at Covehithe 116

4.2 The association between rainfall and cliff retreat 119

4.3 Terrestrial forcing of cliff retreat 124

4.3.1 Coupled hydrology and stability model sensitivity analysis 124

4.3.2 Hydrological response to disturbing rainfall stress 130

4.3.3 FS response to disturbing rainfall stress 134

4.4 Marine forcing of cliff retreat 140

4.4.1 The record of water level at Lowestoft between 1993 and 2008 140

4.4.2 The record of cliff base elevation at the study sites 143

4.4.3 The association between water level and cliff retreat at the study sites 147

Chapter 5 Discussion 148

5.1 The history of retreat in the cliff line at Covehithe 148

5.2 The association between rainfall and cliff retreat 148

5.3 Terrestrial forcing of cliff retreat 149

5.3.1 Coupled hydrology and stability model sensitivity analysis 149

5.3.2 Hydrological response to disturbing rainfall stress 151

5.3.3 FS response to disturbing rainfall stress 152

5.4 Marine forcing of cliff retreat 152

5.4.1 The record of water level at Lowestoft between 1993 and 2008 152

5.4.2The association between water level and cliff retreat at the study sites 154

Chapter 6 Conclusions and further work 155

6.1 Sensitivity study 157

6.2 Hydrological response to disturbing rainfall stress 157

6.3 FS response to disturbing rainfall stress 158

6.4 Marine forcing of cliff retreat 159

6.5 Implications of the findings 160

6.6 Further work 161

References 162

List of Figures

Figure 1.1	Relative rock resistance for Great Britain expressed as six consistent classes (Clayton and Shamoon, 1998)	18
Figure 1.2	The four stages in the cliff retreat process (DEFRA, 2002)	24
Figure 1.3	The variable interaction between potential triggering events and landslides (Brunsden and Lee, 2000)	32
Figure 2.1	Map of the east coast of the UK with insets showing the location of (A) East Anglia and (B) the Suffolk coast (Brooks and Spencer, 2010)	40
Figure 2.2	Map of bathymetry offshore of the East Anglia coastline, showing the depth as mLAT (Chini *et al.,* 2010)	43
Figure 2.3	The location of the main banks off the Suffolk coast from Winterton to Benacre in the UK National Grid Reference system (Horrillo-Caraballo and Reeve, 2008)	44
Figure 2.4	Glacial Isostatic Adjustment map of the vertical land movement (mm/yr) for the UK (UKP09)	47
Figure 2.5	Rose diagrams showing percentage of total against direction for waves modelled at a point 48km offshore of Dunwich, Suffolk, UK	51
Figure 2.6	Regional trends over the period 1961-2006 in the contribution (%) made by heavy precipitation events to total winter and summer rainfall (Maraun *et al*., 2008)	56
Figure 3.1	Research Design: Terrestrial and Marine forcing processes	61
Figure 3.2	The forces acting on a soil slice in a limit equilibrium stability analysis (Krahn, 2004)	76
Figure 3.3	Environment Agency ‘at-a-point’ SDMS survey locations for the Suffolk coast between Benacre and Southwold, named using the EA	

terminology: e.g. SWD2 (after Brooks and Spencer, 2010) 80

Figure 3.4 Typical cliff profile data available for the Suffolk Coast, UK for the 2003 surveys at SDMS monitoring sites SWD3 to SWD7 84

Figure 3.5 The procedure used to configure the SEEP/W model 93

Figure 3.6 The procedures used to configure the SLOPE/W model 94

Figure 3.7 The relationship between the numerical model domain and the SDMS survey data is shown for the January 1996 survey at SWD4 95

Figure 3.8 Photograph (from a site survey conducted May 2005) at Covehithe (SWD4) looking North correlated with schematic showing assigned geotechnical properties 100

Figure 3.9 The hydraulic conductivity curves used in the hydrology modelling 102

Figure 3.10 The volumetric water content functions used in the hydrology modelling 103

Figure 3.11 The 'storm' events in the numerical modelling shown as normalised rainfall profiles 108

Figure 3.12 Schematic showing the method for defining the position of the 'cliff edge' and the position of the 'cliff-beach junction' from the SDMS survey data 114

Figure 4.1 End Point Method cumulative cliff edge retreat from analysis of the SDMS Surveys at the study sites between 1993 and 2008 117

Figure 4.2 The shoreline retreat rate (m a^{-1}) between SWD3 (Covehithe) and SWD7 (Easton) for the period 1992-2008, and the sub-periods 1992-2001 and 2001-8 118

Figure 4.3 Frequency distribution of daily rainfall total (mm) at Wrentham (2.8 km inland from Covehithe) for the period 1993 to 2008 is shown with number of summer/winter events 121

Figure 4.4 Frequency distribution of daily rainfall totals (>10 mm) at Wrentham (2.8 km inland from Covehithe) for the period 1993 to 2008 is shown with number of summer/winter events 121

Figure 4.5 Association between cliff edge retreat rate at SWD3, SWD4, SWD5, SWD6 and SWD7 and the value obtained for the ratio of 2-day rainfall total to the rainfall total in the period between surveys 123

Figure 4.6 Factor of Safety shown with Sensitivity Range for the period from Winter 1993 to Winter 1999 in the Sensitivity Study at SWD4 125

Figure 4.7 Factor of Safety shown with Sensitivity Range for the period from Summer 1999 to Winter 2002 in the Sensitivity Study at SWD4 126

Figure 4.8 Factor of Safety responses in the hydrological sensitivity analysis for the periods; January 1993, August 1993, January 1994 and August 1994 127

Figure 4.9 Factor of Safety responses in the hydrological sensitivity analysis for the periods; January 1995, August 1995, January 1996 and September 1996 (A) and January 1997, August 1997, February 1998 and July 1998 (B) 128

Figure 4.10 Factor of Safety responses in the hydrological sensitivity analysis for the periods; January 1999, July 1999, February 2000 and August 2000 (A) and January 2001, August 2001 and January 2002 (B) 129

Figure 4.11 The relationship between the SEEP/W model output of pore-water pressure contour and water table surfaces (right) and the pore-water pressure response information (left) 130

Figure 4.12 Pore-water pressure responses in the hydrological analysis for Storm 1

	(A); Storm2(B); Storm 3 (C) and Storm 4 (D)	131
Figure 4.13	Pore-water pressure responses in the hydrological analysis for Storm 5 (A); Storm 6 (B); Storm 7 (C) and Storm 8 (D)	132
Figure 4.14	Pore-water pressure responses in the hydrological analysis for Storm 9 (A); Storm 10 (B); Storm 11 (C) and Storm 12 (D)	133
Figure 4.15	FS (Bishop Method) for simulation from 11/08/1997 to 03/02/1998	134
Figure 4.16	FS (Bishop Method) for simulation from 28/01/2003 to 06/08/2003	135
Figure 4.17	FS (Bishop Method) for simulation from 13/09/2002 to 27/01/2003	135
Figure 4.18	FS (Bishop Method) for simulation from 17/01/1999 to 11/08/1999	136
Figure 4.19	FS (Bishop Method) for simulation from 22/01/2005 to 19/07/2005	136
Figure 4.20	FS (Bishop Method) for simulation from 23/07/1998 to 16/01/1999	137
Figure 4.21	FS (Bishop Method) for simulation from 12/08/1999 to 10/02/2000	137
Figure 4.22	FS (Bishop Method) for simulation from 23/08/2000 to 20/01/2001	138
Figure 4.23	FS (Bishop Method) for simulation from 06/01/1993 to 07/08/1993	138
Figure 4.24	FS (Bishop Method) for simulation from 21/07/2006 to 01/02/2007	139
Figure 4.25	The relationship between 2-day rainfall total and reduction in Factor of Safety (FS) in the model shown with the relationship between 1-day rainfall total and reduction in Factor of Safety (FS)	139
Figure 4.26	Positive surges at Lowestoft from tide gauge data in the period 1993 to 2008	140
Figure 4.27	Frequency and temporal distribution of positive surges in the period 1993 to 1997 shown with tidal height (m)	141
Figure 4.28	Frequency and temporal distribution of positive surges in the period 1998 to 2002 shown with tidal height (m)	141
Figure 4.29	Frequency and temporal distribution of positive surges in the period	

	2003 to 2007 shown with tidal height (m)	142
Figure 4.30	The cliff base elevations identified from the analysis for the survey locations SWD3 to SWD7 are shown for the period 1993 to 2001 (top) and the period 2001-2008 (bottom)	143
Figure 4.31	Results of the analyses of water level for stable and unstable phases at the study sites in the period 1993 to 2008	146

List of Tables

Table 1.1 Percentage of coast length which is eroding for selected regions of the UK 17

Table 1.2 Options provided for sea defence planners in the guidance on the production of Shoreline Management Plans (MAFF, 1995) 19

Table 1.3 Retreat rates around the coast of England (Soft Cliffs Manual for Managers, 2002) 21

Table 1.4 Temporal scales for coastal environments (Perillo, 2003) 28

Table 1.5 Primary factors in soft-rock cliff retreat process 29

Table 1.6 Summary of the secondary factors that control retreat rate in soft rock cliffs 30

Table 3.1 Shore-normal SDMS winter survey profile chronology 81

Table 3.2 Shore-normal SDMS winter survey profile chronology 82

Table 3.3 Comment Codes used in the SDMS profiles 83

Table 3.4 Hydrological parameter datasets from the literature 91

Table 3.5 Geotechnical properties from the literature 92

Table 3.6 The rainfall total range taken from disaggregated rainfall information from the archive at Wrentham, the corresponding hourly intensity over 24 hours (in $mmhr^{-1}$), and the boundary flux for these values in the input units of the model ($mday^{-1}$) 99

Table 3.7 Storm events (shown chronologically) used in the simulations derived from analysis of the disaggregated rainfall data at Wrentham in the period 1993 to 2008 107

Table 3.8 Case-study periods used in the simulations to investigate the sensitivity 110

	of FS response to short-term rainfall total at SWD4	
Table 3.9	Case-study periods used in the simulations to investigate the sensitivity of FS response to short-term rainfall total at SWD4	111
Table 3.10	Shore-normal SDMS winter survey profile chronology	115
Table 4.1	End Pont Method cliff edge retreat rates calculated from analysis of the SDMS Surveys	116
Table 4.2	Annual rainfall totals and winter period rainfall totals in the period January 1993 to January 2008 at Wrentham, Suffolk	119
Table 4.3	Summer period rainfall totals and winter period rainfall totals in the period January 1993 to January 2008 at Wrentham	120
Table 4.4	The maximum one-day and two-day rainfall totals in each inter-survey period	122
Table 4.5	Cliff base elevation derived from winter SDMS survey data for the study sites	144
Table 4.6	Cliff base elevation derived from winter SDMS survey data for the study sites	145

Chapter 1 Introduction

1.1 The general significance of cliff erosion

1.1.1 The global importance of cliff erosion

Coastal zones are of key economic and social importance (Turner *et al.,* 1996; Nordhaus, 2006). These areas are occupied by ten percent of the world's population (McGranahan *et al.,* 2007), at densities about three times the global mean (Small and Nicholls, 2003), and include two thirds of the world's mega-cities (e.g. Tokyo, New York, Los Angeles and Rio de Janeiro; Klein *et al.,* 2003). Cliffs front the coastal zone in parts of Japan (Yokota and Iwamatsu, 1999), New Zealand (de Lange and Moon, 2005), Canada (Nairn, 1986), the USA (Swenson *et al.,* 2006), the United Kingdom, France, Denmark, Lithuania and Germany (May and Heeps, 1985; Dubra and Olsauskas, 2001; Eurosion; 2004; Breitung *et al.,* 2011).

Conflict between human occupation and the inherent instability of many cliffed coasts is a problem of increasing magnitude, as any settlements located there are threatened by a wide variety of weather-related hazards (Klein *et al*., 2003; Moore and Griggs, 2002). This is particularly true where coastal cliffs are formed from soft rock (May and Heeps, 1985; Dubra and Olsauskas, 2001; Eurosion; 2004; Breitung *et al.,* 2011), as these coasts are seriously threatened by shoreline retreat. For example, retreat rates in excess of 1 m a^{-1} are experienced in Denmark, Germany, Russia, Japan, New Zealand and Canada (Sunamura, 1992; de Lange and Moon, 2005). Coastal cliff retreat is also well documented in the USA (Komar, 1997; Griggs, 1999; Moore *et al.,* 1999), the Gulf of Mexico (Morton and McKenna, 1999) and the United Kingdom (e.g. Steers, 1951; Cambers, 1976; Pethick, 1996).

Predicting coastal response to the physical drivers that promote retreat is a key challenge in geomorphology (French and Burningham, 2009). Crucially, climate change is expected to affect the frequency, trajectory and strength of storms (IPCC, 2007) and intensify the occurrence of extreme water levels (Wang *et al.,* 2008; Esteves *et al.,* 2011). These changes are expected to lead to greater erosion in sea cliffs (Miller and Douglas, 2004; Wang *et al.,* 2008). Consequently, coastal zone management has been identified as a major challenge for the 21st Century (Sciberras, 2002; Nicholls *et al.,* 2007; Dan *et al.,* 2009). Further research to improve understanding of the causes and impacts of cliff retreat is needed if the threats of climate change are to be mitigated (Cowell and Thom, 1994; French and Burningham, 2009; Anthoff *et al*., 2010; Nicholls and Cazenave, 2010).

1.1.2 Cliffed coastlines and retreat rates around the coast of England, UK

Shoreline retreat is an important issue in England, where regional coastal retreat rates are among the highest found globally (Brooks, 2010). A significant proportion of the coastal cliffs that form the dominant coastal features along many parts of the north-eastern, East Anglian and the south-eastern coasts of England (DEFRA, 2002) are eroding (Table 1.1).

Region	***Coast Length (km)***	***Coast length which is eroding (km)***	***(%)***
Yorkshire and Humber	361	203	56.2
Southeast England	788	244	31.0
East England	555	168	30.3
Northeast England	297	80	26.9
Northwest England	659	122	18.5
East Midlands	234	21	9.0

Table 1.1 Percentage of coast length which is eroding for selected regions of the coast of England

The geology of the cliff sections on the coasts of Yorkshire & Humber, Southeast England and east England makes them prone to high retreat rates, as the lithologies are classified as weak or very weak when expressed as six consistent classes (Clayton and Shamoon, 1998) (Figure 1.1).

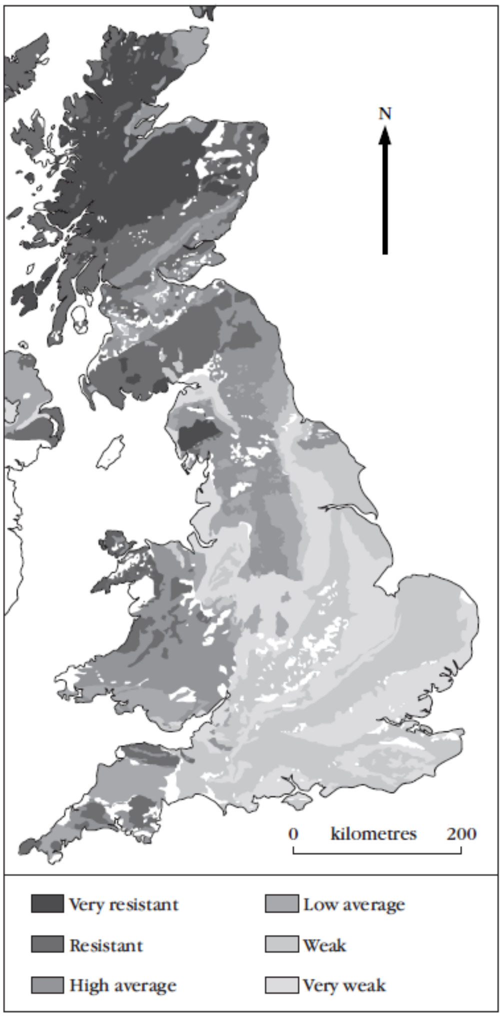


Figure 1.1

Relative rock resistance expressed as six consistent classes (From Clayton and Shamoon, 1998) showing the low resistance rocks of the mainly unconsolidated coast of east England are classified as very weak.

1.1.3 Challenges to coastal governance

Much of the coast of England is seriously threatened by shoreline retreat. Furthermore, as risk is assessed as the coupling of vulnerability and exposure to the hazard (Birkmann, 2007) Figure 1.1 illustrates that the cliffs developed in soft rock lithologies such as those on the coast of eastern England, are at particularly high risk. The issue of coastal landsliding risk has been addressed by the UK planning system (e.g. MAFF 1990, 1992, 1996) and Local Authorities are guided by non-statutory Shoreline Management Plans(SMPs) that present a policy framework for managing coastal erosion and flooding risks (MAFF, 1995). Shoreline Management Plans provide a framework for dealing with coastal flooding and erosion over a large area, usually covering a number of communities and coastal defences. UK Government Guidance (MAFF, 1995) on the production of Shoreline Management Plans provides options for sea defence planners to a) hold the line, b) make no active intervention or c) allow managed realignment (Table 1.2).

SMP Policy	***Definition***
Hold the line	Maintain or upgrade the level of protection provided by defences or the natural coastline
No Active Intervention	A decision not to invest in providing or maintaining defences or management of the coast
Managed Realignment	Manage the coastal processes to realign the 'natural' coastline configuration, either seaward or landward of its present position

Table 1.2

Options provided for sea defence planners in the guidance on the production of Shoreline Management Plans

The MAFF policy (1995) has left a legacy of protected shorelines that require continued investment. Expenditure on coastal defence projects was £300 m in 1996; £600 m in 2007;

£650 m in 2008 (Defra, 2008) and by 2035 is predicted to be £1bn (Environment Agency, 2009). Under a 'high' climate change scenario the 1 in 10 year defence standard could be reduced to 1 in 2-8 years by 2050, with many defences at or below the 1 in 1 year standard by 2080 (Nicholls and Wilson, 2002). This is a key challenge for coastal governance in the UK because the decision has been taken not to invest in providing, or maintaining, defences or management of eroding soft rock cliffs over three future epochs 2025; 2055; and 2105 (Royal Haskoning, 2010). Under this policy of No Active Intervention, increased coastal erosion is likely to have an impact on residents of coastal areas, the environment, tourism and industry. The financial implications alone are considerable, with estimates of annual damage to property of £1.0bn and lost agricultural production worth £5.9m under foreseeable climate change scenarios (Hall *et al*., 2006).

1.1.3.1 Rapid coastal retreat

The coastline of Suffolk has the fastest rate of contemporary retreat in the UK, reaching rates of 5 m a^{-1} locally. Retreat rates of between 1 ma^{-1} and 5 m a^{-1} have been recorded in the soft rocks of Yorkshire, Norfolk, Hampshire and Dorset (Table 1.3). These retreat rates are in stark contrast to those experienced in shorelines developed in more resistant lithologies where historic retreat rates of approximately 0.1 m a^{-1} are more representative (Sims & Ternan, 1988). The retreat rate over historic periods does not tell the whole story. For example, the mean retreat rate at Bindon in Devon was 0.1 m a^{-1} when measured over a period of 54 years (Pitts, 1983). However, long-term values mask the impact of potentially significant individual events, such as the tens of millions of tonnes of rock, landslide debris and beach material that was deposited when a large mass of rocks became detached from the 120 m high cliffs on Christmas Day in 1839 (Gallois, 2010). Furthermore, as can be seen from Table 1.3 and as will be developed in this study, soft rock cliff retreat is a highly site specific phenomenon (Lee *et al*., 2001; Trenhaile, 2002).

Location	Erosion rate m a^{-1}	Source
Covehithe, Suffolk	5.1	Steers, 1951
Cromer-Mundesley, Norfolk	4.95	Mathews, 1934
Southwold, Suffolk	3.3	Steers, 1951
Black Ven, Dorset	3.14	Chandler, 1989; Bray, 1996
Barton-on-Sea, Hampshire	1.9	Barton & Coles, 1984
Holderness, Yorkshire	1.8	Pethick, 1996
Dunwich, Suffolk	1.6	So, 1967
Marl Buff-Kirby Hill, Norfolk	1.1	Hutchinson, 1976
Pakefield, Suffolk	0.9	Steers, 1951
Runton, Norfolk	0.8	Cambers, 1976
Walton-on-Naze, Essex	0.52	Hutchinson, 1973
Stonebarrow, Dorset	0.5	Brunsden & Jones, 1980
Chale Cliff, Isle of Wight	0.41	Hutchinson *et al*., 1981
West Bay (W), Dorset	0.37	Jolliffe, 1979; Bray, 1996
Purbeck, Dorset	0.3	May & Heaps, 1985
Flamborough Head, N. Yorks	0.3	Mathews, 1934
Charton Bay, E. Devon	0.25	Pitts, 1983
White Nothe, Dorset	0.22	May, 1971
Downderry, Cornwall	0.11	Sims & Ternan, 1988
Bindon, E. Devon	0.1	Pitts, 1983

Table 1.3

Retreat rates around the coast of England

1.1.3.2 Global environmental change

In view of recent estimates of accelerating sea level rise (IPCC, 2007), it is clear that this factor must now be taken into account when evaluating cliff retreat risk. Consensus is that the 20th century rise in global sea level was between 1.5 to 2 mm a^{-1} (Miller and Douglas, 2004; Woodworth, 2009) with values around 1.7 mm a^{-1} having been obtained recently for the past century (Church & White 2006) or past half-century (Church *et al.* 2004; Holgate & Woodworth 2004). Rainfall, particularly storm rainfall, is acknowledged as playing a significant role in cliff stability (Sunamura, 1992). Rainfall and surface runoff are two of the 'preparatory processes' that reduce the strength of cliff materials (Greenwood and Orford, 2008). Global climate change is expected to change both the seasonality and intensity of these storm events. For example, since 1950, there have been substantial increases in the number of heavy precipitation events over many land areas around the globe and in Europe, particularly in winter (Moberg *et al.,* 2006). Climate models are currently the best available tool for making projections over the next 100 years (Lowe *et al.,* 2009). However, there is uncertainty in the ability of these models to simulate climate, what the future emissions will be, and the degree to which the effects of natural variability for a particular time in the future can be modelled (Lowe *et al.,* 2009). The likely changes to climate and their consequences for soft rock cliff stability are key issues in this thesis and will be discussed later.

1.1.3.3 Uncertainty in predictions of retreat rates

When formulating Shoreline Management Plans it is necessary to provide an assessment of the potential for landward movement of the cliff line, or to forecast cliff position at some future time. Providing this information is a major challenge to coastal governance as the response of coastal cliffs to environmental inputs can be complex and non-linear (DEFRA, 2002; Dronkers, 2005). This leads to uncertainty in predictions of retreat rates because:

a. cliff retreat can be an episodic and is controlled by both shoreline and slope processes;
b. there are a range of cliff forms and processes and there is inherent variability in the cliff materials;
c. the stability of a cliff over time is determined by the combination of geotechnical factors (e.g. pore water pressure changes) and geomorphological factors (e.g. marine erosion and groundwater levels) at a given time;

d. variations in the size of triggering event, that is needed to initiate failure, complicate prediction of the timing and frequency of a major retreat event;
e. many of the generally accepted causal factors, such as wave height, rainfall etc., are inherently random (DEFRA, 2002).

1.2 Timescales for soft rock cliff erosion and controls on retreat rates

1.2.1 Soft-rock cliffs

Soft rock cliffs are defined as those cliffs developed in erodible rocks that have little resistance such as clays, shales or sandstone, or unconsolidated materials such as sands (Defra, 2002). Soft rock cliffs are often characterised by the presence of rock waste and sediments (sand or pebbles) on the strand (Eurosion, 2004). The UK has a wide variety of such cliffs (DEFRA, 2002). Hutchinson (1984) and Jones and Lee (1994) set out the seven broad categories of cliff type to which these cliffs belong. The sub-types refer to cliffs developed in:

a. weak superficial deposits;
b. weak superficial deposits overlying jointed rock;
c. developed in stiff clay;
d. weak sandy strata;
e. sequences of stiff clays and weak sandy strata;
f. stiff clay with a hard cap-rock;
g. bedded, jointed weak rock.

The Soft Cliffs Manual for Managers (DEFRA, 2002) sets out four stages in the cliff retreat process. These stages comprise a) the detachment of cliff material; b) the transport of this material through the cliff system; c) deposition on the foreshore; and d) subsequent redistribution or removal by marine action as shown in Figure 1.2.

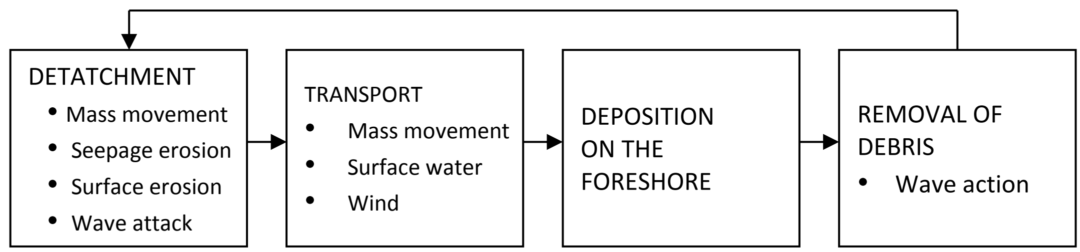


Figure 1.2

The four stages in the cliff retreat process

Soft rock cliffs are sensitive to the balance between marine action and terrestrial mass movement processes such as collapse of the cliff face (e.g. Sunamura, 1982; Mortimore *et al.,* 2004; Richards and Lorriman, 1987; Pethick, 1996). A cyclical and episodic model of the cliff retreat process (Hutchinson, 1973; Everts, 1991; van Rijn, 1998; Brunsden, 2001; Hall *et al*., 2002, Eurosion, 2004) can therefore be set out whereby:

a. waves erode the base of the cliff, undercutting and over-steepening it, causing collapse;
b. the resulting talus is attacked by waves;
c. simultaneously to (b) sub-aerial erosion decreases the slope of the cliff and;
d. once the debris talus has been removed by marine action, undercutting resumes and the cycle repeats.

1.2.2 Soft rock cliff failure processes and mechanisms

The basic types of mass movement that can occur in response to gravitational forces are; Falls, Slides (rotational, compound, translational or mudflows) and Slips (successive or multiple). Slides can be either 'first-time' slides in previously unsheared ground or slides on pre-existing shears. They can be further divided into short-term (undrained) slides with no equalization of excess pore water pressures set up by changes in total stress, or long-term (drained) slides where there is complete equalization. A third category of partial equalization lies between these two. Slip types have been described by Gilroy (1981) and Hutchinson (1986) and Richards and Lorriman (1987) and can be distinguished by whether the position of emergence of the failure toe is in the cliff face, at or near the cliff foot, or in the shore platform. Phenomena observed in coastal slopes in other cohesive materials, which may also occur at Covehithe, are now briefly described. The low glacial drift cliffs of the Holderness coast in Yorkshire coastline (UK) form part of one of the fastest eroding coastlines in Europe (Furlan, 2008). Hutchinson (1986) described a process leading to falls in the cohesive cliffs near Cowden, where rounded notches undercutting the cliffs resulted in the formation of tension cracks in the cliff forming material upslope. Subsequent failure occurred by shearing between the base of the crack and the notch. The cliffs of south-west Isle of Wight exhibit differences in failure type ranging from large rotational slides to shallow failures, whereas the Highdown cliffs display upper shallow toppling or slab failures with shallow slides or falls with undercutting at the base (Hutchinson, 1984).To the north-west of the Isle of Wight, seepage erosion appears to have been most important in giving rise to benches in the cliff profile. Retreat in the Barton Clay cliffs in Hampshire, UK, is characterised by scarp slumping, spalling (including toppling and soil falls), bench sliding (involving movement of colluvium over a preferred bedding plane), debris sliding and mud sliding. Bench sliding accounted for almost all of colluvium moved through the undercliff(Barton and Coles, 1984).The chalk cliffs along the English Channel coast have a relatively rapid long-term retreat rates (of between 0.11 and 0.7 m a^{-1} (see Dornbusch *et al.*, 2006). Retreat along this coast is predominantly by mass collapse of parts of the cliff face or whole cliff sections, causing the cliff top line to retreat often by several metres in one event (Mortimore *et al*., 2004). Chalk flows can also occur (Hutchinson, 2002; Williams *et al.*, 2004). Larger failures tend to occur in higher cliffs composed of stronger chalks (Moses and Robinson, 2011). In addition to large mass collapse, smaller, discrete pieces of the cliff face also periodically fall away as a result of processes such as freeze–thaw, salt weathering, and expansion and contraction caused by heating and cooling or wetting and drying (Moses and Robinson, 2011). Falls with long run-outs that resemble Sturzstroms also occasionally occur (Hutchinson, 2002; Williams *et al*., 2004). Robinson and Jerwood (1987) have reported significant spalling of chalk cliffs although they gave no figures for its contribution to cliff retreat. The Castle Hill landslide at Folkestone, Kent was a retrogressive, multiple, rotational landslide in the Chalk and Gault Clay. The slips adopted a common shear surface by utilising the low strength along a lateral clay extrusion layer formed within the escarpment under the Chalk overburden (Brunsden, 1999). Hutchinson (1988) gives the most important considerations in slope movements involving shearing as being soil fabric and pore-water pressure conditions on the slip surface. Consequently, different types of landslide may be related to different climatic threshold conditions. A number of characteristic climatic settings have been defined for inland mass movements. Shallow translational slides and debris flows in steep catchments are often associated with high intensity rainstorms. Landslides tend to be triggered within minutes or hours of the event. For example, surface run-off supplies water to debris masses which have accumulated within and adjacent to stream channels. This increases the pore pressures within the debris, initiating a debris flow (Common, 1954). Shallow landslides are often associated with a rapid rise in groundwater levels in response to single storm events. Eventual failure is then associated with critical pore water pressure thresholds being exceeded (Terlien, 1996; Corominas and Moya 1996) or as a result in the increased weight of the saturated soil. Harp (1997) has reported landslides were triggered in the hours and days following exceptional rainstorm activity and Casale and Margottini (1995) also describe how widespread catastrophic landslide activity has been associated with exceptional one- and two-day rainfall totals that exceeded all previous historical maxima. Deep-seated landslides are generally associated with prolonged heavy rainfall. Positive pore pressures along a shear surface, induced by a rising groundwater table often trigger this type of failure. As it is the relative pore water pressure (the ratio between pore pressure and the total normal stress on the shear surface) which determines stability, the absolute amount of water for triggering deeper landslides is greater than for shallower slides. In general, longer periods of antecedent heavy rainfall that will be needed to initiate deeper slides. The rainfall period may vary from several days (e.g. Reid 1994) to many months (e.g. Lee *et al.* 1998). In many areas, it may be that pattern of wet years that appears to control the occurrence of landslides (e.g. Bromhead *et al*. 1998).The association between rainfall and cliff retreat will be developed later in this thesis.

1.2.3 Timescales for soft rock cliff erosion

The cyclical process described in Section 1.2.1 typically repeats at a timescale of years, decades and tens of decades, centuries and millennia (Brunsden and Jones, 1980; Schumm and Lichty, 1965; Cambers, 1975; Cowell *et al.,* 2003; Nicholls *et al,* 2007; Cambers, 1976; Pethick, 1996, Maddrell *et al*., 1999; Halcrow, 2003). Defra (2002) identify three relevant timescales appropriate to erosion in soft-rock systems:

a) short term behaviour on sub-annual and annual scales, where retreat appears to be a highly variable process; characterised by periods of no activity punctuated by short phases of retreat;
b) medium term behaviour over, decades and tens of decades, where the retreat rate appears relatively constant and there is balance over time in the sediment budget; and
c) long term behaviour such as the response of the cliff line to environmental changes over millennia e.g. the Holocene climate and sea level changes.

This concept was developed by Perillo (2003) who provided a range of temporal scales that defined short-term, medium-term and long-term and added ‘Microscale’ events, which operate over time periods of minutes and seconds (Table 1.4).

	Megascale	***Macroscale***	***Mesoscale***	***Microscale***
Time	Century	Years/Months	Days/Hours	Minutes/Seconds

Table 1.4

Temporal scales for coastal environments

The issue of timescale is important in coastal management, particularly as models of coastal behaviour often reconstruct changes over millennial time scales or incorporate process studies at sub-annual scales (Rodriguez *et al.,* 2001; Storms *et al.,* 2002; Stolper *et al.,* 2005). Unfortunately, the generally accepted timescale of climate change requires insight into processes at decadal to century scales, the scale at which understanding is least developed (de Groot, 1999; Donnelly *et al.,* 2004, Nicholls *et al.,* 2007). The research in this thesis will attempt to contribute to meeting this need.

1.2.4 Controls on retreat rates

<u>*1.2.4.1 Primary factors*</u>

It is widely accepted that sea cliff erosion is determined by the relative intensity of the resisting and the destabilising forces acting on the cliff (Sunamura, 1983). In turn this is determined by the lithology, the cliff structure and the marine boundary conditions at the cliff base (Table 1.5).

Factor	Sources
Cliff lithology	Lithology controls resistance to destabilising forces (Benumof and Griggs, 1999;Benumof *et al*., 2000; Del Rio and Garcia, 2009)
Cliff structure	Cliff discontinuities (Greenwood and Orford, 2008) reduce the overall strength of the cliff (Sunamura, 1983).
Marine boundary conditions at the cliff base	Energy expended against the cliff by the forces of wave impact (Quigley *et al*., 1977; Trenhaile, 1987; Sunamura, 1992); the tractive force of the wave up-rush (Robinson, 1977; Kamphuis, 1987; Nairn*et al*., 1997) and the local bathymetry with features such as offshore banks (Robinson, 1980; Halcrow, 2003, Pye and Blott, 2006) all control the wave energy arriving at the cliff base.

Table 1.5

Primary factors in soft-rock cliff retreat process

1.2.4.2 Secondary factors

Secondary factors exert a less direct control on retreat rates than the primary factors outlined in Section 1.2.4.1. Commonly accepted secondary factors that control soft sea cliff retreat rate are summarised in Table 1.6.

Factor	*Sources*
Presence and characteristics of a protecting beach	A protective beach at the cliff toes can act as a buffer zone by dissipating wave energy (Sunamura, 1983; Lee, 2008). Seasonal variation in beach height can affect the degree of protection and hence retreat rate (Lee, 2008).
Storm events	Storm events have been strongly correlated with cliff erosion (e.g. Griggs and Johnson, 1983; Komar, 1998; Storlazzi and Griggs, 1998; Lee, 2008).
Wave and tide climate	Tidal range and wave climate determine the maximum elevation of daily water levels (e.g. Lee, 2008) and the exposure of the coast to storm wave fronts (shore normal waves being the most destructive) (e.g. Del Rio and Garcia, 2009).
Cliff hydrology	Suction dissipation has been proposed as a failure mechanism for clay cliffs on the Holderness coast of Yorkshire (Quinn *et al.*, 2010), Pleistocene Crag cliffs in Suffolk (Brooks *et al.,* 2012) and emphasised as a secondary control in cliff failures at Pacifica, California by Collins and Sitar (2008) and Young *et al*. (2009).
Development and human activity	Coastal engineering structures placed at the cliff foot may prevent marine erosion at the toe, even if sub-aerial processes continue to destabilise the cliff (Lee *et al*., 2001, Jones and Lee 1994).

Table 1.6

Summary of the secondary factors that control retreat rate in soft rock cliffs

The primary and secondary factors outlined in Sections 1.2.3.1 and 1.2.3.2 act in a complex way and individual factors may dominate, dependent on field conditions (Hampton and Griggs, 2004). For example, Brooks *et al*. (2012) propose that cliff geology acts both as a primary control in relation to suction loss and as a secondary control through its interaction with basal marine conditions in cliffs on the eastern coastline of England. The relative importance of primary and secondary controls on retreat rate is a crucial issue that will be discussed later.

1.2.5 Episodic cliff erosion: triggering events and preparatory processes

1.2.5.1 The Sunamura (1983) model

Soft rock cliffs exhibit considerable variation in retreat caused by the changing balance between terrestrial mass movement processes and marine action (e.g. Sunamura, 1982; Pethick, 1996). However, the process of soft sea-cliff retreat follows the general scheme suggested by Sunamura (1983):

1. Coastal erosion caused by wave action forms a retreating cliff and this process is promoted by low cliff material strength
2. Basal erosion causes slope steepening, with mass movements being triggered at times of high rainfall totals or intensity
3. Debris is supplied to the base of the cliff by mass-movements, thus protecting the coast from further retreat
4. These deposits are removed by the action of long-shore currents and wave action until the cliff base is again exposed to erosion
5. A new cycle of basal erosion–mass-movement–transport–basal erosion can then begin

In step two of Sunamura's scheme, basal erosion causes slope steepening, with mass movements being triggered at times of high rainfall totals or intensity. The triggering of mass movements at times of high rainfall totals or intensity is complicated by the proposition by Brunsden of the existence of redundant events.

1.2.5.2 Brunsden's concept of redundant events

Brunsden and Lee (2000) propose that failure is not an inevitable consequence of the arrival of a storm that removes material from the cliff toe, or conditions that raise groundwater levels in the cliff. In order to fail the cliff must already be in a state of deteriorating stability, which makes it prone to the effects of an initiating storm event. Brunsden and Lee (2000) suggest that:

a) Some triggering events of a particular magnitude may be redundant i.e. unable to initiate cliff retreat until preparatory factors lower the margin of stability to a critical value; and

b) Equally sized triggering events may not necessarily both lead to retreat events, as the response of a cliff to storms of a particular size is controlled by the antecedent conditions.

The variable interaction between potential triggering events and landslides set out by Brunsden and Lee (2000) is shown in Figure 1.3.

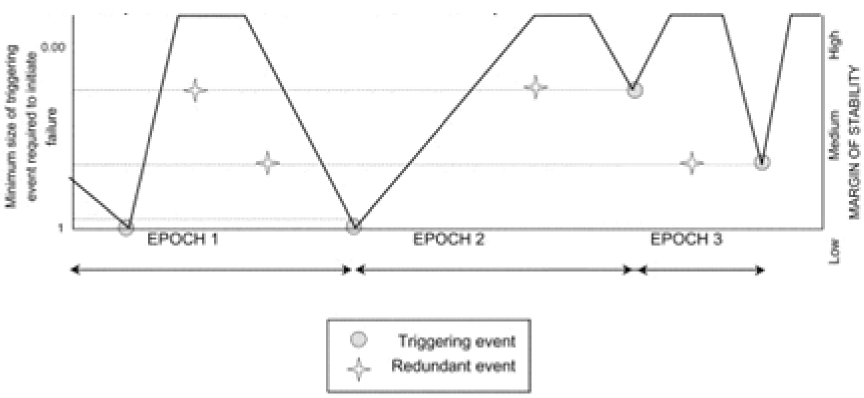


Figure 1.3

The variable interaction between potential triggering events and landslides

(after Brunsden and Lee, 2000)

The scheme in Figure 1.4 makes it possible to recognise that there are preparatory factors and triggering factors (Brunsden and Lee, 2000; Lee *et al*., 2001).

1.2.5.3 The relationship between preparatory and triggering factors

Lee *et al*., (2001) set out the complex relationship between triggering and preparatory factors. Simplistically, as preparatory factors progressively reduce the margin of safety in the cliff, so the size of triggering event required to initiate failure becomes smaller. Events of a given magnitude therefore fail to initiate instability until preparatory factors have lowered the margin of stability to such an extent that one event becomes critical. Consequently, there may be variable time periods between retreat events depending on the sequence of differing magnitudes of rainfall events. This further explains why retreat in soft-rock cliff does not conform particularly well to common statistical models (Brunsden and Lee, 2000; Lee, 2005).

1.2.5.4 Future scenarios after change in external forcing factors

Increases in storm surges and extreme water levels as a result of global environmental change are expected to intensify coastal retreat rates, particularly on low angle shorelines (Michener *et al.*, 1997; Esteves *et al*, 2011; Lozano *et al.,* 2004; Tsimplis *et al.,* 2005) or where the highly erodible nature of soft rock cliffs makes them particularly sensitive to the impact of sea level rise (French, 2001; Lee, 2008). Changes in storminess and precipitation under climate change are also widely expected to affect the future stability of soft rock cliffs (Pierre and Lahousse; 2006, Nicholls *et al.,* 2007; Masselink and Russell, 2007). Higher storm energies may lead to increased beach erosion (Maddrell *et al*, 1999; Halcrow, 2003). Shoreline migration and sediment redistribution may also occur as a consequence of greater wave heights that may be associated with increased storminess (Dan *et al.*, 2009). For these reasons, further research into the response of soft rock cliffs to environmental drivers such as water level and precipitation is timely.

1.3 Research needs for better understanding of soft cliff erosion

1.3.1 Recent research advances

Reduction in soil suction on infiltration and groundwater flow has become understood as a critical mechanism for mass failure on terrestrial hill slopes (e.g. Campbell, 1975; Brooks and Anderson, 1995; Wilkinson *et al.,* 2000;Wilkinson*et al*.,2002; Brooks *et al.,* 2004). Research into the stability of river banks (typically *ca*. 5m high banks composed of fluvial materials and exhibiting a complex dynamic hydrology) has progressively sought to account for: a) a more realistic bank geometry and the influence of tension cracks (Osman and Thorne, 1988); b) positive pore water pressures (Simon *et al*., 1991; Darby and Thorne, 1996) and, c) the effects of negative pore water pressures in the unsaturated part of the bank (Rinaldi and Casagli, 1999; Casagli *et al*., 1999; Simon *et al*., 2000). Changes in pore water content and pressures are recognised as one of the most important factors controlling the onset and timing of instability in these banks (Thorne, 1982; Springer *et al*., 1985) and the incorporation of these factors in bank process models is one of the major areas of recent progress (Dapporto *et al*., 2001, 2003; Simon *et al*., 2002; Rinaldi *et al*., 2004).Similarly, the role of pore water pressure in cliff failures has been emphasised by Collins and Sitar (2008) at Pacifica, California, and Young *et al.* (2009) in southern California. Recently, high-resolution datasets with a fine temporal resolution have been applied to disaggregate the small scale variability in the retreat history at a given cliff site (Burningham and French, 2006, Brooks and Spencer, 2010; Brooks *et al.*, 2012). Morphological information obtained from Light Detection and Ranging and terrestrial laser scans (Collins and Sitar, 2008); GPS derived field monitoring (Baptista *et al.,* 2011); or from digitised aerial photographs and historical maps (e.g. Brooks and Spencer, 2010) is now available to parameterise models and allow insight into cliff line dynamics. Such approaches have provided information on the role of the 'beach wedge area' as a major control on cliff retreat (Lee, 2008; Quinn *et al.,* 2010) and the spatial and temporal variability in coastal soft rock cliff retreat over annual and decadal scales (e.g. Brooks *et al*., 2012). Importantly, Brooks *et al.* (2012) have matched archival datasets on retreat with records of sea surface water levels, wind strength and direction, and rainfall to assess the relative roles of marine and terrestrial forcing under the range of event magnitudes in high (ca. 17 m) cliffs. Their modelling included detailed assessment of the dynamic hydrology and negative pore-water pressure regimes. Taken together, these developments have allowed unprecedented insight into the negative pore-water pressure regimes that may control temporal and spatial variability in soft rock cliff retreat rates.

1.3.2 The remaining gaps that need to be addressed

Quinn *et al.* (2010) suggest retreat in low (<7 m) cliffs in clay materials on the Holderness coast, eastern England, is through mass failure, under negative pore water pressure (suction) dissipation. A plausible alternative mechanism for cliff failures in low soft rock cliffs might involve the formation of localised saturated zones within the cliff (Rulon and Freeze, 1985) which cannot be tested using the method of Quinn *et al.* (2010). Brooks and Spencer (2012) have modelled the contribution of suction dissipation in soft rock cliffs, but this work did not attempt to evaluate the contribution of localised positive pore-water pressure regimes. The hypothesised contribution of positive pore-water pressure to failure mechanisms has not been evaluated in low (<7 m) rock cliffs, a type present along stretches of the eastern coastline of the UK and elsewhere. New research may help pinpoint a more specific role for positive pore-water pressure zones in the preparatory and trigging processes for cliff failure in soft rock cliffs. This may have benefit when assessing the potential for cliff failure under future rainfall regimes on climate change, as changes in rainfall patterns may promote conditions that lead to the formation of zones saturation in soft rock cliffs.

<u>1.3.2.1 The non-conformance of soft sea-cliff retreat to common statistical methods</u>

Soft rock cliff erosion does not conform well to statistical extrapolation from survey reports, maps and other historical records. Ibsen and Brunsden (1996) have described the use and problems of historical archives in their study of the temporal occurrence of landslides at

Ventnor, Isle of Wight, UK. Key difficulties include accessing, extracting and analysing data that has not been collated for scientific use, and accounting for unknowable errors caused by the editing and recording process over time. In addition, the data are usually unplanned or fortuitous, and the haphazard nature of the record means some archives may remain undiscovered and unanalysed. Furthermore, historic records alone cannot be used where future conditions are not expected to resemble past conditions (Hall *et al*., 2002). Indeed, Hall *et al*. (2002) propose that if a site is characterised by very rare mass-movements, few events may have been recorded over time. In these cases, regression techniques will be of little value, despite having the advantage of being the most straightforward approach to predicting cliff retreat. Hall *et al*. (2002) also argue that linear regression models are least valid at sites that are characterised by strongly episodic retreat processes. Additionally, from a practical viewpoint, field based study could be difficult to conduct, not least because of the short time periods of observation in comparison to what may be long periods between events. The limitations of extrapolating from historical retreat rates have also been put in context by Lee (2005) and Lee (2008), using the example of the cliffs on the Suffolk coast, England. When retreat measured in repeated annual beach profile surveys were compared to calculated values, they were found to be significantly different. For these reasons, a numerical modelling approach is desirable.

1.3.2.2 The incomplete understanding of the role of rainfall infiltration in the retreat of soft sea-cliffs

None of the research discussed in 1.3.1 focuses on to what extent positive pore water regimes, which may arise after high-intensity storm rainfall events, contribute to failure in soft rock cliffs in highly heterogeneous lithologies. In particular, no research has explored how climate controls the long-term, seasonal and short-term pore-water pressure heads, how topography controls the localised positive pore-water pressure gradients and how water level controls the incidence of slope undercutting in soft sea-cliffs. The saturated-unsaturated flow and pore-water pressure changes, which may contribute to failure in such cliffs, can be evaluated using combined hydrology-stability models. Investigations using this modelling approach, applied with relevant field data to provide a detailed model parameterisation, have the potential to provide insight into the hydrological processes that control failure in soft-rock coastal cliffs.

1.3.3 The specific role of modelling in meeting the research needs

It is proposed in this thesis that numerical modelling (e.g. Brooks *et al*., 2012) has been proven in the evaluation the forcing factor of suction loss against marine forcing through ongoing basal processes in soft rock cliffs. Accounting for the heterogeneity in soil, the topographic conditions and the complexity of the spatial and temporal rainfall inputs required provide challenges when parameterising such models (Graham and McDonnell, 2010). However, detailed stability analysis is only made possible by using such techniques (see Section 1.3.1). Brooks *et al*., (2012) have demonstrated that it is possible to exploit the techniques available to hillslope modellers, particularly numerical simulation of the dynamic hydrology, to elucidate the processes that control instability in soft sea-cliffs. A detailed numerical modelling approach can be justified because field methods, despite being derived from observations made in real systems, have disadvantages. The need to base future expectations on past behaviour can, for example, reduce the value of extrapolation from the historical record in complex or rapidly changing environments. Furthermore, data such as mass-movement inventories or hazard maps are rarely reported in the literature and in general, field techniques are also not able to provide reliable estimates of the timing of future events. Accepting that there is a need to consider modelling approaches, stochastic methods could be applied as they can model erosion as a series of discrete events. A stochastic technique can also accommodate input uncertainty by defining a probability distribution for each input parameter and calculating a factor of safety probability distribution. These models of past retreat may, however, be less valuable in systems where there is a complex interdependence of variables and there is uncertainty in the description of the process. In these situations, a process description approach can be used to investigate the proposition that periods of rainfall intensity can induce susceptibility to failure in soft sea-cliffs caused by localised regions of positive pore-water pressure.

1.4 Thesis Outline

The thesis has the following structure:

Chapter 1 Sets out the general significance of cliff erosion, cliffed coastlines and retreat rates around the UK and challenges to coastal governance. The timescales for soft rock cliff erosion, the controls on retreat rates, and relevant cliff failure processes and mechanisms are then described. The need for better understanding of the role of rainfall infiltration in the retreat of soft sea-cliffs is set out and the specific role of modelling in meeting the research needs established.

Chapter 2 Sets out the regional geological setting and process environment for the east coast of England and the southern North Sea, and places the study site cliffs at Covehithe Suffolk in context. The Chapter concludes with the reasons Covehithe is a suitable site for study.

Chapter 3 Provides a detailed description of the research design which was followed, including the research methodology, input data collection methods, model parameterisation and data analysis methods.

Chapter 4 Provides the history of retreat in the cliff line at Covehithe and the results of the investigations into: a) the association between rainfall and cliff retreat, b) the terrestrial forcing of cliff retreat, and c) marine forcing of cliff retreat at the study sites.

Chapter 5 Provides a detailed discussion of the research findings in Chapter 4

Chapter 6 Sets out the conclusions from this research and the recommendations for further work

Chapter 2 The Study Site: cliffs at Covehithe Suffolk

2.1 Background to the study area

2.1.1 Regional setting

The research in this thesis is focused on the rapidly retreating cliffs of the Suffolk coast, UK. The region between Lowestoft (in the north) and Southwold (in the south) is important because historic and contemporary coastal retreat rates here are among the highest found globally, as well as within the UK. This area contains several cliff sections which, while not particularly high, stretch for significant distances alongshore. The geology of the Suffolk coast makes the cliffs prone to high retreat rates which delivers large quantities of sand-sized sediment to the near-shore zone. The coastal stretch in this research is located between two major near-shore sandbank systems, Dunwich-Sizewell to the South, and the Great Yarmouth-Lowestoft Bank system to the north. The offshore sandbanks are highly dynamic (Robinson, 1966; Carr, 1979; Robinson, 1980; Reeve and Fleming, 1997; Horrillo-Caraballo and Reeve, 2008; Pye and Blott, 2006) and have significant effects on the inshore wave climate. This area has seen little direct involvement of coastal management schemes so presents an opportunity for relatively uncomplicated analysis and assessment of the possible drivers of historic and contemporary change in the shoreline. For all the above reasons, the Suffolk coastline presents one of the greatest future management challenges for the region in particular and the UK as a whole as it undergoes such rapid retreat. The setting of the study area within the UK together with the location of East Anglia (Inset A), the Suffolk coast (Inset B) and the main coastal features between Lowestoft and Southwold are shown in Figure 2.1.

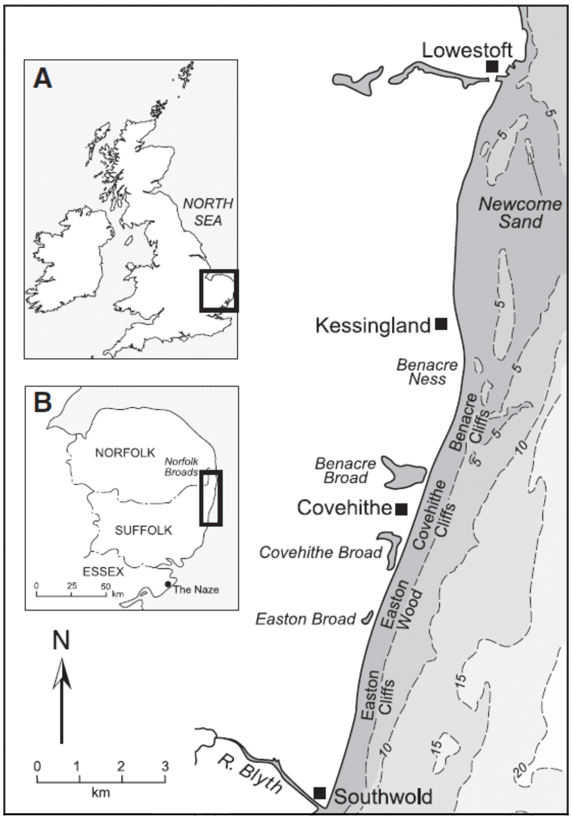


Figure 2.1

Map of the east coast of the UK with insets showing the location of (A) East Anglia and (B) the Suffolk coast (after Brooks and Spencer, 2012). The coastal bathymetry is also shown. Depth contours are in meters below lowest astronomical tide (mLAT).

2.1.2 The nature of rapidly eroding soft cliffs

2.1.2.1 Cliff morphology and height

The three major cliffed sections in the study region (Figure 2.1) comprise a 3km stretch south of Lowestoft facing the Newcome Sand, an 8km stretch between Benacre and Southwold and a 3km cliff line between Dunwich and Minsmere (Brooks, 2010). To the North the cliffs reach a maximum elevation of 16 m (Lee, 2008). Moving southward, cliff elevation ranges from between 6 to 8m at Benacre to up to 14 m at Covehithe and Easton Woods (Brooks, 2010). Between Dunwich and Minsmere the cliffs reach a maximum elevation of around 17 m

(Brooks, 2010). The cliffs are frequently fronted by a beach of gravels and coarse sands with large inter-annual fluctuations in beach elevation, ranging from no beach being present, to one covering significant parts of the cliff base (Lee, 2008).

2.1.2.2 The geological structure of typical soft cliffs in the region

The stratigraphy of the coastal region of East Anglia has been reviewed in Brooks (2010) and Brooks *et al.* (2012) is comprised of Pliocene to Early/Mid Pleistocene marine deposits overlying eroded Palaeogene and Cretaceous basement rocks (Moorlock *et al*., 2000; Gibbard and Zalasiewicz, 1988; Gibbard *et al*., 1998). Borehole studies between Aldeburgh and Orford in the south suggest Calcarenites are present (Coralline Crag from the late Early/Middle Pliocene) as well as coarse-grained shelly sands (iron-stained Red Crag from the later Pliocene to early Pleistocene) below about -5m OD (Zalasiewicz *et al*., 1988), which also outcrops offshore in the region (Brooks, 2010). These early Pliocene to early Pleistocene deposits are overlain by the more recent Norwich Crag Formation, consisting of alternating and complex strata of sands and clays. The Chillesford Sand Member of the Norwich Crag, a well-sorted fine to medium sand, is dominant in the south of the region. On moving northward this disappears and is replaced laterally by coarser-grained, shelly sands which are very similar in character to the older, underlying Red Crag (Gibbard and Zalasiewicz, 1988). At places alongshore sediments of the Crag were deposited as intertidal mudflats, and are composed of grey silty-clay with thin layers of fine-grained sand. These deposits are highly fossiliferous (West *et al*., 1980; Moorlock *et al*. 2000), as typified by exposures in the cliffs of Easton Bavents. The silty-clays are date from the Baventian stage of the Early Pleistocene, (Funnell and West, 1977; Zalasiewicz *et al*., 1988).

The soft cliffs in the region are composed of Pliocene and early-mid Pleistocene marine deposits overlying a Palaeogene and Cretaceous basement (Brooks *et al.,* 2012). The basal layer of clays and silt-clays is overlain by moderately and weakly cemented sand, gravel and thin clays of the Crag group (Gibbard and Zalasiewicz, 1988, Moorlock *et al*. 2000, Cruickshanks, 2004, Lee, 2005). The characteristic sands and interbedded thin clays within the Crag have been well described by Funnell (1961), West (1961) West (1963), Funnell and West (1977), West (1980), Gibbard *et al*. (1998), Zalasiewicz *et al*. (1991) and Gibbard *et al*. (1991). The cliffs in the region are capped with a 1-2m thick soil layer (Brooks *et al.*, 2012).The Norwich Crag can also be seen further to the north in the cliffs of Easton Woods and at the southernmost end of the Covehithe cliffs (Long, 1974). The Baventian clays overlying the Crag here dip northwards from Easton Woods for about 1 km, and it is in the cliffs of Covehithe that the coarser sand and gravel deposits of the Westleton Beds become evident, overlying the clays (West, 1980). The Westleton Beds at Covehithe contain gravel lenses (Hey, 1967) with rounded flints cut into the sands of the beach face (Brooks, 2010). The Westleton Beds at Covehithe are overlain by the Kesgrave Formation of predominantly gravels, and the overlying Corton sands assigned to the Anglian Glacial Period (Gibbard and Zalasiewicz, 1988). There is a capping of decalcified Lowestoft Formation (Anglian) till, also seen at Dunwich (Brooks, 2010). Further north the cliffs of Benacre comprise a lower Baventian Clay, overlain by Westleton Bed marine sands, and gravels and capped by the Corton sands (Brooks, 2010).

2.1.3 Regional bathymetry

2.1.3.1 Southern North Sea

The North Sea is a shallow shelf sea with connections to the north Atlantic and is dominated by strong tidal currents and frequent strong winds (Tomczack and Godfrey, 1994). The North Sea first formed during the Permian with the principal basins coming into existence at the same time that the original super-continent began to break up (Shennan *et al*., 2000). The bathymetry in the region is complex and is characterised by the presence of nearshore and offshore structural features such as sandbanks and channels that affect both the tidal regime and surge levels (Brooks, 2010) and wave propagation towards the shore (Chini *et al*., 2010). The coastal process environment is determined by how prevailing waves, tidal regime, surge levels and sea level trends are modified by the local and regional bathymetry.

2.1.3.2 East Anglian coast

The bathymetry of the North Sea offshore of the East Anglian coast between Sheringham and Southwold is characterised by the presence of long narrow sandbanks (Stansby *et al*., 2006; Pye and Blott, 2006) (Figure 2.2) that reduce depths at points 1-2 km offshore to the range 0 - 5 mLAT.

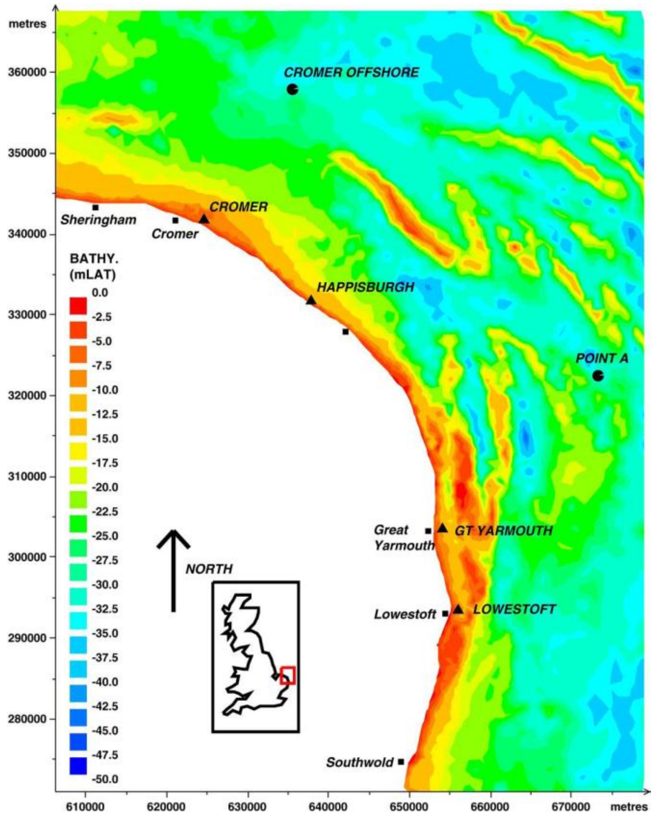


Figure 2.2

Map of bathymetry offshore of the East Anglia coastline, showing the depth as mLAT

(Chini *et al.,* 2010)

The banks off the East Anglian coast are highly mobile (Horrillo-Caraballo and Reeve, 2008; Park and Vincent, 2007) and interact with waves and with the adjacent beaches (Stansby *et al*., 2006; Dolphin *et al*., 2007) in a complex manner. Waves generated offshore are subjected to processes that transform their height, period and direction as they propagate through coastal waters (Dean and Dalrymple, 2002). The complex bathymetry determines the shift in wave direction by refraction, shoaling, and wave energy dissipation mainly due to bottom friction and depth-induced breaking (Chini *et al*., 2010). The consequences of these interactions are critical to the coastal dynamics of the region and their impact will be discussed later in this Chapter.

2.1.3.3 Offshore configuration of the Suffolk coast

The bathymetry of the Suffolk coast is dominated by the Great Yarmouth-Lowestoft Bank system to the north and the Dunwich-Sizewell bank to the South (Figure 2.3).

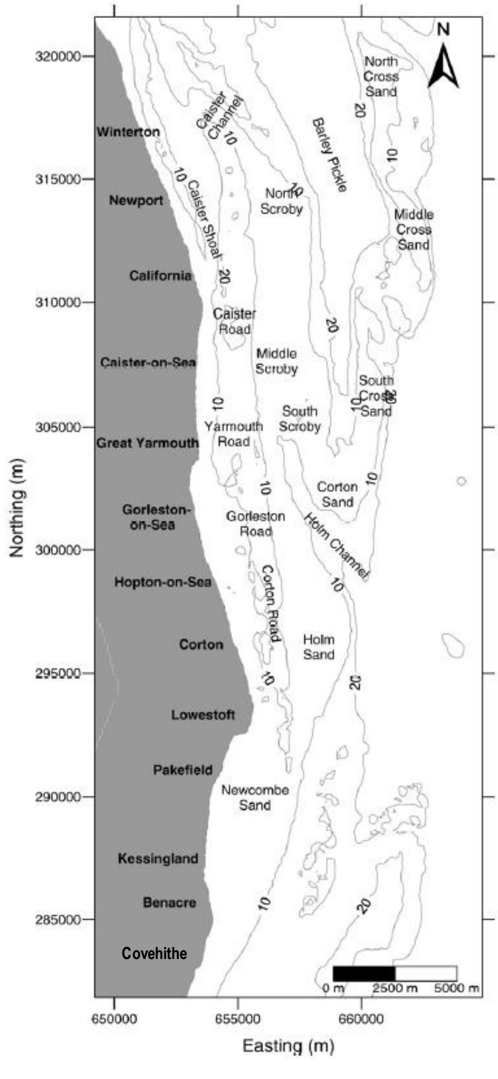


Figure 2.3

The location of the main banks off the Suffolk coast from Winterton to Benacre in the UK National Grid Reference system(after Horrillo-Caraballo and Reeve, 2008)

The principal morphological features of the bank system between Winterton Ness and Benacre are: a) Caister Shoal which is located approximately 1 km offshore and runs parallel to the mainland between Winterton and Newport, b) North and Middle Scroby approximately 2km offshore and also parallel to the mainland between Newport and Great Yarmouth c) the three segments of the Cross Sand running parallel to the Scroby Sands but further offshore, Corton Sands and d) Holm Sands, approximately 3km east of Lowestoft and the Newcome Sand between Pakefield and beyond Benacre to Covehithe (Horrillo-Caraballo and Reeve, 2008; HR Wallingford, 2002). These sandbanks are all highly dynamic and their shape and extent have changed significantly in historic times (Carr, 1979; Robinson, 1980; Pye and Blott, 2006; Horillo-Caraballo and Reeve, 2008). The influence of these sandbanks on coastal erosion is complex (Halcrow, 2001; Pye and Blott, 2006). Recent research has suggested the slowing of rates in the Dunwich-Minsmere cliffs since the 1920s to values between 0.5 and 1 m a^{-1} (Pontee, 2005; Pye and Blott, 2006) may relate to the development of the Sizewell-Dunwich sandbank and the development of a coarse-grained protective beach from material released from the retreating cliffs (Brooks, 2010).

2.1.3.4 Near shore configuration of the Suffolk coast

In common with the bank system offshore, the nearshore features along this coast are constantly changing as they are also in equilibrium with the prevailing wave and tide conditions. For example, historical shoreline change has been affected by the movement of Benacre Ness, thought to be around 23 m a^{-1} (with short-term rates being up to 70 to 100 m a^{-1}) (Williams and Fryer, 1953; Robinson, 1966; Babtie Group and Birkbeck College, 2000; Foody *et al.*, 2005). A detailed investigation into the current nearshore bathymetry in region between Southwold and Benacre (for location see Figure 2.1) has been provided by Brooks (2010). This bathymetric assessment indicated that in the north of the region there near shore deepening is associated with high rates of coastal retreat. Along the coast between Covehithe and Benacre a bathymetric deepening of between 3 and 6 m was reported as having taken place over the past 125 years. Further to the north from Covehithe the bathymetric deepening was found to have been in excess of 6 m. Brooks (2010) found that the highest rates of shoreline change were associated with the greatest bathymetric deepening over time. The situation was most acute at Benacre, as a channel is oriented almost exactly towards the North East, which is the direction of approach of the largest waves (Blott and Pye, 2006). Continued progression of Benacre Ness northward will increase the extent of the shoreline that is exposed to such waves, resulting in higher retreat rates in future and a potential new source of sediment supply (Brooks, 2010).

2.2 Sea level history

2.2.1 Long term sea level changes (Holocene)

The regional sea-level history of the last 10,000 years has been particularly influential to present day trends in shoreline position (MCCIP, 2007). After melting of the ice sheets, sea levels changed through a combination of global changes in sea level and localised displacement of the land to achieve their present levels (Shennan *et al*., 2000; Shennan and Horton, 2002). Information has been obtained from geological data on the former shoreline (e.g. Shennan, 1989) or by direct measurement of present day vertical land movements using GPS techniques and changes in gravity using an absolute gravimeter (e.g. Baker, 1993 and Neilan *et al*., 1998). The consensus is that the relative sea level was approximately 30m lower than present around 9000 years BP (Coles and Funnell, 1981; Shennan and Horton, 2002; Jones *et al*., 2004) with several regressive and transgressive phases (Brew, Funnell and Kreiser, 2002). At 7,500 years BP global mean sea level was approximately 15 m below present (Shennan *et al*., 2000) and at this time, the coastline of east England had a very different shape and was located more than 10 km seaward of the present coastline. Sea level rose rapidly until 600years ago, after which it remained at approximately the same level due to the compensatory effect of subsidence of the bottom of the North Sea (Eisma, 1987). Sea level attained its approximate present position during the seventeenth century (Carr, 1969).

2.2.2 Sea level history of the last century

The effect of recent global sea-level rise on the UK coastline must be considered in combination with the changes in the land level associated with isostatic effects, in particular rebound of the formerly glaciated areas in the north, and collapse of the forebulge of areas near the ice margin in the south (Shennan & Horton, 2002)(Figure 2.4).

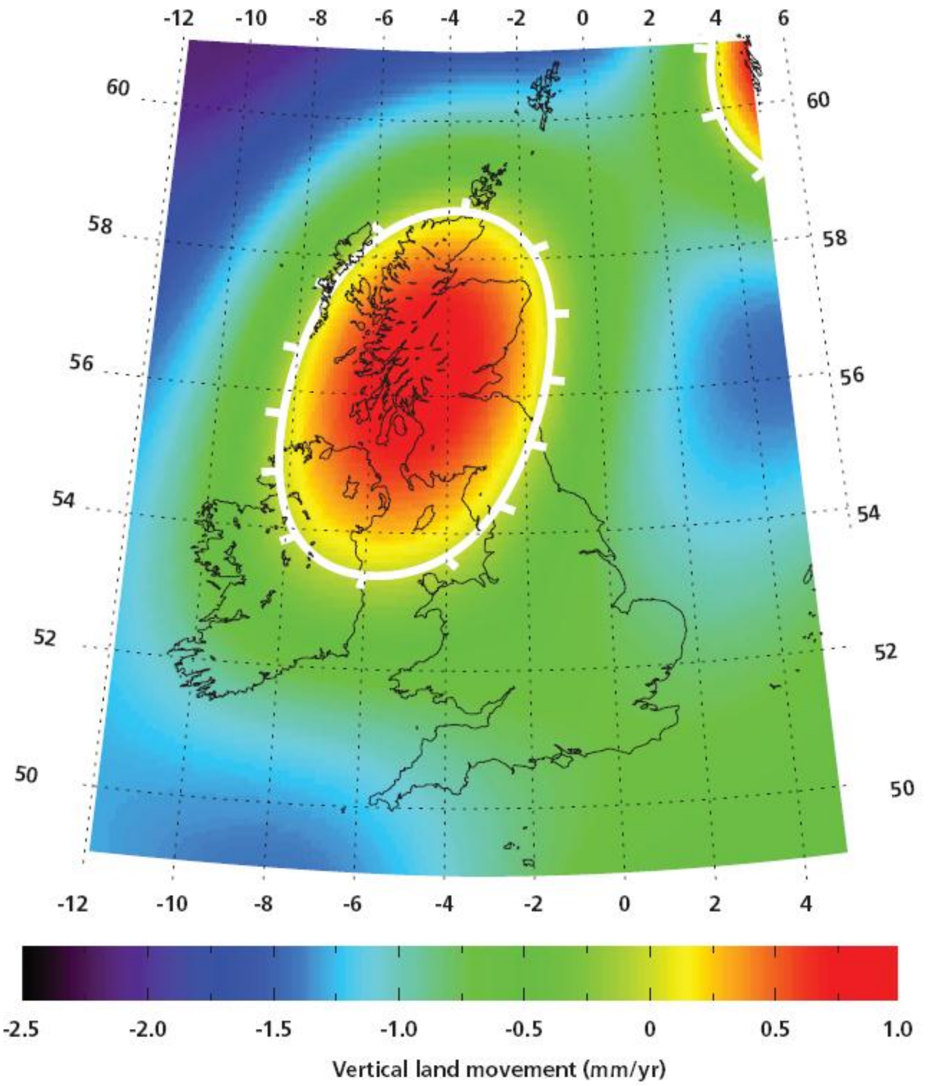


Figure 2.4
Glacial Isostatic Adjustment map of the vertical land movement (mm/yr) for the UK (UKP09)

Isostatic adjustments of the British Isles are a major factor in relative sea level rise in the south east UK (Shennan and Horton, 2002; Shennan *et al*., 2006). The southern North Sea has been characterised by a gradual sea level rise (estimated at approximately 2 mm a^{-1} (Shennan and Horton, 2002; French and Burningham, 2003; Pye and Blott, 2006). Comparison of tide gauge, geological and geodetic trends has provided an estimate of 1.4 ± 0.2 mm/yr for the climate-related change in the UK Mean Sea Level since 1901 with increases in the study region of between 2.47 ± 0.23 mm a^{-1} and 2.57 ± 0.33 mm a^{-1} (Shennan and Horton, 2002; Woodworth *et al*., 2009).

At Lowestoft, twentieth century mean sea-level rise has been estimated at 1.81 ± 0.48 mm a^{-1} (Shennan & Horton, 2002). Recent estimates for Lowestoft show a higher rate of relative sea-level rise. This has been calculated variously at between 2.4 mm a^{-1} (1964 to 2001; French & Burningham, 2003) and 2.47 ± 0.23 to 2.57 ± 0.33 mm a^{-1} (1956 to 2006; Woodworth *et al*., 2009). Using tide gauge records from Lowestoft for the period since the mid-1970s Pye & Blott (2006) identified a rise of 13 cm between 1975 and 2005. This corresponded to a rate of relative sea-level rise of 4.3 mm a^{-1}.

2.2.3 Current trends in sea level

Against a background of sea level rise, coastal retreat is likely to accelerate, particularly in places characterised by high historic rates of change. The UK Climate Impacts Programme's UKCP09 projections (Lowe *et al.,* 2009) are that UK coastal absolute sea level rise (excluding Isostatic realignment) for 2095 may range from approximately 12cm to 76cm. The UKCP09 report does not include a discussion of the Global Positioning System measurements of land elevation change in the British Isles by Teferle *et al*., (2009) and Woodworth *et al*., (2009). The results obtained by Teferle *et al*. (2009) are consistent with the geological data of Shennan and Horton (2002) for isostatic movements in the British Isles. Using the UKCP09 (Lowe *et al.,* 2009) user interface, Brooks *et al*. (2012) predict a rise in relative sea level (against a 1990 baseline) at Lowestoft of 34 cm by 2050 and of 70 cm by 2095. These rates are equivalent to sea-level rise of 5.7 mm $a^{-1}$and 6.7 mm a^{-1}, respectively.

2.3 Process environment

2.3.1 Rainfall

Rainfall is one of the most significant triggering factors for slope failure (Rahardjo *et al*., 2009). This section sets out typical annual rainfall totals and introduces the inter-annual variability and seasonality of rainfall in the study region.

Regional annual rainfall for East Anglia in the period 1910 to 2011 ranged from a minimum of 346 mm (in 1921) to a maximum of 779 mm (in 2001) (www.met.gov.uk). The mean annual regional rainfall for East Anglia over the same period was 611 mm (SD 88 mm). On the Suffolk coast, twentieth Century annual rainfall totals were typically 550 mm (Neal and Phillips, 2009). Specifically at Wrentham (2.8 km inland from Covehithe) annual rainfall totals in the period 1993 to 2008 ranged from a minimum value of 465.0 mm (in 1996) to a maximum value of 807.5 mm (in 1993) (UK Meteorological).

Seasonal minimum and maximum rainfall total values for the East Anglian region were highly variable between 1910 and 2011. Winter rainfall total values ranged from 57 mm (in 1934) to 288 mm (in 1915) and summer rainfall total values ranged from 57 mm (in 1921) and 322 mm (in 1912) (www.met.gov.uk). For Suffolk, the long-term summer (June, July and August) rainfall mean was 142 mm (1971 to 2000) with considerable inter-annual variability (Neal and Phillips, 2009). Locally, rainfall totals for summers ranged from a minimum value of 183 mm (in 1993) to a maximum of 433 mm in (2007). Winter period rainfall totals ranged from a minimum value of 221 mm in 2003 to 540 mm in 2008 (data for Wrentham).

Daily mean rainfall values at Wrentham (for days with < 0.1 mm of rain) in the period 1993 to 2008 ranged between 3.3 mm (SD 5.5 mm) and 5.4 mm (SD 7.3 mm). Crucially for the research in this thesis, these mean values masked extreme rainfall events. Examples of daily extremes at Wrentham were 48 mm on 11th October 1993, 34 mm on 9th August 1999, 69 mm on 15th October 2002 and 70 mm on 27th May 2007.

2.3.2 Tides

The tidal regime in the study area is semi-diurnal with a Mean Spring Tidal Range of 1.90 m. Mean High Water Springs reaches 1.04 m ODN with a Highest Astronomical Tide of 1.50 m ODN at Lowestoft (Burningham and French, 2008; Brooks *et al.,* 2012). Tidal range increases in a southward direction, with a spring tidal range of 1.9m at Lowestoft; 2.0m at Southwold; 2.3m at Orford Ness and 3.1m at Felixstowe (French and Burningham, 2003).

2.3.3 Waves

The magnitude of wave run-up (Ruggerio *et al*., 2001) and the intensity of wave processes at the beach and cliff base (Lee, 2008) are critical to coastal erosion. Waves in the southern North Sea waves are typically of low-moderate energy, attaining average heights of 0.4-0.5m (Fortnum and Hardcastle, 1979). Winds are of key significance to wave direction and strength. Kuang and Stansby (2004) found that nearshore significant wave heights are affected when these wind speeds are higher than 10 m s^{-1}. In the case of local extreme wind, significant wave height can be increased by 0.6 m along the coast. When the wind regime is translated to wave response, as has been carried out by the UK Meteorological using the European Waters Wave Model for a location 48km offshore from Dunwich (Figure 2.5), the waves originating from the northeast were the largest (>2.2m) as a result of the higher fetch from this direction (Carr, 1979; Pye and Blott, 2006). The orientation of the Suffolk coastline (parallel to the 20-200 degree radials in Figure 2.5) makes this situation particularly damaging as strong onshore winds, generating the highest (non fetch-limited) waves, are likely to coincide with high water levels.

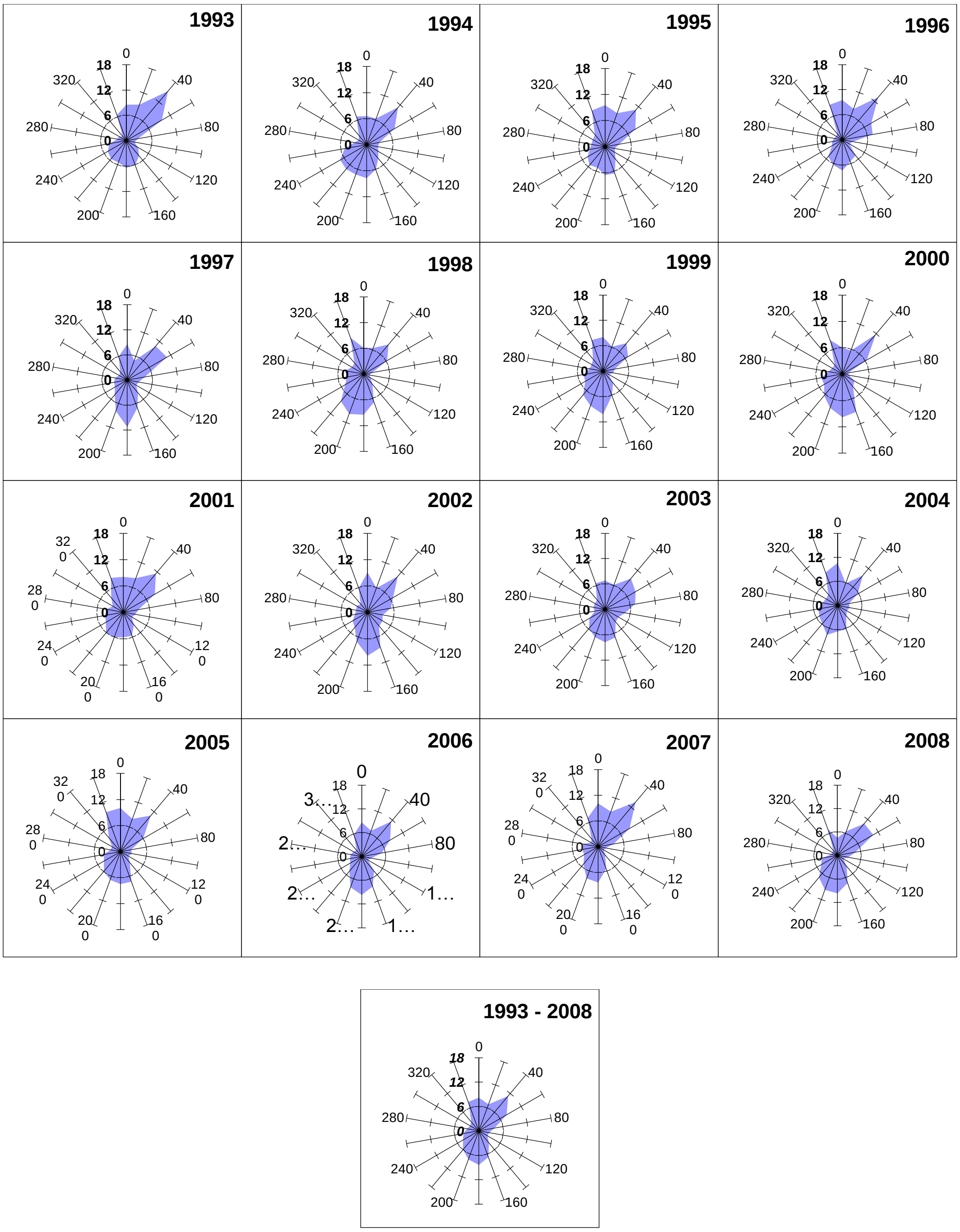


Figure 2.5

Rose diagrams showing percentage of total against direction (radial axes - degrees true) for waves modelled at a point 48km offshore of Dunwich. Wave directions are predominantly south-westerly but with a north-easterly component.

2.3.4 Sediment transport, sediment cells and sand bar dynamics

In the relatively shallow waters of the southern North Sea, sediment released by cliff retreat in near shore and offshore regions is of great significance, particularly as it might affect subsequent shoreline retreat (Brooks and Spencer, 2010). For example, the Shoreline Management Plan (Royal Haskoning, 2010) cites the need to allow coastal retreat to continue at Covehithe in order to maintain the sediment supply for beaches and sandbanks to the south. The importance of sandbank development in offering coastal protection has been emphasised by Robinson (1980) and more recently by Stansby *et al*. (2006) and Horillo-Caraballo and Reeve (2008), with the growth of the Dunwich-Sizewell Bank being cited as a potential reason why coastal retreat rates have slowed in the region. Pye and Blott (2009) have presented evidence for the link between sandbank development and associated cliff retreat rate decline at Dunwich-Minsmere. The publications by Carr (1981), as well as Pye and Blott (2009), suggest that one possible sediment source for the growth of the Bank is from cliffs to the north, namely Easton cliffs and Covehithe.

The sandbanks along the Suffolk coast have important implications for the wave and current regime acting along this coastline (Clayton, 1989; Robinson, 1966). Seaward directed horizontal pressure gradients, caused by tidal surges, drive cross shore near bed currents (Hequette *et al*, 1995). These currents, combined with high-energy waves significantly increase the potential for sediment transport. Indeed, once the waves have supplied the power to mobilise the sediment, the direction and magnitude of the resultant transport will be strongly influenced by the residual surge currents (Hequette *et al*, 1995). It is therefore likely that considerable offshore sediment transport takes place during high wave energy and surge events (Hequette and Hill, 1995; HR Wallington). There is also evidence to suggest that surge driven currents can instigate liquefaction of fine-grained sediments (Nelson, 1982). The sediment systems are highly dynamic and there have been significant changes in the morphology and position of the banks and offshore structures in the region over time (Dolphin *et al*., 2007). The general direction of sediment transport is southward with offshore sediment transport at Lowestoft and Kessingland, in the north, and at Dunwich and Thorpeness, in the south (e.g. McCave, 1978; Vincent, 1979; Clayton *et al.,* 1983; Blott and Pye, 2006). Storm direction can cause variation in the sediment transport pathways. For example, high-energy northerly storms drive southerly transport (Brooks *et al.,* 2012) whereas low-energy waves from the south produce northerly transport (Pontee, 2005).

2.4 Extreme events

Increases in the frequency and magnitude of storms may affect the future stability of coastal cliffs, as coastal flooding and storm surge risks increase with increasing windstorm activity (Flather and Smith, 1998; Tsimplis *et al*., 2005). However, it is important to distinguish storms from storm surges, as very few storms are actually accompanied by significant surges. Storms (as these will affect waves) and surges (elevated wave conditions and water level) should be considered separately when analysing the drivers for coastal change in the region. This is because it is possible to have a surge with high waves (for example the 1953 storm surge event; Wolf and Flather, 2005) or with little wave activity (for example the 1978 event; Steers *et al.,* 1978). The distinction between changes in storm surge risk due to windstorms and those due to background sea level is also important because of differences in their relative predictability. So, three extreme event scenarios can be envisaged and underpin the research in this thesis:

a) Extreme rainfall (which may, or may not, be associated with storm-force winds)

b) Extreme surges (water level could also be elevated depending on tide level)

c) The situation where both of the above coincide, reinforcing the significance of storms and storm surges

2.4.1 Development of extreme events in the North Sea

The shallow bathymetry of the southern North Sea, the mesotidal regime and the passage of low pressure weather systems make the Suffolk coast vulnerable to periodic surges (Pugh, 1987; Lamb, 1991; Baxter, 2005). Brooks *et al*., (2012) describe three different synoptic conditions where surges arise in the southern North Sea: south-east tracking (e.g. the disaster of 31st January to 1st February 1953); east tracking (e.g. 2nd to 3rd January 1976) and southern North Sea events (e.g. 12th January 1978). These surges significantly exceed the tidal range on occasion (Pugh, 1987; Muir Wood *et al*., 2005). For example, the storm surge of 31st January to 1st February 1953 reached a height 4.6 m CD (i.e.: 3.1 m OD) at Lowestoft, which was 1.62 m above the Highest Astronomical tide of 2.98 m above sea level (Horsbaugh *et al*., 2008).

2.4.2 Impacts of extreme storms and storm surges

Extreme storms and storm surges can cause rapid retreat in coastal cliffs (Williams, 1956; Steers *et al.,* 1979) and short-term retreat rates exceeding 10ma^{-1} have been attributed to single events of this kind (Steers, 1953; Williams, 1956; Steers *et al*., 1979). The 1953 surge event which reached 3.44 m ODN at Lowestoft (Rossiter, 1954) was associated with storm force winds of >25 m s^{-1}, gusting to over 50 m s^{-1} (Baxter, 2005) and extreme offshore wave conditions (Wolf and Flather, 2005). This event was the worst natural disaster to occur in the United Kingdom during the twentieth century (Baxter, 2005). In eastern England 307 lives were lost, 24,000 houses were damaged, 160,000 acres of agricultural land were flooded with salt water, and transportation links were impassable (Summers, 1978). The cost of such an event occurring today is not well understood, but the damage caused by the 1953 surge event was estimated to be equivalent to £5 billion in 2003 money (RMS, 2003).

2.4.3 Storms, storm surges and climate change: future trends

The UKCP09 climate projections suggest that UK rainfall is likely to continue to become more polarised in the future. The projected changes in seasonal rainfall (spring, summer, autumn and winter) from the baseline (1961-90) for low and high emissions scenarios (UKCIP09) from the 2020s to 2080s are a) for spring, the projections are for relatively minor increases in rainfall (0 to +5%) with little change over time., b) for summer, a decrease in rainfall is expected, ranging from -10% to -25% , c) for autumn the impacts are similar to spring (0 to +5%), and d) for winter, increases in rainfall of +5% to +20% are projected (Knox and Daccache, 2011). As illustrated in Figure 2.6, East Anglia is already showing a trend towards increased importance of heavy rainfall events during winter and a trend towards decreased importance of heavy rainfall events during summer (Moberg *et al.,* 2006; Mauran *et al.,* 2008). Much of the rainfall in the UK is produced by frontal processes, which have a typical duration of 5 days (Brown *et al.,* 2008). The total amount of rain from a storm might not change, but the temporal characteristics are predicted to alter. For example, a typical 1 in 5 year storm might last for 3 hours during the present day but could only last 2 hours (with more intense rainfall) in the future (Met , 2010). Similar conclusions were reached by Fowler and Wilby (2010) and Fowler *et al.,* (2010).

The return periods of extreme rainfall events with a given return level are also likely to change. When the return levels of daily rainfall events with return periods of 20, 30, 50 and 100 years were calculated (Met , 2010) using UKCIP09 projections the biggest increases in frequency occurred over Suffolk. Increased precipitation and consequent higher groundwater levels may increase cliff failure and retreat (Hosking and McInnes, 2002; Codignotto, 2004; Pierre and Lahousse, 2006). Rising sea levels and greater storm activity also suggest that storm surge risk is likely to increase along many coasts, especially since the rate of increase in extreme sea level could be greater than the increase in mean values locally. Lowe and Gregory (2005) project increases in extreme sea level (storm surges with a 50-year return period) along the entire coastline of the UK. Changes in atmospheric storminess have the potential to cause the height of storm surges to change (Lowe and Gregory, 2005) and storm surge risks increase as windstorm activity increases (Flather and Smith, 1998; Tsimplis *et al*., 2005).

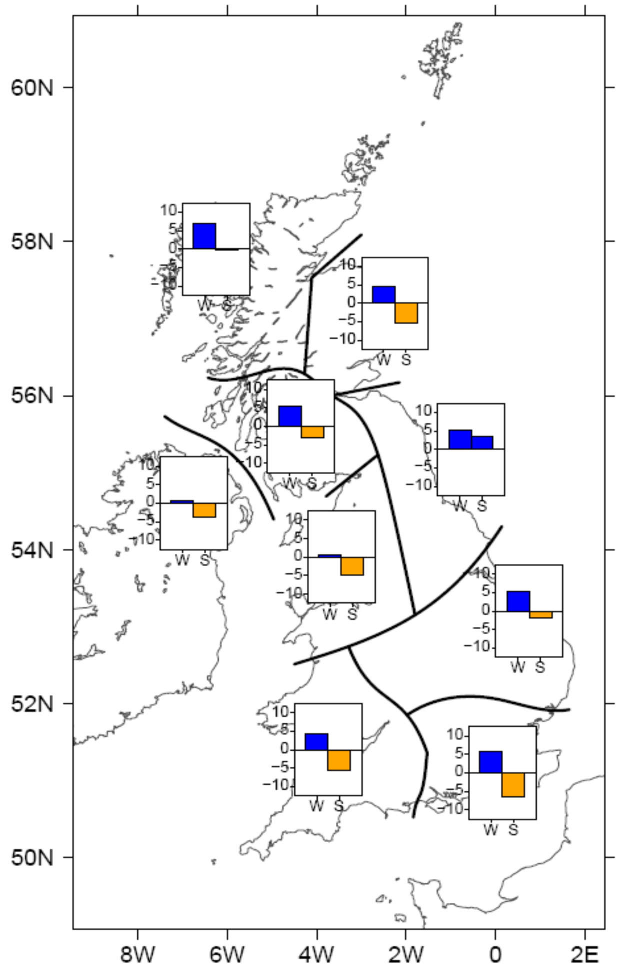


Figure 2.6

Regional trends over the period 1961-2006 in the contribution (%) made by heavy precipitation events to total winter (left-hand bars labelled "W") and summer (right-hand bars labelled "S") rainfall (Maraun et al., 2008).

2.5 The suitability of Covehithe for study

The Suffolk coastline presents one of the greatest future management challenges for the UK as a whole and the East Anglian region in particular, as it undergoes such rapid retreat. At Covehithe, 6 km north of Southwold (Figure 2.1), mean cliff retreat rates have been quantified at 1.8–4.5 ma^{-1} between the 1880s and 1950s (Cambers, 1976). For the period 1883–2008, mean retreat rates of 2.33±0.22 to 3.49±0.40 ma^{-1} have been suggested (Brooks and Spencer, 2010). Covehithe forms part of Sub-cell 3c Policy Development Zone 2 of the Suffolk Coastal District Council/Waveney District Council/Environment Agency Shoreline management Plan (Royal Haskoning, 2010). In this plan a decision has been taken not to invest in providing or maintaining defences or management of the eroding soft rock cliffs. Under a policy of No Active Intervention, increased coastal erosion is likely to have an impact on residents of coastal areas, the environment, tourism and industry. This situation makes Covehithe a microcosm of the problems facing rapidly eroding soft-rock shorelines in the United Kingdom.

Covehithe has been the subject of interest for some time. For example, Whitaker (1887) noted that some of the erosion at Covehithe was caused by the sliding down of masses of earth from the upper parts of the cliff, rather than by the undermining of the cliffs by the sea. The presence of clays in the strata along this section of coast (Section 2.1.2) may offer some insight into the mechanism that initiated the failures observed by Whittaker. The ground waters in the Crag group are hydraulically isolated (Moorlock *et al*., 2000) a situation that may allow hydrological features such as local perched water tables to form. Lateral movement of groundwater in these cliffs could also occur (Lloyd and Hiscock, 1990). Landslides in other cliffs are reported to occur predominantly when the water table is elevated and the cliff-forming material is saturated with water (Pethick, 1975; Hutchinson, 1972; Duperret *et al*., 2004; Lageat *et al*., 2006). To what extent a mechanism involving subaerial rather than marine controlof the cliff retreat process could not, until recently, be tested in detail. Covehithe provides an opportunity for numerical modelling of cliff failure events that potentially occur as a result of the dynamic hydrology brought about by the geological setting of the cliffs.

The description of the process environment of the North Sea already presented, together with the wealth of information on the geological characteristics of the soft-rock cliffs at Covehithe, illustrate the valuable contextual background information available for this site. Crucially, the advent of Differential Global Positioning Systems has lead to significant improvement in data availability and accuracy of cliff surveys conducted in the field. The Environment Agency Sea Defence Management System program (introduced in the following Chapter) has provided biennial field surveys of the coastal profile at points along the Suffolk coast, including Covehithe. Thus, there is a detailed at-a-point temporal record of coastal profile change spanning two decades. This information allows ‘erosion hotspots’ to be identified, which can be examined in detail using a physically based hydrology-stability model that simulates both unsaturated and saturated zone hydrology. Chapter 3 sets out theresearch design and the methodology.

Chapter 3 Research Design and Methodology

Rainfall stress is considered to be important in the failure of soft rock sea cliffs because: a) it may set up loss of soil suction as observed in other cohesive slopes, and b) landslide activity may be related to a critical water content comprising of antecedent water content in the slope and the additional water contribution of a particular rainfall event. The ability of a physically-based hydrological model to describe the pore-water pressure within the slope over time may be valuable when investigating the response to rainfall stress. Differences in the response to short term high intensity rainfall, compared with those for longer term rainfall taking place over a number of days or weeks, may be important. Physically-based models use either a finite difference or finite element scheme to solve equations of saturated and unsaturated flow through a 2-dimensional slice of a landslide. When linked with stability analysis models they provide a tool for simulating dynamic hydrological conditions. This approach accounts for the hydrological conditions and their dynamic variation with time in response to rainfall infiltration. Unprotected cliffs such as those at Covehithe, Suffolk, may respond to high water levels (such as may occur in storm and surge events) with an accelerated rate of cliff retreat.

The gaps in current understanding the hydrological and stability response to rainfall infiltration in soft rock sea cliffs identified in Chapter 1, together with the need to establish a link between retreat in such cliffs and changing water levels, lead to the following Research Questions:

1. What are the patterns of retreat behaviour in the cliffs along the Suffolk coast around Covehithe?
2. How do terrestrial controls on retreat influence the observed cliff behaviour, in particular is there a demonstrable association between rainfall and cliff retreat?
3. What effect does rainfall stress have on the dynamic hydrology in the heterogeneous cliff lithologies present at Covehithe?

4. How long do changes in soil suction on rainfall infiltration persist, i.e. are the cliffs in an unstable state for extended periods of time?
5. What is the effect of other influences on the stability of the cliff, e.g. the potential for water contact and hence erosive force at the cliff base?

Some of these questions were partly answered in the literature review, but all required further investigation. The research design employed detailed archival datasets combined with numerical modelling to enhance understanding of the highly dynamic geomorphological system at Covehithe, Suffolk. The design focussed on Terrestrial and Marine forcing of cliff retreat (Figure 3.1) investigating the process response to activation by extreme rainfall events and by high water levels during surges. Two complementary approaches were used. Analysis of at-a-point cliff and beach morphology surveys and water level information for five cliffed sections of coastline was combined with a detailed investigation at one of these sites, including hydrology-stability modelling at a fine temporal scale. The analysis using the at-a-point survey data was primarily aimed at questions (1), (2) and (5). The detailed numerical modelling of the hydrological response to rainfall stress and the consequent changes in cliff stability at the in-depth study site was aimed at questions (3) and (4). The research design is shown in Figure 3.1 with the activation mechanisms and process responses to Terrestrial and Marine forcing included in the approach shown in the shaded boxes.

The specific aims were to:

1. Quantify temporal variation in retreat for soft rock cliffs of Suffolk, eastern England from 1993 to 2008;
2. Assess terrestrial process drivers for the observed cliff retreat under a wide range of rainfall events using cliff and beach morphology datasets, matched with rainfall total records (including information on exceptional storm events);

3. To simulate suction loss within the geologically complex cliffs of Suffolk, eastern England, and to link the dynamic hydrology during rainfall infiltration specifically to observed retreat;
4. Assess marine process drivers for cliff retreat under a wide range of events using cliff and beach morphology datasets, matched with water level records (including information on extreme storm surge events).

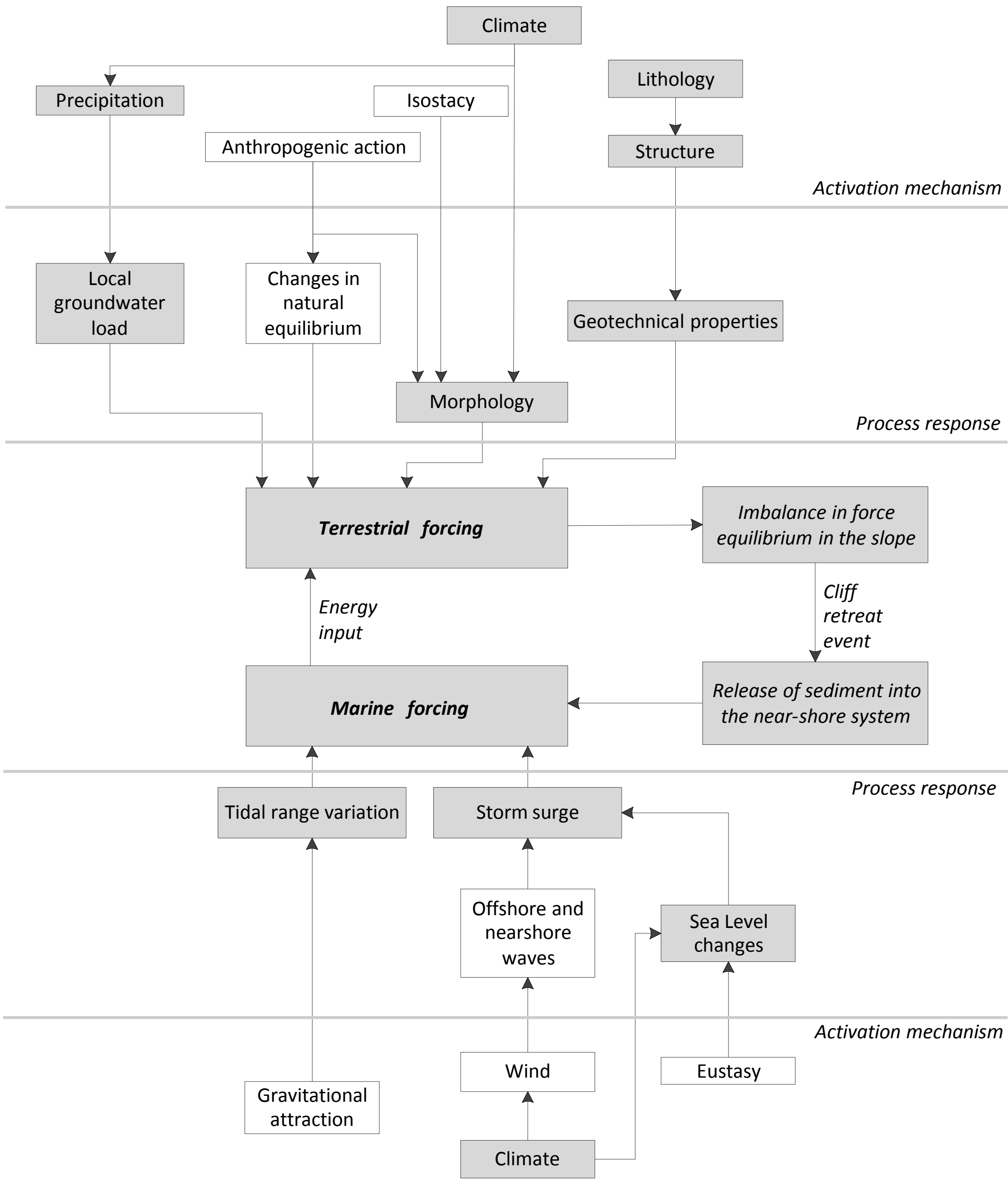


Figure 3.1 research Design: Terrestrial and Marine forcing processes

3.2 Methodology

3.2.1 Models that have been used to elucidate cliff retreat

Historically, the literature on coastal cliffs was dominated by descriptive analyses (e.g. Arber, 1940, Steers, 1946) rather than models of the observed behaviour. In 1973, Hutchinson provided one of the first models of slope development and this work, together with the work of Barton (1973), Sunamura 1973) and Cambers (1976) established modelling approaches to sea-cliff erosion. The most straightforward approach to predicting retreat is by using historical data in a continuous linear model which determines the retreat distance at a given time by simple linear regression theory (Cowell *et al*., 1997). This approach can be developed further to incorporate random sampling of retreat rates using a Monte-Carlo sampling procedure so that a probabilistic description of cliff position at any year in the future can be obtained (Halcrow, 2007). Historical retreat information can be obtained from archive material such as surveys and maps (Brunsden, 1974; McGreal 1979; Ibsen and Brunsden, 1996; Pethick, 1996; Lee, 2005) or from geo-rectified maps and photos digitised into a Geographical Information System (GIS). For example, Moore and Griggs (2002) and Moore *et al*. (2003) reported an improved method of determining cliff retreat rates using GIS and predicting future cliff position. Brooks and Spencer (2010) have used GIS platforms that synthesise data from digitized aerial photography and historical maps to investigate at-a-point temporal change and alongshore variation in cliff dynamics. Hapke and Richmond (2002) investigated the impact of seismic and storm events on episodic cliff retreat by using three-dimensional mapping to analyse cliff failure styles and retreat magnitudes. They found storms had a greater impact on both the linear extent of cliff failure and the amount of retreat than seismic events. Lee (2005) has used published data and expert judgement, to evaluate retreat in the eroding cliffs at Covehithe, Suffolk. The factors determining cliff retreat, such as sea-level, wave climate and cliff material resistance to erosion, were considered separately and probability distributions for the impact of each factor were estimated in an analysis informed by historical survey data.

These approaches benefit from being generally straightforward to undertake, having a clear methodology and having the ability to be used to determine the impact of various scenarios (Halcrow, 2007). Their main disadvantages relate to situations where a study site is characterised by very rare mass-movements, so that few events may have been recorded over time, or there are strongly episodic retreat processes (Lee and Clark, 2002; Hall *et al*. 2002). Long-term trends can be obscured by large-scale, shorter-term variations in cliff dynamics. The model outputs are usually a single future retreat rate, meaning that the short-term impact of episodic landslide events will not be represented (Halcrow, 2007). Other problems include difficulties accessing, extracting and analysing data that has not been collated for scientific use and the impossibility of accounting for unknowable errors caused by the editing and recording process over time (Ibsen and Brunsden, 1996). Consequently, extrapolation of historical rates appears extremely unreliable unless it is supported by an understanding of the dynamic behaviour of the cliff–beach system and the energy and sediment inputs over the observation period.

Coastal process models incorporate the relationships between the processes of cliff retreat. This simplest way this can be done is relating retreat directly to the destructive force of wave power and the resistive force of material strength (Sunamura, 1983). More recently probabilistic stability modelling have included representations of beach and foreshore erosion as well as sediment transport (the Sunamura model was derived for cliffed shorelines having no dissipative beach or shore-face sediment layer) (e.g. Bray and Hooke, 1997; Hall *et al*., 2002; Halcrow, 2007; Walkden and Dickson, 2008). Sallenger *et al*. (2002) have identified the linkages between El Niño-driven storm events, beach width and episodic cliff erosion. Hall *et al*. (2000) identified stretches of cliff-line which behaved in broadly the same way. Each of these stretches, or ‘Cliff Behaviour Units’ will fail, and stabilise after failure, in a consistent way. The analysis does not include the exact parameters of failure (such as angle assumed after failure) because they cannot be predicted precisely, due to factors such as temporal variations in pore pressure and local variations in cliff strength and composition.

Lee *et al*. (2001) and Hall *et al*. (2002) have provided probabilistic models for determining cliff retreat that incorporate a description of the uncertainties by representing key values as normally-distributed random variables, with means and variances obtained from a geomorphological assessment. Process cliff behaviour models can be combined with stochastic and other probabilistic techniques, often based on Monte Carlo sampling (e.g. Meadowcroft *et al*. 1997). Their approach uses a shoreline analysis technique to study the effects of cross-shore and long-shore sediment transport processes on the long-term erosion rates of soft cliffs. In their model the cliff retreat was assumed to proceed by means of a series of discrete mass-movements, the size and frequency of which was then modelled as random variables in a stochastic analysis.

Bruun (1962) presented an empirical model for deriving the shoreline response to sea level rise, applicable to low-lying shores with a sediment covered shore platform. The Bruun model can be modified to predict the retreat increase due to sea level rise taking into account the sediment budget (Dean 1991). This approach is considered to be a more realistic adaption of the Bruun Rule for eroding cliffs (Bray and Hooke 1997) as the Bruun (1962) approach has been reported as providing shoreline positions that underestimate retreat by more than an order of magnitude (Nicholls and Stive, 2004). Trenhaile (2000) presents a platform change model that incorporates the sensitivity of shore platform morphology to variability in parameters such as tidal range, material resistance and to wave climate. Cliff-PLAN (Meadowcroft *et al*. 1999; Hall *et al*. 2000; Walkden *et al*. 2001) uses random sampling of the input parameters from probability distributions (Monte Carlo simulation) to represent uncertainty in the cliff retreat process. The model simulates the retreat of an unprotected coastal slope (developed in London Clay) and is based on cross-shore models of beach and cliff behaviour. The main stages in the model are:

1. Monte Carlo selection of wave conditions and water level from an appropriate probability distribution
2. Calculation of the wave approach angle and longshore drift rates
3. Calculation of wave run-up
4. Estimation of cliff toe/foreshore erosion and of the stability of the cliff (factor of safety) using the relevant stability tables
5. Where the factor of safety is less than unity, cliff failure takes place and the cliff is retreated to the amount specified in the relevant stability table. The debris from the cliff is then distributed on the beach where it protects the toe of the cliff for subsequent time-steps
6. The beach plan position and beach level are updated at all sections in the model.

Although probabilistic predictions like Cliff-PLAN can address some of the variability in the retreat process, these may be subject to uncertainty too. In particular, although stochastic methods can represent the random arrival of storms or rainfall, they may be less appropriate for representing uncertainty where it arises from an incomplete description of the retreat process itself (Lee *et al*., 2002).

Walkden and Hall (2005) have developed the SCAPE (Soft Cliff and Platform Erosion) model. The model treats a soft rock coast as a set of subsystems (shore platform, beach, cliff, talus and wave and tidal process regime), which are described in the model as a sequence of interlinked cross-shore profiles. The shore platform is assumed to be the central regulator of coastal retreat. SCAPE includes a number of processes and their interactions:

a) Wave transformation using linear wave theory;
b) Sediment exchange between the beach and a near-shore bar using the COSMOS model (Nairn and Southgate, 1993);
c) Longshore sediment transport using a one-line beach model described in the Shore Protection Manual (CERC, 1984);

d) Erosion of the shore platform and cliff toe as described in Walkden and Hall (2005);

e) Delivery of a debris talus to the beach; and

f) The effect of shore parallel coastal structures such as seawalls, palisades and groynes.

SCAPE has been applied to the northeast Norfolk coast from Weybourne to Happisburgh and has been used to investigate the profile form and the response to increased sea-level rise of the Naze peninsula in southern England (Walkden & Hall, 2005 and Walkden and Dickson, 2006). In the Naze study, the output of SCAPE differed fundamentally from Bruun's conceptual model where an equilibrium profile is migrated upward and landward on sea-level rise, maintaining its shape relative to still water level. More recently, Walkden and Dickson (2008) have modelled the time evolution of shore profiles under variable rates of sea level rise, and identified a critical beach volume below which the beach exerts little influence on equilibrium retreat rates. Dickson *et al*. (2007) applied SCAPE to the evolution of 50 km of the NE Norfolk coastline under a broad set of indicative climate-change scenarios. Erosion rates were found to be sensitive to, but not a simple linear function of, sea-level rise and may be more sensitive to changes in offshore wave direction than to wave height. Their results revealed a broader range of responses and lower overall vulnerability to sea level than predicted by application of a simple Bruun rule approach. The model was further developed with parameter redundancy identified to reduce the model to a simpler form (Walkden and Dickson, 2008). Brooks and Spencer (2012) have applied SCAPE (and a group of similar shore platform approaches) to model future shoreline retreat of the series of soft rock cliffs located along the Suffolk Coast, UK.

Probabilistic modelling addresses uncertainty; however, where the uncertainty arises from an incomplete description of the retreat process in the model (see Lee *et al*., 2002) it may be that probabilistic techniques are less appropriate. For example, in SCAPE most attention is given to the processes acting on the platform, whilst the hydrology of the cliff is represented more simplistically. In situations where the dynamic hydrology is highly variable, such as in soft-rock cliffs, this may not be representative. In these applications models capable of including the detailed physical processes may be able to provide more insight into the way these natural systems operate.

3.2.1.1 Physically based computer modelling: recent advances

In recent decades, important advances have been made in the development of catchment-scale hydrological models (Brutsaert, 2005). Mathematical descriptions of the hydrological system in these models follow the physical, the conceptual, or the systems approach (Brutsaert, 2005). Bittelli *et al.*, (2010) have divided recent modelling advances into three categories based on whether the approach a) simplifies the dimensions of the model, b) simplifies the domain, or c) replaces physical equations with simplified, semi-empirical models. The SHE (Système Hydrologique Européen) model (Bathurst and Connell, 1992) is a physically based model in the first category that simplifies the dimensions of the problem by modelling two-dimensional surface and groundwater flow coupled through a one-dimensional solution of the water flow equations. The Distributed Hydrology Soil Vegetation Model (DHSVM) is a similar physically based, distributed model (Wigmosta and Lettenmaier, 1999). MODFLOW (Harbaugh *et al.*, 2000), MACRO (Jarvis, 1994) and HYDRUS-2D/3D (Simunek *et al*., 1998) utilise simplified domains for saturated/unsaturated flow. In these models, the physical flow and transport equations are solved rigorously, but only with reference to a simplified spatial domain, while simplifying or omitting processes, such as surface–groundwater interactions or surface runoff (Bittelli, 2010). In the third category of models a proper description of the key hydrological processes is included, but the physical equations are simplified. Recent examples include TOPMODEL (Beven and Kirkby, 1979) the Soil and Water Assessment Tool (SWAT) (Arnold *et al*., 1999) and the GIS based Soil Moisture Routing (SMR) model (Frankenberger *et al.,* 1999). A key recent advance is the development of coupled hydrology-stability models.

Over recent decades small scale hydrological models such as that in HYSWASOR (Van Genuchten, 1980) HILLFLOW (Bronstert, 1994) and GWFLUCT (Terlien, 1996) have increasingly been used with slope stability models. Among the available models, the CHASM (Anderson and Howes, 1986; Anderson *et al*., 1988; Brooks *et al*. 1993) and GEO-SLOPE - SEEP/W with SLOPE/W (Geoslope, 2004) models are of particular interest. In these models, the formulation directly couples the output of a detailed hydrological analysis with determination of slope stability.

The CHASM model began as a 1-Dimensional model in the early 1980s and was later extended to 2-dimensions and developed further by Brooks *et al*., 1995 and Brooks and Collison, 1996. The model has been described in Collison *et al*. (1995) and applied in Collison and Anderson (1996), Anderson, *et al*. (1994) and Lloyd *et al*. (2004). CHASM uses a two-dimensional finite difference hillslope hydrology model to predict transient pore pressures. The finite difference model employs Darcy's law, with unsaturated hydraulic conductivity being derived by the Millington Quirk method (Millington and Quirk, 1959). The pore pressure data (positive or negative) are incorporated into a stability model using Bishop's method to yield a Factor of Safety (Bishop, 1955).

The GEO-SLOPE suite of models (SEEP/W and SLOPE/W) were developed at the University of Saskatchewan and subsequently commercialised (as CHASM has been). GEO-SLOPE allows for geological variation in simulations of dynamic hydrological responses to rainfall and subsequent slope stability analyses to be undertaken. The model suite is comprised of a coupled hydrological-slope stability model in which a Finite Element pressure and saturation solver analyses the seepage problem and these data are used in slope stability analysis using a range of limit equilibrium methods. The applications of this model will be discussed in detail later in this thesis.

Coupled hydrology and stability models are widely used as a platform for research into the effect of positive pore water pressures in the assessment of overall slope stability (Simon *et al*., 2002; Dapporto *et al*., 2003; Rinaldi *et al*., 2004; Casagli *et al*., 2005). Approaches typically obtain distributed pore-water pressures using a finite element technique,which are then be used in a limit equilibrium analysis to determine slope stability (e.g. Fredlund and Barbour, 1992,; Ng and Shi, 1998). Rahardjo *et al*. (2003) then extended the approach by establishing a water table below the unsaturated zone near to the slope surface. The effect of rainfall infiltration on slope stability was then determined by calculating the pore water-pressures in the slope and using these values in a limit equilibrium stability analysis. It is probable that the rainfall was applied to the model as an edge boundary flux, although this is not stated explicitly. The transient pore-water pressure distributions were then used in a stability analysis to calculate a Factor of Safety. The ability to incorporate a description of rainfall flux in this way makes dynamic hydrology and stability models a powerful tool to investigate complex hydrological problems.

3.2.1.2 Soil hydraulic conductivity modelling

During rainfall, water infiltrates the soil from the surface and redistributes in the pore space. The saturation of a soil can be expressed as the relative proportion of the pore space which is occupied by water (V_w) to the total volume of the pores (V_v); the ratio of the current water content (w) to the saturation water content (w_{sat}); or the ratio of the void space occupied by water (e_w) to the total void space (e) (Bear, 1979; Freeze and Cherry, 1979). These relationships are shown in Equation 1:

$$S_r = \frac{V_w}{V_v} = \frac{w}{w_{sat}} = \frac{e_w}{e} \qquad \text{(Equation 1)}$$

The redistribution of water creates zones of saturation. Bear (1979) and Freeze and Cherry (1979) define zones according to the relative proportion of the pore space which is occupied by water. In this model, a groundwater table exists below which is a zone of saturation in which all pores are completely filled with water. Above the groundwater table, in the unsaturated zone, the pores contain air, water vapour and water.

The ease with which water moves through the soil is termed the Soil hydraulic conductivity. The flow of water within a fully saturated soil is normally taken to behave in accordance with Darcy's law, which for one-dimensional flow has the form (Equation 2):

$$v_x = -k_x \frac{\partial h}{\partial x} \qquad \text{(Equation 2)}$$

Where v_x denotes flow (velocity) of water in the x direction, k_x is the coefficient of permeability in the x direction, and $\frac{\partial h}{\partial x}$ is the hydraulic gradient in the x direction. Darcy's law also applies to flow through unsaturated materials (Richards, 1931; Childs, 1969; Freeze and Cherry 1979) and in this situation is a function of the pore water pressure (Bouwer, 1964, Freeze and Cherry 1979). In an unsaturated soil Darcy's law takes the form shown in Equation 3, where $k_x(\psi)$ is the coefficient of permeability as a function of suction:

$$v_x = -k_x(\psi)\frac{\partial h}{\partial x} \qquad \text{(Equation 3)}$$

Above the groundwater table, soil pores contain air, water vapour and water. Pore-water pressures in this region are below atmospheric pressure. This negative pressure head of water is termed matric suction (Fredlund and Rahardjo, 1993). Matric suction in soil is associated with the pressure difference between water as the wetting phase and air is the non-wetting phase in the unsaturated zone (Bear, 1979). Because it is a capillary action effect, the magnitude of the pressure difference is a function of the radius of the pore space between grains. The pore space is controlled by the particle size distribution and the heterogeneity within the soil. For example, where there is a distribution of void sizes within a soil, or, as in the case of silty clays, the interstitial spaces between larger grains have been filled with finer material, the capillary rise will be less uniform and will vary throughout the soil. The basic relationship between matric suction and the degree of saturation in a porous medium, such as soil, is well established (Bear, 1979; Freeze and Cherry, 1979). Starting from a fully saturated state, water initially begins to drain from the larger pores. As the drainage process continues, and the matric suction (i.e. the differential pressure between the air and water) increases, the air-water interface can move into increasingly smaller pores (Childs, 1969 and Bear 1979). A soil moisture characteristic curve (SMCC) describes the amount of water retained in a soil (as volumetric water content, or saturation) under equilibrium at a given matric suction (Childs, 1969). Water content and suction affect the permeability and shear strength of unsaturated soils (Barbour, 1998). Because the Soil Moisture Characteristic Curve (SMCC) defines the relationship between the suction and the volumetric water content of the soil (Fredlund and Rahardjo, 1993), this curve can be used to derive permeability functions for use in unsaturated groundwater flow problems (Fredlund and Rahardjo, 1993).

Soil Moisture Characteristic Curves are usually plotted as volumetric water content values at a given soil suction, where volumetric water content equals the degree of saturation multiplied by the porosity (Freeze and Cherry, 1979). Typically a soil moisture characteristic curve is highly nonlinear. As the matric suction values commonly extend over several orders of magnitude for the range of water contents in most soils, these values are often plotted on a logarithmic scale. The water content values can be expressed as gravimetric water content w, volumetric water content θ, or degree of saturation S (for a detailed review of these relationships see Nam *et al*., 2009). Soil Moisture Characteristic Curves are generally 'S' shaped, although in some soil types the shape of the function may be less well defined. The exact shape is defined by 3 parameters; the residual volumetric water content, the saturation volumetric water content and the air entry value (Fredlund and Xing, 1994). The residual water content is the water content at the point when continuity of the liquid phase is lost and the air entry value is the matric suction where enters the largest pores (Fredlund and Xing, 1994). Typically, soils with finer particles have higher air entry value and saturation water content (Nam *et al*., 2009). The wider range of pore sizes that typically characterise soils with a mixture of fine and coarse particles results in 'flattening' of the SMCC.

A variety of experimental methods are available to provide the information necessary to obtain the soil moisture characteristic curve and these have been well reviewed and evaluated (e.g. Agus and Schanz, 2007; Patrick *et al*., 2007). Most of the available studies show comparable results from the different test procedures, provided the tests are conducted appropriately (Nam *et al*., 2009). Along with the development of experimental methods to obtain soil moisture characteristic curves by direct saturation/desaturation testing of soil materials, approaches have been proposed for fitting analytical functions to the results of measurement of other properties (e.g. Arya and Paris, 1981; Brakensiek *et al*., 1981; Fredlund and Xing, 1994 and Houston *et al*.,2006). Many of these techniques are derived from pore-size distribution data through micromechanical relationships between effective pore size and soil suction (Sillers *et al*., 2001). One of the most frequently used of these models is that proposed by van Genuchten (1980). The model is based on the same basic relationships for predicting hydraulic conductivity of unsaturated soil proposed by Mualem (1976) and uses three parameters to fit the curve to measurements derived from soil pore-size distributions. The Fredlund and Xing (1994) model uses a similar three-parameter equation but fewer iterations are required to obtain convergence of the curve fitting parameters than in the van Genuchten model (Nam *et al*., 2009). Houston *et al*. (2006) have developed the original equation of Fredlund and Xing (1994) by using fitting parameters based on particle-size and soil plasticity.

Darcy's law in its unsaturated form has been used by Freeze and Cherry (1979) to develop an equation for continuity of flow for transient flow through an unsaturated soil in terms of the volumetric moisture content of a soil unit (Equation 4):

$$\frac{\partial}{\partial x}\left[k(\psi)\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[k(\psi)\frac{\partial h}{\partial y}\right]+\frac{\partial}{\partial z}\left[k(\psi)\frac{\partial h}{\partial z}\right]=\frac{\partial \theta}{\partial t} \qquad \text{(Equation 4)}$$

Where θ is the volumetric moisture content (the volume of water divided by the total volume of the soil unit). A similar equation is presented by Ng and Shi (1998). Freeze and Cherry further developed the continuity of flow equation to give the Richards Equation (Richards, 1933) (Equation 5) which forms the basis for many numerical hydrological models:

$$\frac{\partial}{\partial x}\left[k(\psi)\frac{\partial \psi}{\partial x}\right]+\frac{\partial}{\partial y}\left[k(\psi)\frac{\partial \psi}{\partial y}\right]+\frac{\partial}{\partial z}\left[k(\psi)\left(\frac{\partial \psi}{\partial z}+1\right)\right]=C\frac{\partial \psi}{\partial t} \qquad \text{(Equation 5)}$$

Where ψ = pore water pressure

And C = Specific moisture capacity, such that:

$$C=\frac{\partial \theta}{\partial \psi}$$

The right hand side of the continuity of flow equation and the right hand side of the Richards equation both represent the change in water storage within the soil. This behaviour is determined for a given soil by the shape of the soil moisture characteristic curve, which shows how the water content varies with varying suction. Information on the Soil Moisture Characteristic Curve is therefore of key importance in the analysis of saturated-unsaturated flow in soils using numerical models.

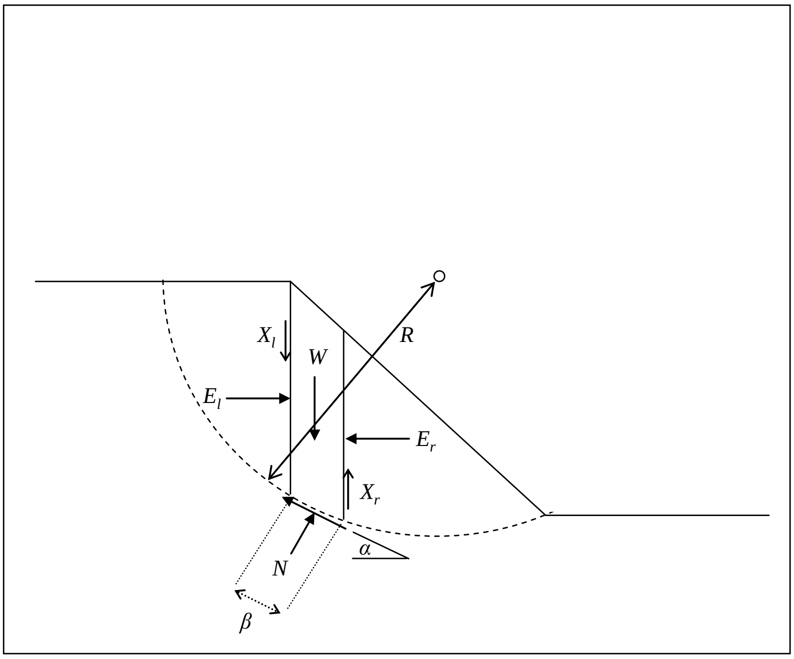
The soil moisture characteristic curve can be used with a measurement of the saturated hydraulic conductivity to derive values for the hydraulic conductivity at a range of suctions (Chulds and Collis George, 1950; Millington and Quirk, 1959; Brooks and Corey, 1964; Van Genuchten, 1980; Maulem, 1986). Shallow failures in soil slopes are commonly attributed to the total or partial loss of matric suction during rainfall infiltration with little evidence of the rise of the groundwater table (Fredlund and Rahardjo, 1993; Lawton *et al*, 1992; Ng and Shi, 1998; Kim *et al*, 2004, Fourie *et al*., 1999; Chen *et al*., 2004; Travis *et al*., 2010).In all the literature on cliff retreat that investigates the role of rainfall (e.g. Collins and Sitar, 2008 and Quinn *et al*., 2010) it is suction dissipation that is cited as being important. Unsaturated zone hydrology is central to the argument that loss of suction develops within the cliffs. The novelty of the research in this thesis lies in this approach and application of unsaturated zone modelling underpins the conclusions in this research.

3.2.1.3 Slope stability modelling

In a slope stability analysis it is usual to search for the critical slip surface, using the factor of safety as an indicator of stability. Slope instability occurs when the driving forces for mass-movement exceed the resisting forces holding material in place. This relationship can be expressed as a ratio of the resisting forces to the driving forces, and is termed the Factor of Safety. If the Factor of Safety (FS) is less than or equal to one, the slope will fail because the driving forces equal or exceed the resistance. If the FS is greater than one then the slope will be stable, as the resisting forces exceed the destabilising forces.In a Limit equilibrium stability analysis the Factor of Safety is determined by passing a notional slip surface through a representation of the geometry being analysed and dividing the slip area into vertical slices (Figure 3.2). The commonly used methods of slices then use the following equations of statics in solving for the Factor of Safety:

1. The summation of forces in a vertical direction for each slice, with the equation being solved for the normal force at the base of the slice *(N).*
2. The summation of forces in a horizontal direction for each slice is used to compute the interslice normal force *(E).*
3. The summation of moments about a common point for all slices. This is the moment equilibrium Factor of Safety*(F_m).*
4. The summation of forces in a horizontal direction for all slices. This is the force equilibrium Factor of Safety*(F_f).*

Analytically, all of the limit equilibrium methods are very similar. Fellenius (1936) developed the Ordinary or Swedish method of slices and in the mid-1950s Janbu (1954) and Bishop (1955) further developed and extended the method. The availability of computers made it possible to more readily handle iterative calculations and as a result more rigorous formulations such as those of Morgenstern and Price (1965) and Spencer (1967) were introduced. The general limit equilibrium (GLE) formulation (Fredlund and Krahn, 1977; Fredlund *et al*. 1981) is based on using two equations (an idea first published by Spencer, 1967) to allow for a range of interslice shear-normal force conditions to be included. The differences between the methods primarily relate to which equations of statics are included. In the Fellenius (1936) method the interslice normal and shear forces are not included. The Janbu (1954) method, the Morgenstern and Price (1965) method or Bishop's simplified method (1955) specifies the interslice force conditions, empirical correction factors or interslice forces that are included.



Where:

N = the normal force at the base of the slice (kN)

E = the horizontal interslice normal forces (subscripts *l* and *r* designate the left and the right sides of the slice, respectively)(kN)

W = the total weight of the slice(kN)

X = the vertical interslice shear forces (subscripts *l* and *r* designate the left and the right sides of the slice, respectively)(kN)

R = the radius for a circular slip surface (m)

α = the angle between the tangent of the centre of the base of each slice to the horizontal. Conventionally this value is taken as positive when the angle slopes in the same direction as the overall slope of the geometry (degrees)

β = the base length of the slice (m)

Figure 3.2

The forces acting on a soil slice in a limit equilibrium stability analysis

(Krahn, 2004)

The stability analysis methods outlined in Section 4.3.4.2 focus on values for the shear resistance relative to the down-slope shear force for a given slope angle. Shear resistance is defined in the Coulomb strength equation (Equation 6):

$$\tau = c' + \sigma \tan \phi' \qquad \text{(Equation 6)}$$

Where, τ = shear strength (kN/m^2), c' = cohesion (kN/m^2), σ = normal force and ϕ' = angle of internal friction ($^{\circ}$). This equation incorporates the cohesive and frictional properties of the soil but does not take into account the dynamic soil moisture conditions which may develop prior to failure. The role of soil moisture content in modifying soil shear resistance was included by Terzaghi (1920) by the introduction of a pore-water pressure term into the Coulomb strength equation. In the Coulomb equation shear strength of a partially or fully wetted soil is defined (Equation 7) as:

$$s = c' + (\sigma_n - u)\tan \phi' \qquad \text{(Equation 7)}$$

Where: s = is shear strength, c' = effective cohesion, ϕ' = effective angle of internal friction, σ_n = total normal stress and u = pore-water pressure.

3.2.1.4 Coupled hydrology-stability modelling

Coupled hydrology-stability models offer the possibility of incorporating the geotechnical characteristics of a study site (such as cohesion and friction angle) in addition to accounting for the influence of specific environmental parameters, such as rainfall and water table level on pore-water pressure. The GEO-SLOPE suite of SEEP/W coupled with SLOPE/W (GEO-SLOPE International Ltd.) has been widely used to analyse transient seepage under various rainfalls and initial conditions in soil slopes. Rahardjo *et al* (2003) have modelled rainfall infiltration into residual soil slopes using GEO-SLOPE and included a discussion of how this could be linked with field pore-water pressure monitoring results. The seepage analyses were undertaken for a 30m high slope with an angle of $45^{o}$with initial conditions for these models developed by establishing a water table in a steady state simulation. The precipitation was modelled as an incident rainfall rate equal to the saturated hydraulic conductivity to the slope. It is probable the rainfall was applied to the model as an edge boundary flux, although this is not stated explicitly. The transient pore-water pressure distributions were then determined, and a factor of safety was calculated for each time step in the transient analyses by importing the pore-water pressure head files into the Slope/W model.

Fredlund and Barbour (1992) have also used GEO-SLOPE to model rainfall infiltration as a specified flux boundary. Initial conditions for the transient analyses were set up by applying a small rainfall flux to a generated hydrostatic pore-water pressure distribution, then allowing the system to equilibrate to steady-state. From these steady state conditions, Fredlund and Barbour conducted two transient analyses, to model a short-duration high-intensity storm and a period of lower-intensity rainfall taking place over a period of five days.

Dapporto *et al*. (2001) have analysed the pore water pressure response to rainfall for inland slopes in central Italy). Field observations of characteristic slope geometries were established before detailed mechanisms of these failures were then investigated. Rinaldi and Casagli (1999), Casagli *et al*. (1999) and Simon *et al*. (2000) have used a similar approach to successfully model highly heterogeneous lithologies using GEO-SLOPE. The stability analyses principally focussed on the short-term dynamic hydrology rather than long-term steady state solutions. Initial conditions were developed for the models by establishing a water table and calculating pore-water pressures analytically. Model boundary conditions were applied as a 'total head versus time' function for the nodes along the bank profile. No information was provided on the other boundary conditions in the model. To achieve the results reported the edge conditions are likely to have been no-flow boundaries, although this is not stated explicitly.

Recently, Brooks *et al*. (2012) have applied GEO-SLOPE to model dynamic coupled hydrology-stability in soft-rock cliffs. Their study, focussed on Covehithe (SWD3), has successfully modelled cliff face failures driven by variations in rainfall inputs and consequent suction loss. The cliff face stratigraphy was included in the model simulations by digitising shore-normal surveys and rainfall totals between 10 and 70 mm were then modelled, with further simulations conducted based upon series of three daily totals spaced at 5-day intervals. A case-study was also undertaken modelling actual rainfall events occurring within a period of very low rainfall, a period of high total rainfall occurring largely on a single day; and a period of high rainfall spread over several days.

3.2.2 The history of retreat in the cliff line at Covehithe

The Environment Agency has surveyed the whole of the Suffolk coastline as part of their Sea Defence Management System (SDMS) project, with information available from 1992. Bi-annual field surveys have recorded the coastal profile at points spaced at 1km intervals stretching from the Humber to the Thames Estuary. These surveys are available for the period from 1992 and provide a detailed temporal record of cliff edge position over time. Data have been obtained using the Global Positioning System which reduces vertical errors to between ±0.5m (for soft surfaces) and gives a horizontal accuracy of ±0.2m (Lee, 2008). The accuracy in these surveys, together with information on when they were taken, provides a valuable resource for the analysis of temporal and spatial variability in retreat rates along the Suffolk coast. The relevant locations to the research in this thesis where at-a-point surveys are available in the EA SDMS program (SWD3, SWD4, SWD5, SWD6 and SWD7) are shown in Figure 3.3.

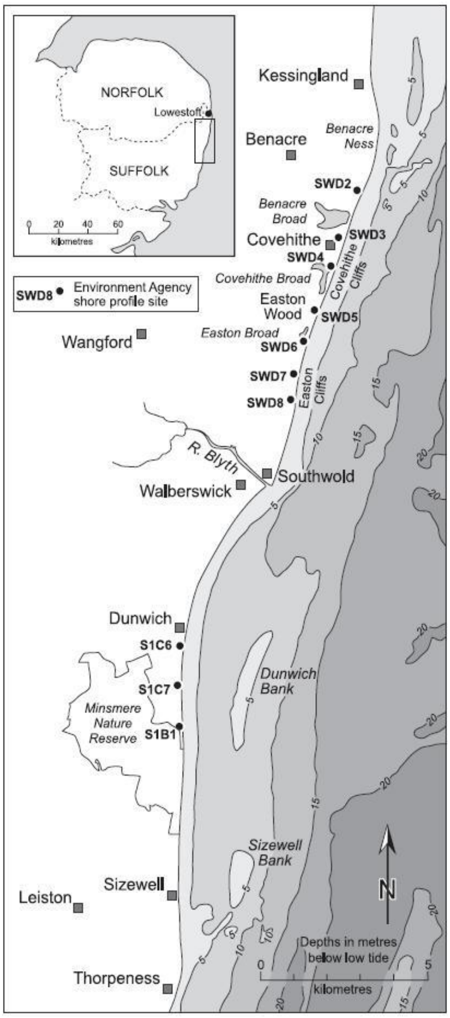


Figure 3.3

Environment Agency 'at-a-point' SDMS survey locations for the Suffolk coast between Benacre and Southwold, named using the EA terminology: e.g. SWD2 (after Brooks and Spencer, 2010)

Surveys were available for 'summer' (usually surveyed in July or August) and 'winter' (usually surveyed January or February) at discrete sections of the cliff line between Benacre and Easton. This study has used information in the period 1993 to 2008 for the locations SWD3, SWD4, SWD5, SWD6 and SWD7 (Figure 3.3). The date for each of the surveys included in this study is shown in Table 3.1 and Table 3.2.

	Survey Availability				
	SWD3	SWD4	SWD5	SWD6	SWD7
06/01/1993	✓	✓	✓	✓	✓
09/01/1994					✓
10/01/1994	✓	✓			
15/01/1994				✓	
16/01/1994			✓		
12/01/1995	✓				✓
13/01/1995			✓		
27/01/1995				✓	
15/01/1996					✓
18/01/1996	✓	✓	✓	✓	
22/01/1997	✓	✓			
23/01/1997					✓
08/02/1997			✓	✓	
04/02/1998	✓	✓		✓	✓
16/01/1999					✓
17/01/1999	✓	✓		✓	
11/02/2000	✓	✓	✓	✓	✓
21/01/2001			✓	✓	✓
07/02/2001	✓	✓			
07/01/2002					✓
08/01/2002			✓	✓	
22/01/2002	✓	✓			
28/01/2003	✓		✓	✓	✓
29/01/2003		✓			
17/01/2004	✓		✓	✓	✓
21/01/2005	✓		✓	✓	✓
22/01/2005		✓			
06/02/2006			✓	✓	✓
08/02/2006	✓	✓			
02/02/2007		✓			
17/02/2007	✓		✓	✓	✓
30/01/2008			✓	✓	✓
31/01/2008	✓	✓			

Table 3.1

Shore-normal SDMS winter survey profile chronology

	Survey Availability				
	SWD3	SWD4	SWD5	SWD6	SWD7
07/08/1993				✓	✓
08/08/1993	✓	✓	✓		
04/08/1994					✓
05/08/1994		✓	✓	✓	
08/08/1994	✓				
17/08/1995					✓
21/08/1995	✓	✓	✓	✓	
09/09/1996					✓
10/09/1996	✓	✓	✓		
12/09/1996				✓	
09/08/1997	✓		✓	✓	✓
11/08/1997		✓			
23/07/1998	✓	✓			
24/07/1998			✓	✓	
06/08/1999					✓
12/08/1999	✓	✓	✓	✓	
02/08/2000			✓	✓	✓
23/08/2000	✓	✓			
30/08/2001		✓	✓	✓	✓
31/08/2001	✓				
24/07/2002	✓		✓		✓
13/09/2002		✓			
24/07/2003	✓				
06/08/2003			✓	✓	✓
07/08/2003		✓			
26/07/2004					✓
27/07/2004	✓	✓	✓	✓	
19/07/2005			✓	✓	✓
20/07/2005	✓	✓			
18/07/2006			✓	✓	✓
21/07/2006	✓	✓			
21/08/2007	✓	✓	✓	✓	✓

Table 3.2

Shore-normal SDMS summer survey profile chronology

The SDMS survey records consisted of a series of comma delimited, ASCII format 'Value' (.val) files and 'String' (.str) files, each with a header to identify the profile, the month, and the year it was measured. The string files were imported into Excel spreadsheets for analysis. These string files contained the comment codes used by the Environment Agency surveyors to record surface characteristics at each of the measured points along the profiles. The meaning of these codes is given in Table 3.3.

Code	***Description***	***Code***	***Description***
B	Boulders	P2	Marker 2
CE	Cliff edge	GR	Grass
CF	Cliff face	GS	Gravel and sand
CT	Cliff top	S	Sand
G	Gravel	W	Water
GM	Gravel and mud	X	Mixture
P1	Marker 1	ZZ	Unknown

Table 3.3
Comment Codes used in the SDMS profiles

The value files were also imported into Excel spreadsheets for analysis. Each value file contained the following profile information:

- Distance (relative to a horizontal baseline)
- Easting
- Northing

Typical Environment Agency cliff profile data are shown in Figure 3.4.

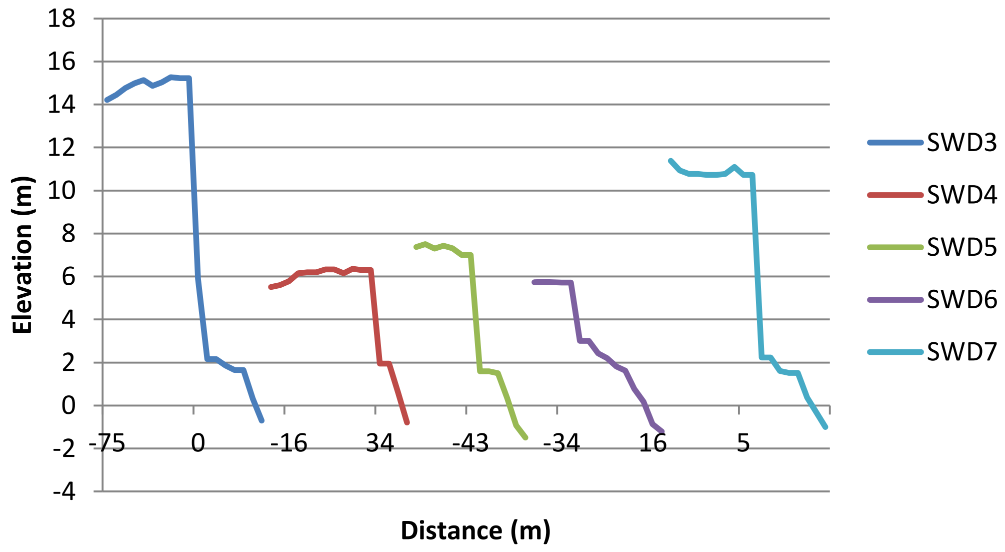


Figure 3.4

Typical cliff profile data available for the Suffolk Coast, UK for the 2003 surveys at SDMS monitoring sites SWD3 to SWD7 (for locations see Figure 3.3)

Retreat rate was determined by taking the difference in position of the cliff edge between surveys and dividing by the time elapsed between surveys. Where there were intermediate surveys, the retreat was calculated using the oldest and youngest surveys and was an End Point Rate (EPR). Linear regression rate (LRR) could also have been obtained using the SDMS surveys. However, whilst this method has the advantages of using all available shorelines and providing a statistically robust analysis it is prone to outlier effects (Dolan *et al*., 1991). The SDMS datasets describe episodic retreat, where extreme retreat superimposed on periods of relative stability would show as outliers, the analysis in this research used the EPR methodology only. To undertake an end-point analysis it is necessary to define the cliff position over time and the cliff-edge was selected as the marker for use in the analysis. The cliff edge was, in general, well recorded in the SDMS data and a typical cliff edge is shown for each of the locations in Figure 3.4.However, some of the SDMS surveys did not always record the morphology of the cliff face at a high level of topographic detail. In addition some survey locations (see Table 3.1 and Table 3.2) the record was incomplete. There were also records that suggested the cliff edge moved seaward between surveys. No information was found in the literature indicating it likely there had actually been build-up of this cliff line during the time period of this study. The seaward changes in cliff edge position between these surveys were each approximately 0.2m. Lee (2008) provides information on the error terms in SDMS surveys. The acceptable range in the horizontal accuracy for the surveys is ±0.2m therefore such small seaward movements are likely to be attributable to measurement error.

Confidence in the accuracy of the SDMS surveys was important. This is because it is a key assumption in the analyses presented in this thesis is that where it has been recorded in sufficient detail, the cliff edge identified in the EA surveys can be used as a reliable marker of shoreline position to calculate retreat rates between surveys. There is some debate as to what extent the EA profile data are accepted as providing accurate cliff top location information (e.g. Brooks *et al*., 2012). Brooks *et al*, 2012 argue that they need to be supplemented by aerial photograph analysis when assessing whole cliff sections. In this study it was necessary to accept that there are issues with both the accuracy of the data as well as the representativeness of at-a-point information.

A detailed analysis of contemporary retreat rates was undertaken at the study site usifn the SDMS survey data to determine at-a-point retreat distances and rates over the 15 years between 1993 and 2008, disaggregated into 6-monthly steps. Annual rates of shoreline retreat were determined by using the winter–winter EA data (normally January - January) from 1993 to 2008. Summer profiles (normally August – August) for these locations were then used to split the years into 6-month intervals. The cliff sections located at Benacre and at Easton Bavents (Figure 3.3) were excluded from this analysis because the low-height Benacre cliffs were considered to be similar in morphology to those at South Covehithe, and there have been coastal engineering interventions at Easton Bavents (Brooks and Spencer, 2010).

3.2.3 The association between rainfall and cliff retreat

The availability of reliable daily rainfall total information for the study site offered considerable potential for identifying 'extreme' rainfall events of the kind that are linked with slope failure (see Section 2.4). Daily rainfall data were extracted from the UK Meteorological data repository for weather station at Wrentham (2.8 km inland from Covehithe) for the period January 1993 to January 2008. The maximum one-day and two-day rainfall totals in each inter-survey period were then determined. The association between rainfall and cliff edge retreat rateat SWD3, SWD4, SWD5, SWD6 and SWD7 determined by the EPR method was then compared with a proxy of rainfall total using the approach of Collins and Sitar (2008).

3.2.4 Terrestrial forcing of Cliff retreat

Terrestrial forcing of cliff retreat at Covehithe was evaluated using coupled hydrology and slope stability modelling of groundwater flow, the loss of soil suction on infiltration and other key features in the dynamic hydrological response to rainfall stress in the soft-rock cliffs at Covehithe. Experience modelling dynamic hydrology and slope stability (e.g. Rinaldi and Casagli, 1999; Casagli *et al*., 1999; Simon *et al*., 2000; Dapporto *et al*., 2001; Dapporto *et al*.2003; Rinaldi *et al*., 2004; Brooks *et al*., 2012) suggested that it was necessary to:

a) Identify a combined hydrology and slope stability computer model that incorporates the geometrical characteristics and specific environmental parameters such as rainfall that control the processes of soft sea-cliff stability
b) Conduct a Sensitivity Study to establish appropriate parameters for this model at an in-depth study site, in order to demonstrate that it is an appropriate analytical tool to investigate the processes that control episodic soft sea cliff erosion
c) Extend the Sensitivity Study into a detailed Case Study using the model to investigate the relationship between rainfall intensity and the stability of soft sea-cliffs, validating these findings with appropriate in-depth morphology data of actual failure events.

Further, the experience of modelling recession processes using both stochastic and deterministic techniques found in the literature suggested that to represent the study site conditions accurately the model of soft sea-cliff processes should have the following attributes:

a) The physical basis of the model must include representations of the dynamic hydrology, the slope profile and the strength of the cliff materials
b) The water table can be at any position within the cliff, as determined by the result of a finite-element hydrological analysis
c) Slope Stability calculations using an appropriate shear surface morphology must be used to establish whether the given groundwater conditions, geophysical properties and geometry are such that the cliff will be unstable
d) Good integration of the dynamic hydrology with slope stability calculations

This modelling approach takes into account the effect of negative and positive pore water pressures in the assessment of overall slope stability. Whether failure actually takes place or not is determined in the analysis by a combination of the pore water pressure, the geotechnical properties of the cliff materials, and the normal and down slope forces acting at a potential slip surface. The GEO-SLOPE software SEEP/W and SLOPE/W (GEO-SLOPE International Ltd., 2004) was used to assess cliff hydrology and stability. This software allows for geological variation in simulations of dynamic hydrological responses to rainfall, making it highly suitable for the investigations. The dynamic hydrology was modelled using the 2-dimensional finite element model SEEP/W. The package consists of three elements. These are DEFINE, for inputting the profile to be analysed and specifying the hydrological parameters, SOLVE for running the model, and CONTOUR for viewing the results. The program capabilities of SEEP/W and its formulation are described in detail in the User Manual (GEO-SLOPE, 2004). The model applies a mass balance relation and Darcy's Law, using information in the appropriate Soil Water Characteristic Curve and conductivity function, to simulate the flow of water through the material. SEEP/W uses a differential equation (Equation 5.1)to describe the mass balance relation and Darcy's Law,

$$\frac{\delta}{\delta x}\left(Kx\frac{\delta H}{\delta x}\right)+\frac{\delta}{\delta y}\left(Ky\frac{\delta H}{\delta y}\right)Q=\frac{\delta\vartheta}{\delta t} \qquad \text{Equation 3.1}$$

where H is total head, K_x and K_y are hydraulic conductivity in the x and y directions respectively, Q is the applied boundary flux, ϑ is the volumetric water content and *t* is time. The model obtains a solution by dividing the physical problem to be analysed into a series of regions, in each of which the differential equations are approximately solved. Each region is referred to as an element and the elements are connected at specific points, referred to as nodes. The software assembles and solves the equations for each region to generate the solution over the entire problem domain. The inputs required by the SEEP/W model were the geometry of the slope, the Soil Water Characteristic Curve, the conductivity function of each of the soil materials present, and the boundary conditions (e.g. rainfall input and initial water table position).

The Slope Stability calculations were performed in the limit-equilibrium slope stability software SLOPE/W. The inputs required by the SLOPE/W model were the morphology of the slope, the geotechnical properties of the soil materials (the unit weight, cohesion and the internal friction angle) and the pore-water pressure distribution throughout the slope. The pore-water pressure distribution could be uploaded directly from the output of a SEEP/W model analysis. There were two key outputs from the slope stability model. These were the minimum Factor of Safety, and a graphical representation of the shape of the critical slip surface under the instability conditions modelled.

3.2.4.1 Coupled hydrology and stability model parameterisation

Information on the shore-normal profile of the cliffs at the study site, the hydraulic conductivity and soil moisture characteristics, and the geotechnical properties of the cliff forming materials was needed to parameterise the numerical models. The biannual Environment Agency SDMS (EA SDMS) transects set out and analysed in Chapter 3were the primary resource available for information on the cliff and beach morphology. The limitations and the context of the EA SDMS surveys have been discussed in Chapter 3. Survey information was available for five distinct cliffed sections (Easton Cliffs, Northend Warren, Easton Woods, Covehithe and Benacre). The availability of a fifteen-year record of biannual surveys of cliff morphology at these locations provided multiple opportunities for the simulation of suction loss within geologically complex cliffs. The modelling in this thesis has focussed on the period 1993 to 2008 and the Covehithe SWD4 site. There were key benefits to study of the low (ca. 6m) high cliffs at SWD4 rather than the higher (ca. 14m) cliffs alongshore at SWD3 and study over this period. These were the ability to evaluate the hydrological significance of discontinuities in cliff lithology at a fine spatial and temporal scale, and the ability to compare and contrast the findings with the analysis of Brooks *et al.*, (2012). The latter being particularly important, as there are range of cliff heights along this coast and the conceptual model for different modes of cliff retreat under different forcing controls at the 14-17m high cliffs at SWD3 proposed by Brooks *et al*. (2012) has not yet been tested in the lower (*ca.* 6m in height) cliffs alongshore.

The SEEP/W hydrology model required information on the appropriate Soil Moisture Characteristic Curve and Hydraulic Conductivity Function, to simulate the flow of water through each of the soil materials present at the study site. To assign these functions a detailed description of the soils was required. As has been set out in Chapter 2, the cliffs at Covehithe have been well surveyed (e.g. Hey, 1967; Long, 1974 and more recently by West *et al*., 1980) and the soils have been described in review by Moorlock *et al*. (2000). The literature was searched for descriptions and parameter information (Hydraulic Conductivity Functions and Soil Moisture Characteristic Curves) for material types referred to in the site surveys at Covehithe mentioned above and discussed in Chapter 2. The search was primarily conducted using the Wentworth Scale terms (e.g. very coarse sand, coarse sand, medium sand, fine sand, very fine sand, coarse silt, medium silt, fine silt, very fine silt and clay) used in the literature to describe the cliff forming material reported at Covehithe. Where authors had used non Wentworth descriptors, materials were reclassified for this study with the most appropriate Wentworth Scale material type. The soils for which hydraulic conductivity and SMCC information were available are shown, with the source, in Table 3.4.

Soil type	*Conductivity m s^{-1}*	*Conductivity Function*	*SMCC*	*Source*
Clayey Till	1.50E-10	yes	no	Yang and Yanful, 2002
Purple Silty Clay	2.80E-09	yes	yes	Rahardjo *et al*., 2003
Clayey Silt	8.40E-09	yes	yes	Geo-Slope, 1999
Clayey Silt	1.00E-08	yes	yes	Dapporto *et al*., 2001
Sandy Clayey Silt	1.50E-08	yes	yes	Geo-Slope, 1999
Clayey silt with sand	1.00E-07	yes	yes	Dapporto *et al*., 2001
Clayey Sand	1.00E-07	yes	yes	Indrawan *et al*., 2006
Low impermeable Soil	1.00E-07	yes	no	Tsaparas *et al*., 2002
Silt	1.90E-07	yes	no	Yang and Yanful, 2002
Silt	2.50E-07	yes	yes	Rodgers and Mulqueen, 2005
Macroporous Mud	4.98E-07	yes	yes	Hughes *et al*., 1998
Orange Silty Clay	7.80E-07	yes	yes	Rahardjo *et al*., 2003
Silty Clay	8.30E-07	yes	yes	Gasmo *et al*., 2000
'Moderately permeable soil'	1.00E-06	yes	no	Tsaparas *et al*., 2002
Silty Sand	1.40E-06	yes	yes	Rinaldi *et al*., 2004
Silty Sand with Silt Layers	1.40E-06	yes	yes	Rinaldi *et al*., 2004
Estuarine Mud	1.74E-06	yes	yes	Hughes *et al*., 1998
Fine Sand	4.30E-06	yes	yes	Geo-Slope, 1999
Fine Sand	4.30E-06	yes	yes	Rodgers and Mulqueen, 2005
Silty Sand	1.00E-05	yes	yes	Dapporto *et al*., 2001
Sand	1.00E-05	yes	yes	Rinaldi *et al*., 2004
Moderately Permeable soil	1.00E-05	yes	no	Tsaparas *et al*., 2002
Colluvium	1.25E-05	yes	yes	Blake *et al*., 2003
Clayey Sand	2.31E-05	yes	yes	Hughes *et al*., 1998
Sand	5.40E-05	yes	yes	Geo-Slope, 1999
Sand with Cobbles	5.40E-05	yes	yes	Rinaldi *et al*., 2004
Sand	5.40E-05	yes	yes	Rodgers and Mulqueen, 2005
Uniform sand	1.00E-04	yes	yes	Geo-Slope, 1999
Sand, gravel and cobbles	1.00E-04	yes	yes	Rinaldi *et al*., 2004
'Very permeable soil'	1.00E-04	yes	no	Tsaparas *et al*., 2002
Fine sand	1.90E-04	yes	no	Yang and Yanful, 2002
Silty sand	2.31E-04	yes	yes	Hughes *et al*., 1998
Sand and gravel	6.00E-04	yes	yes	Rinaldi *et al*., 2004
Medium Sand	3.82E-03	yes	yes	Indrawan *et al*., 2006
Coarse sand	7.30E-03	yes	no	Yang and Yanful, 2002
Gravelly sand	7.60E-02	yes	yes	Indrawan *et al*., 2006

Table 3.4

Hydrological parameter datasets from the literature

The literature based approach set out above was also used to obtain information on the geotechnical properties of materials representative of the soils at the study site (Table 3.5).

Soil type	***Unit Weight kN/m^3***	***Cohesion kPa***	***Friction angle (deg.)***	***Phi$_b$ (deg.)***	***Source***
Colluvium	18	1	40	-	Dietrich *et al*., 1995
Silty Sand	18	2	35	25-35	Rinaldi *et al*., 2004
Silty Sand with Silt Layers	18	2	35	25-35	Rinaldi *et al*., 2004
Sand	18	1	37	20-30	Rinaldi *et al*., 2004
Sand with Cobbles	18	1	37	22.5-37	Rinaldi *et al*., 2004
Colluvial Soil	18.9	4.7	35.7	31.7	Tofani *et al*., 2006
Homogeneous Colluvium	19.5	4.4	34.3	-	Ibraim and Anderson, 2002
Colluvium	19.6	0	25	-	Al-Homoud *et al*., 1997
Colluvial Soil	19.7	5.7	31.8	31.8	Tofani *et al*., 2006
Silty Sand	20	8	38	-	Bakir and Akis, 2005
Clay	20	5	22	-	Ng and Lee, 2002
Gravel	20	0	45	-	Skinner and Rowe, 2005
Sand Backfill	20	0	35	-	Skinner and Rowe, 2005
Weathered Silty Clay	20	1	25	24	Tsaparas *et al*., 2002
Orange Silty Clay	21	20	26.5	23	Rahardjo *et al*., 2003
Cohesive Silty Clay	21.4	16-37	29-32	-	Malet *et al*., 2005
Clayey silt with sand	14.9-19	2.9	32.5	20-32.5	Dapporto *et al*., 2001
Colluvium	15-19	5	24	-	Debray and Savage, 2001
Silty Sand	16-19.7	2	35	30-35	Dapporto *et al*., 2001
Loose Silty Sand	17*	10	25	6.6	Kim *et al*., 2004
Loose Well Graded Sand	17*	10	25	10.9	Kim *et al*., 2004
Silty Sand with Gravel(b)	17-18.6	1-3	36	23.5-36	Dapporto *et al*., 2005
Fine to Coarse Sand and Silt	17-19.2	20	32	-	Debray and Savage, 2001
Clay and Silt	17-20	20	24	-	Debray and Savage, 2001
Medium Silty Sand	18*	10	29	7.8	Kim *et al*., 2004
Medium Well Graded Sand	18*	10	29	12.9	Kim *et al*., 2004
Fluvial deposit	18-20	40	32	-	Debray and Savage, 2001
Dense Silty Sand	19*	10	33	9.1	Kim *et al*., 2004
Dense Well Graded Sand	19*	10	33	15.1	Kim *et al*., 2004

Table 3.5

Geotechnical properties from the literature

The procedure to configure the SEEP/W model is shown in Figure 3.5.

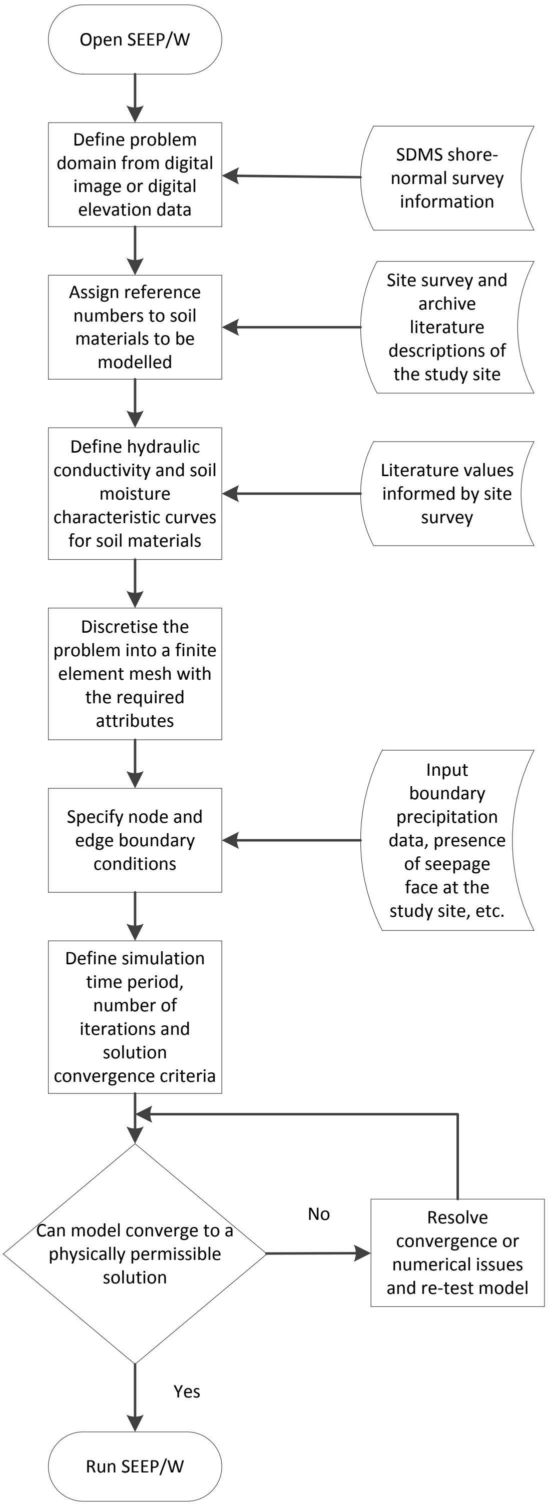


Figure 3.5

The procedure to configure the SEEP/W model

The procedure to configure the SLOPE/W model is shown in Figure 3.6.

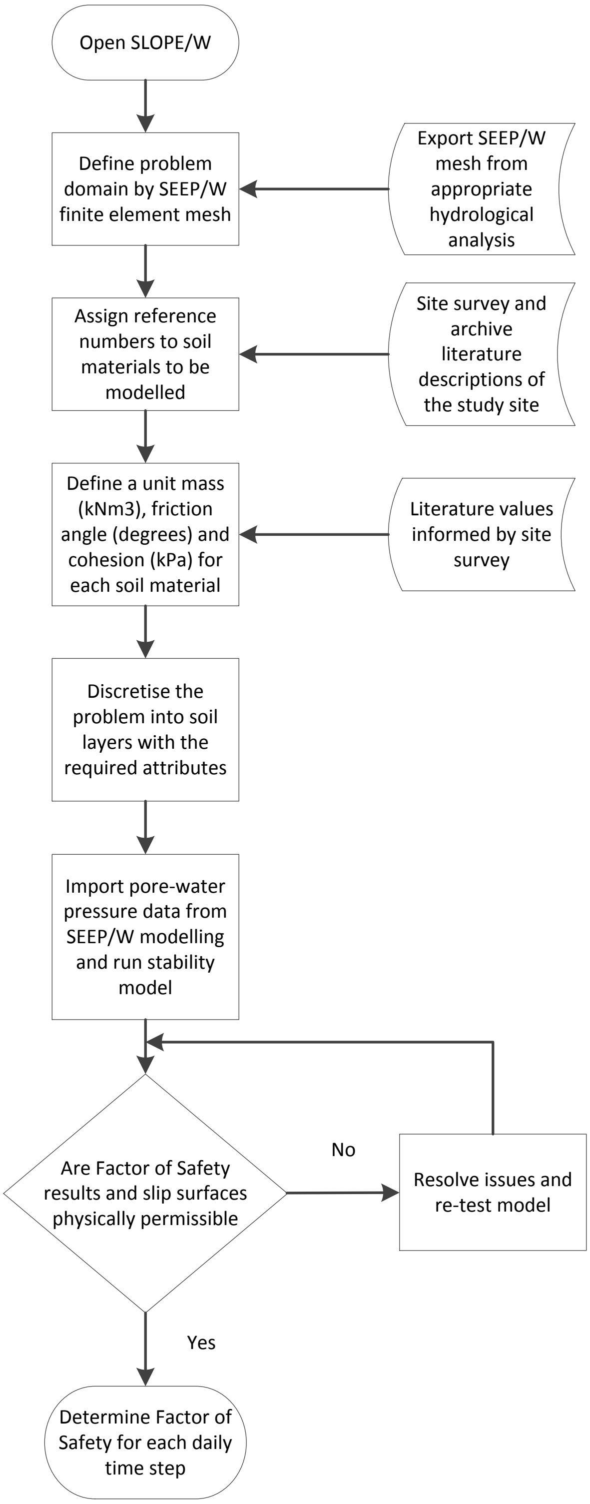


Figure 3.6

The procedures used to configure the SLOPE/W model

The GPS distance and elevation values in the SDMS surveys were used to define the geometry in each of the SEEP/W and SLOPE/W models. See earlier in this Chapter for details of the format of the records and the information provided at each GPS survey data point. The distance and elevation data were digitised into the model using the GUI/DRAW function. Discretisation of the January 1996 survey at the SWD4 location in a SLOPE/W model is illustrated in Figure 3.7.

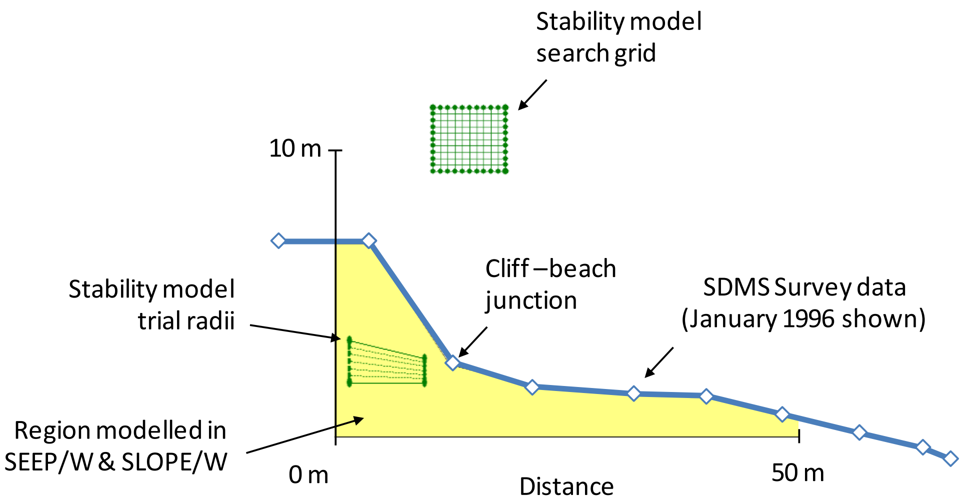


Figure 3.7

The relationship between the numerical model domain and the SDMS survey data is shown for the January 1996 survey at SWD4.

A sensitivity study, comprised of a series of steady-state hydrology-stability analyses, was conducted to provide context for the geotechnical parameterisation of the study site. The aim was to determine whether the computed Factor of Safety in typical cliff geometries at SWD4 was more sensitive to variations in the value used for friction angle than to variations in the value used for cohesion. This was potentially useful information, as a simple model is, in general, easier to run and interpret than a more complex one. If the effects of changes in geotechnical parameterisation on the response of the model were found to be small, these parameters could be parameterised more simply in later analyses than if an exact specification was likely to be required to represent the study site. The transient hydrology was not included in the model at this stage. As the Sensitivity Study was a steady-state analysis, it was only necessary to specify the shore-normal beach and cliff profiles, the unit weight, a hydraulic conductivity function to represent the cliff-forming materials, the initial water table position and the range of cohesion values and friction angle values to be investigated. It was not necessary to specify the soil moisture characteristics as would be required for a simulation of unsaturated flow. This was because the pressure solver did not require information on the detailed soil-moisture characteristics of the cliff-forming materials to calculate the steady-state pore water pressures.

Geotechnical properties were taken from the literature (Table 3.5) to set a range of values for friction angle and cohesion for use in the sensitivity analysis. The stability models in the Sensitivity Study were parameterised to represent a cliff forming material with a unit weight of 16kN/m3. This is the value for the unit weight of a typical sandy material taken from Krahn (2004). A range of values for the friction angle and cohesion of the cliff forming material was then selected for the scenarios to be modelled according to a uniform probability distribution function, rather than randomly as in a probabilistic or stochastic analysis (see Krahn, 2004). The mean value for the friction angle of the cliff forming material taken was 30 degrees and values ranged from 20 degrees to 40 degrees. The mean value for the cohesion of the cliff forming material was 10 kPa and the range was from 0 kPa to 20 kPa (see table 3.5).

It was desirable to model the complex Crag material as a single unit in the sensitivity study, for ease of computation and to avoid numerical convergence issues. No hydraulic conductivity data for the Crag as a geological unit was found in the literature; however, a value for saturated hydraulic conductivity for Coralline Crag was available. Coralline Crag is a carbonate-rich moderate to poorly-sorted sand with low mud content (Moorlock *et al*., 2000) that outcrops in the Aldeburgh area near to Covehithe. This information was incorporated into the model by taking the conductivity-pressure function for sand (Geo-Slope, 2004) and scaling it to represent a material of saturated hydraulic conductivity of 2.15 x10^{-4} ms^{-1}. Other studies (e.g. Hughes *et al*., 1998) have used this scaling approach where exact hydraulic functions are not available to describe soil materials. The value of 2.15 x10^{-4} ms^{-1} was used for the conductivity parameterisation as it was the mid-range value provided for the saturated hydraulic conductivity of Coralline Crag (BGS, 2005).

The steady-state analyses conducted in the Sensitivity Analysis required the location of the water table to be specified in the model. The Crag group is considered to be a single water bearing unit, although the presence of clay lenses, can allow local perched water tables to be formed (Moorlock *et al*., 2000). It was not possible to obtain local water level data for the Crag aquifer at Covehithe, although confidential borehole data were known to exist in the area (BGS, 2005). The initial water table was therefore taken as being at 1m (OD) from archive regional groundwater data (BGS, 2005) and a steady state simulation was then run to determine the applicable pore-water pressures in each modelled cliff slope. Other studies (e.g. Brooks *et al*., 2012) have successfully used this approach when detailed field water table data were unavailable. The starting point of 1m OD was reasonable, as the British Geological Survey 'Hydrogeological map of Southern East Anglia', 1:125 000 (1981) shows the range of water levels in the Crag as being between 0m and 5m above OD. Moorlock *et al*., (2000) also cite the water table in the Crag Group at locations from south of Lowestoft to Southwold as being with this range.

The sensitivity analysis was conducted by varying Cohesion between 10 kPa and 20 kPa in increments of 2.5, while at the same time varying friction angle from 20 to 40 degrees in 2.5 degree increments, thereby generating 81 combinations of these parameters that were included as model runs. The combinations were run for the survey transects in the period January 1993 to January 2002 at the SWD4 location, making 1620 model runs in total. The second part of the sensitivity study consisted of an analysis of the implication for the factor of safety of variation in the rainfall total and saturated hydraulic conductivity values used in the models. As no hydraulic conductivity functions were found for the Coralline Crag that could be used in parameterising the model. Instead, it was decided to identify a sand material where full hydraulic conductivity function data were available, and use this to build a simple conductivity scenario for the initial sensitivity study. This was done by taking the conductivity-pressure function for sand (Geo-Slope, 2004) as described above, then scaling these values to derive the hydraulic conductivity functions for materials of saturated hydraulic conductivity of 2.15 $x10^{-3}$ ms^{-1}, 2.15 $x10^{-4}ms^{-1}$and 2.15 $x10^{-5}ms^{-1}$. The midpoint of the identified range was as close as possible to the mid-range saturated hydraulic conductivity of the Coralline Crag of 1.7 $x10^{-04}$ to 2.6 $x10^{-04}ms^{-1}$. It was desirable to model that Crag as a single geological unit for the sensitivity study. The median friction angle and cohesion values obtained in part one of the sensitivity study (cohesion = 10 kPa, Friction angle = 30degrees, Unit weight = 1.8 kNm^{-3}) were used for the geotechnical parameterisation of these models. Later in the research the hydraulic conductivity parameterisation was modified to more accurately reflect the complex lithology of the Crag material at Covehithe.

A simple rainfall scenario was required to set the sensitivity analysis in context. The disaggregated rainfall total information for Wrentham in the period 1993 to 2008 suggested that rainfall total input steps of 24 mm, 48 mm, 72 mm, 96 mm and 120 mm would be appropriate maximum daily rainfall total values for input to the numerical seepage model. These steps are shown in Table 3.6 as rainfall total (in mm), the corresponding hourly intensity over 24 hours (in mm h^{-1}), and the boundary flux for these values in the input units of the model (m day^{-1}).

Rainfall Total (mm)	***Intensity ($mmhr^{-1}$)***	***Boundary Flux Input ($mday^{-1}$)***
24	1	0.024
48	2	0.048
72	3	0.072
96	4	0.096
120	5	0.120

Table 3.6

The rainfall total range taken from disaggregated rainfall information from the archive at Wrentham (see Chapter 3), the corresponding hourly intensity over 24 hours (in $mmhr^{-1}$), and the boundary flux for these values in the input units of the model ($mday^{-1}$)

This was necessarily a simplified rainfall scenario, as no antecedent rainfall information was included in this parameterisation. Daily rainfall data was incorporated in the detailed modelling later in the research, to more accurately parameterise the temporal patterns, and to allow the incorporation of antecedent rainfall conditions into the modelling. The SEEP/W and SLOPE/W models were then used to determine the overall minimum Factor of Safety after 24 hours of rainfall at each of the twenty study EA SDMS profiles between January 1993 and September 2002, under each of the potential input conditions. The parameterisation used in subsequent modelling was refined by cross-matching the soil materials at the study site (see earlier in this Chapter) with the literature (Table 3.4 and Table 3.5). Typical values for cohesion and friction angle of sands, silts and clays found in the literature were around0-20 kPa and 20°-40° (Table 3.4). A physical site survey verified the material types present and this information was then used to determine the number and thickness of the soil layers to be included in numerical models. The lithology at the site was modelled with four material types (Figure 3.8): weakly-cemented sand, coarse flint, pebbles and gravel, iron-cemented sand and a Basal silty-clay. On the foreshore the basal silty-clay was covered by a seasonally variable layer of beach sand. Figure 3.8 also shows an inset image of the flint, sand and pebble layer and the basal silty clay.

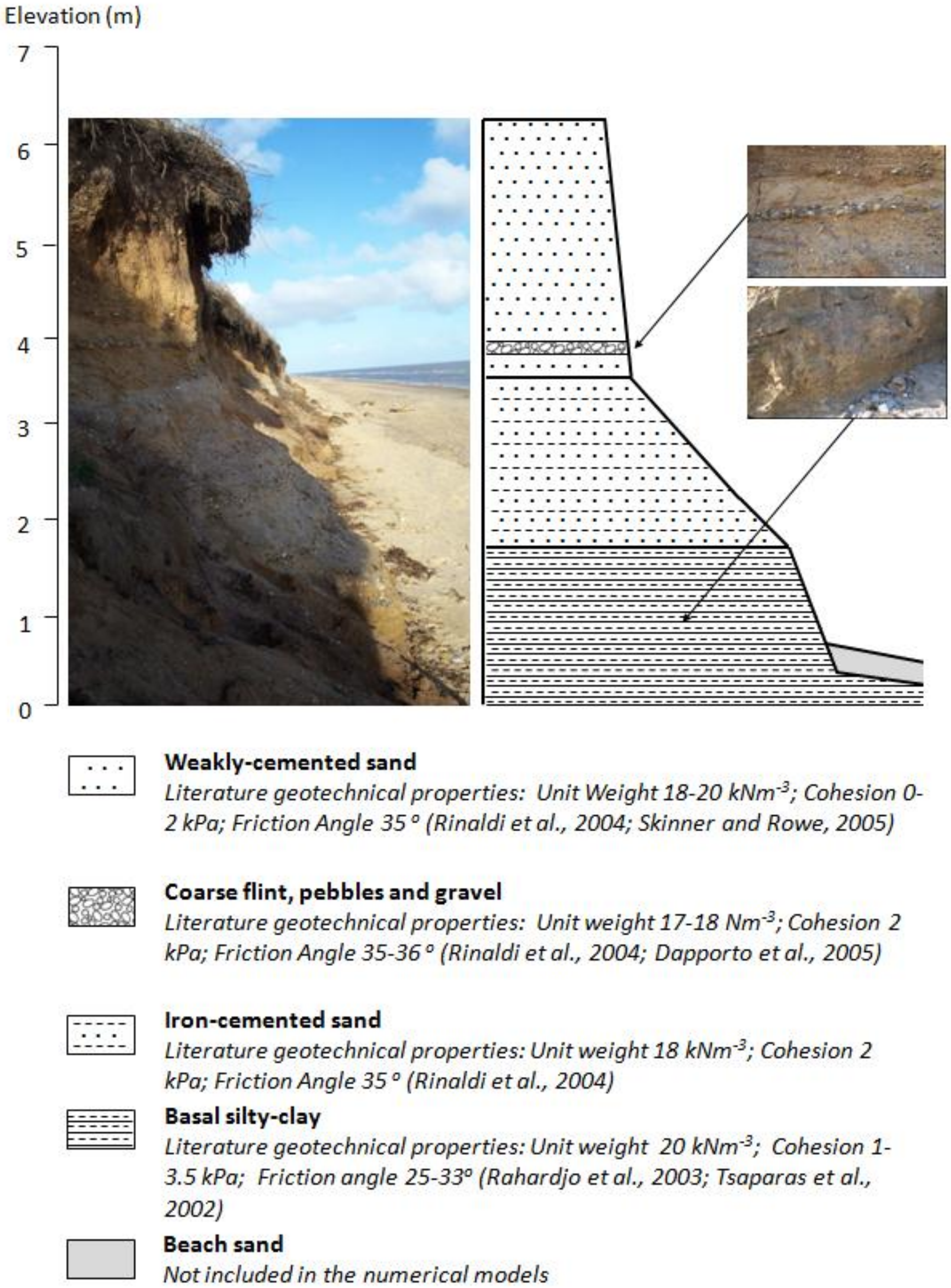


Figure 3.8

Photograph (from a site survey conducted May 2005) at Covehithe (SWD4) looking North correlated with schematic showing assigned geotechnical properties

Values of Unit weight 18; Cohesion 2 kPa; Friction Angle 35° were assigned for the weakly-cemented sand and the Iron-cemented sand in the model. This was reasonable as values for cohesion and friction angle for medium sand are low to zero and 28°-36°, depending on density (Peck *et al*., 1974). The coarse flint, pebbles and gravel in sand layer was assigned values that were consistent with those reported by Rinaldi *et al.* (2004) and Tsaparas *et al.* (2002) for similar material types. Values of 20.2 kNm^{-3}, 3.5 kPa and 33° were assigned for unit weight, cohesion and friction and for the silty-clay basal unit. The values assigned for the basal silty-clay were towards the lower end of typical values (Table 3.5) but they were consistent with the parameters reported of a Silty Sand with Silt Layers (Rahardjo *et. al*., 2003).

The model requires the hydraulic conductivity function of each of the soil materials present to be input. Hydraulic conductivity curves were assigned from the literature to represent the weakly cemented sand, iron-cemented sand and silty clay at the study site in the SEEP/W models (Figure 3.9). The coarse sand, pebble and gravel layer was modelled using the function for weakly cemented sand.

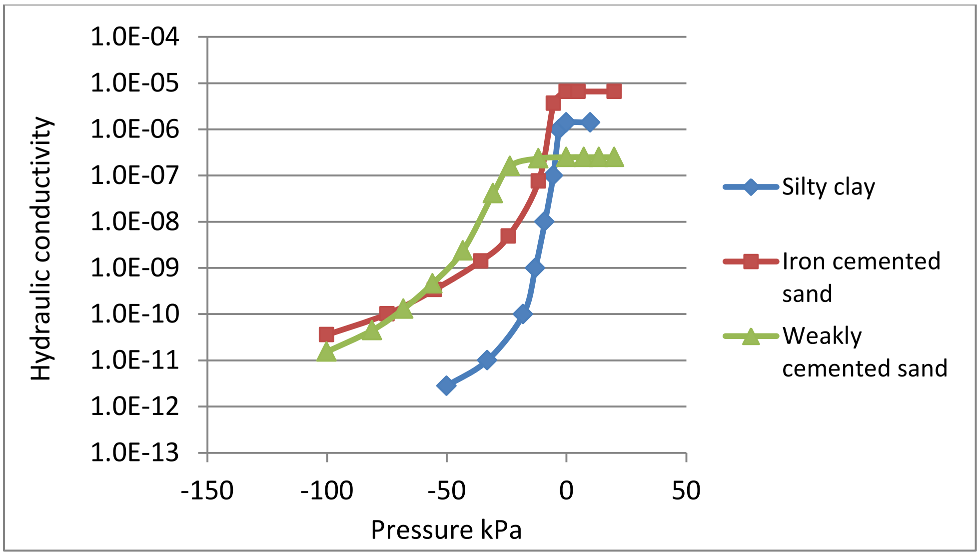


Figure 3.9

The hydraulic conductivity curves used in the hydrology modelling

(see Figure 3.8 for sources)

During transient flow, the amount of water entering a unit volume of a porous medium may be larger or smaller than the amount of water exiting. This can result in an amount of water either being retained or released. The ability of the cliff-forming materials to store water in this way must be defined by inputting a Soil Moisture Characteristic Curve for each material type in the model. Such curves can sometimes be obtained by sampling the soils then using textural class to define continuous soil moisture content and pressure relationships (e.g. Van Genuchten, 1980; Arya and Paris, 1981; Brakensiek *et al*., 1981), however due to the spatial variability in the soils at Covehithe conducting a sampling approach was problematic. Instead, the wide range of published data (Table 3.5) was consulted and volumetric water content functions were assigned to represent the weakly cemented sand, iron-cemented sand and silty clay in the SEEP/W models (Figure 3.09).

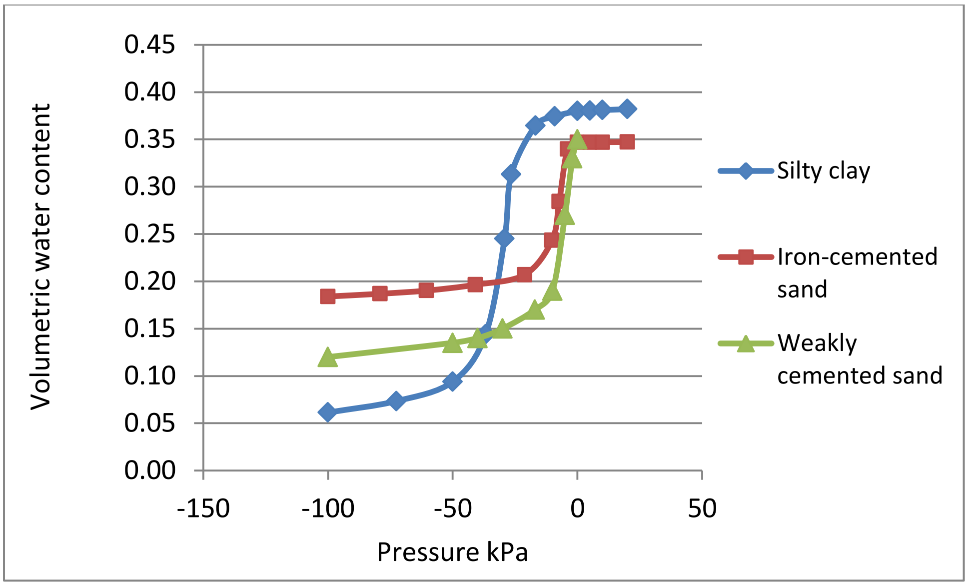


Figure 3.9

The volumetric water content functions used in the hydrology modelling (see Figure 3.8 for sources)

Survey evidence at the study site (from November, 2005) revealed seepage from the face of the cliff had occurred under certain hydrological conditions. To replicate this behaviour in the model a seepage face (see Rulon and Freeze, 1985) was created along the region of the model representing the face of the cliff. This was done by setting a review boundary for each of the finite element mesh nodes. This review flag meant that whenever the calculated nodal pore pressure reached zero, the head was set to the elevation of that node. This boundary type permitted no water flow into the model, but allowed formation of a seepage face. This boundary was able to represent the situation observed at the site survey, where under certain conditions water is able to flow from the face of the cliff. The left side of the mesh, the right side, and the base, were each assigned as a no-flow boundary. This allowed the phreatic surface to move freely at each end of the mesh, and therefore provided no artificial restriction on the response of the pore-water pressure to rainfall. The SEEP/W model required the total daily rainfall to be input to the upper surface of the finite element mesh as a flux boundary. An infiltration rate (in the model input units of ms^{-1}) was calculated for each day in the simulations by taking the total rainfall for each day from the Wrentham observation data. This rainfall was evenly applied to the top surface of the model over the 24-hour period. This was repeated for each daily time step in each of the scenarios modelled and each of the daily rainfall flux information was compiled into an input boundary function to parameterise the model. No allowance was made for canopy run-off or interception (meaning that all of the rainfall was taken as entering the model) and no ponding of water was permitted to occur on the input surface in the model. During dry periods no evaporation was allowed. This was considered reasonable as the high permeability of the soils at Covehithe meant that rainfall would rapidly permeate down through the cliff and away from the surface

It was necessary to establish realistic initial conditions in the model before beginning the analyses. Sometimes it is possible to input starting-point pore-water pressure information to a model directly, for example using data from field measurement of soil suction in instrumented slopes (see Hughes *et al*, 1998 and Rahardjo *et al.*, 2003). This is desirable, as when these pore-water pressure values are used in model analyses they accurately reflect those present in the field. However, as was the case at Covehithe in this study, appropriate initial conditions data are often not available. In these situations, it is possible to estimate the values required using a numerical method. Where the initial depth of the groundwater is known, a technique whereby limiting pore water pressures are selected to represent typical ranges encountered in the field can be used (Tsaparas *et al*., 2002). The method then allows the initial pore water pressures above the water table to become negative until they reach the appropriate limiting value, after which they remain constant. However, it is then necessary to identify a pore-pressure dataset for a similar lithology and geometry to that being modelled, to set an appropriate value of maximum allowable negative head to allow calculation of the initial nodal pore water pressures. This restricts the use of numerical methods to situations where detailed information on the position of the water table is available. As no such data existed at Covehithe setting a limiting pore water pressure was not possible for the research in this thesis. Instead, the initial nodal pore-water pressure distribution required for a dynamic simulation was obtained by running a steady state simulation in SEEP/W. To do this a constant rainfall value was input as a flux boundary condition along the horizontal component of the top edge of each of the models. The value chosen for the constant rainfall was important, as many authors (e.g. Lumb, 1975) have found rainfall-induced failures to be related to the duration and intensity of the antecedent rainfall. It was initially thought that applying 'low intensity' rainfall over a number of days might be appropriate. However, this raised a number of questions. Foremost being; a) how is 'low intensity' rainfall defined, b) should the applied rainfall be continuous, or variable, and c) how can separation between the rainfall used to set initial conditions and subsequent rainfall events be shown. To avoid these difficulties, the minimum practicable rainfall value was input as a flux boundary condition along the horizontal component of the top edge of each of the models. A value of $1.16e^{-09}$ ms^{-1} was chosen as it equated to less than 0.1mm of rainfall when taken over a 24-hour period. The remainder of the top of the model in a steady state analysis (representing the cliff face and the upper portion of the beach) was set as a review by elevation boundary. This boundary condition allowed the formation of a seepage face without allowing net inflow to the model. The sides of the model and the base were set as no-flow boundaries. Each of the SEEP/W models was then run until a numerically converged steady state was achieved.

The simulation results provided no information on how long it would take for steady-state to be reached in the field, just that the pressure distributions would, at some undetermined future time, reach the modelled values. For this reason it was not possible to say whether the steady state values generated for use in the coupled hydrology-stability model analyses accurately reflected those present in the field. In any case as it is not practicable to instrument the cliffs at the study site with tensiometers to obtain real field data, some form of numerical estimation is required. Other available techniques such as specifying the location of the water-table and ground surface suction (e.g. Gofar *et al.*, 2007; Lu and Godt, 2008) then running the model from these initial conditions with zero rainfall to obtain an equilibrium pore pressure distribution would have been equally valid. Possible errors in achieving representative field conditions were judged to be of secondary importance to the need to maintain a clear distinction between triggering rainfall events and the initial pore-water pressure conditions in the cliff-slope.

Simulations were run using a regular mesh of rectangular and triangular elements, approximating a finite-difference mode. The maximum number of iterations allowed was set to 25 which produced model convergence with the minimum achievable water balance error. The tolerance was less than 0.1%. An element size of 10 cm was sufficient to produce a consistent mesh and to achieve model stability over the range of rainfall applied. This element size produced models with approximately 6800 elements and 7000 nodes (January 1999 model values). Once numerical issues were resolved, model runs took between 12 and 24hours to converge to a stable solution. Output pore-water pressure maps for each day modelled were visualised in the CONTOUR element of the SEEP/W software and nodal pore-water pressure and saturation data were exported into MS Excel for analysis. Flow vectors were visualised directly in SEEP/W. The pore-water pressure and head files produced for each day of the hydrological analysis were available for use with the SLOPE/W stability model.

3.2.4.2 Hydrological response to disturbing rainfall stress

The hydrological response to disturbing rainfall stress was investigated by setting variability in rainfall as a disturbing stressor against the discontinuous retreat which characterises the archival records at SWD4. Information on the magnitude of individual rainfall events in the study period was therefore required, as high rainfall total events were hypothesised to be the key triggering stressors for retreat. The focus in the modelling was high magnitude events which are acknowledged to bring about a rapid response in coastal systems (Williams, 1956; Steers *et al*., 1979). Sequences of high rainfall during storms allow the rainfall contributions from intermediate days to generate a cumulative effect hypothesised to lead to considerable loss of suction in the cliff. The disaggregated rainfall data made it possible to identify such 'high magnitude rainfall events'. The occurrence of days with >25 mm rainfall in the period 1993 to 2008 was used to identify candidate events which might be included in an analysis of the hydrological response in the cliffs. Storms where the rainfall total was >40 mm were then emphasised, because suction loss in the cliff system was hypothesised to be greater overall after a sequence of days with high individual daily totals. The analysis of the disaggregated rainfall data on this basis suggested twelve storm scenarios (shown chronologically in Table 3.7) were representative of the study period (1993 to 2008). These events are shown as a normalised rainfall profile in Figure 3.11.

Storm event start	***Storm event end***	***Storm event reference***	***Storm event rainfall total (mm)***	***Applicable SDMS survey dataset***
24/05/1993	29/05/1993	1	44.1	06/01/1993
29/08/1994	02/09/1994	2	48.7	05/08/1994
27/08/1996	30/08/1996	3	82.4	08/01/1996
16/12/1997	20/12/1997	4	41.4	11/08/1997
27/07/1998	01/08/1998	5	48.6	23/07/1998
05/08/1999	10/08/1999	6	61.5	17/01/1999
13/09/2000	16/09/2000	7	32.4	23/08/2000
10/10/2002	17/10/2002	8	91.9	13/09/2002
24/07/2003	28/07/2003	9	42.1	16/01/2003
14/09/2005	19/09/2005	10	29.9	20/07/2005
09/08/2006	14/08/2006	11	65.0	21/07/2006
25/05/2007	30/05/2007	12	91.5	02/02/2007

Table 3.7

Storm events (shown chronologically) used in the simulations derived from analysis of the disaggregated rainfall data at Wrentham in the period 1993 to 2008

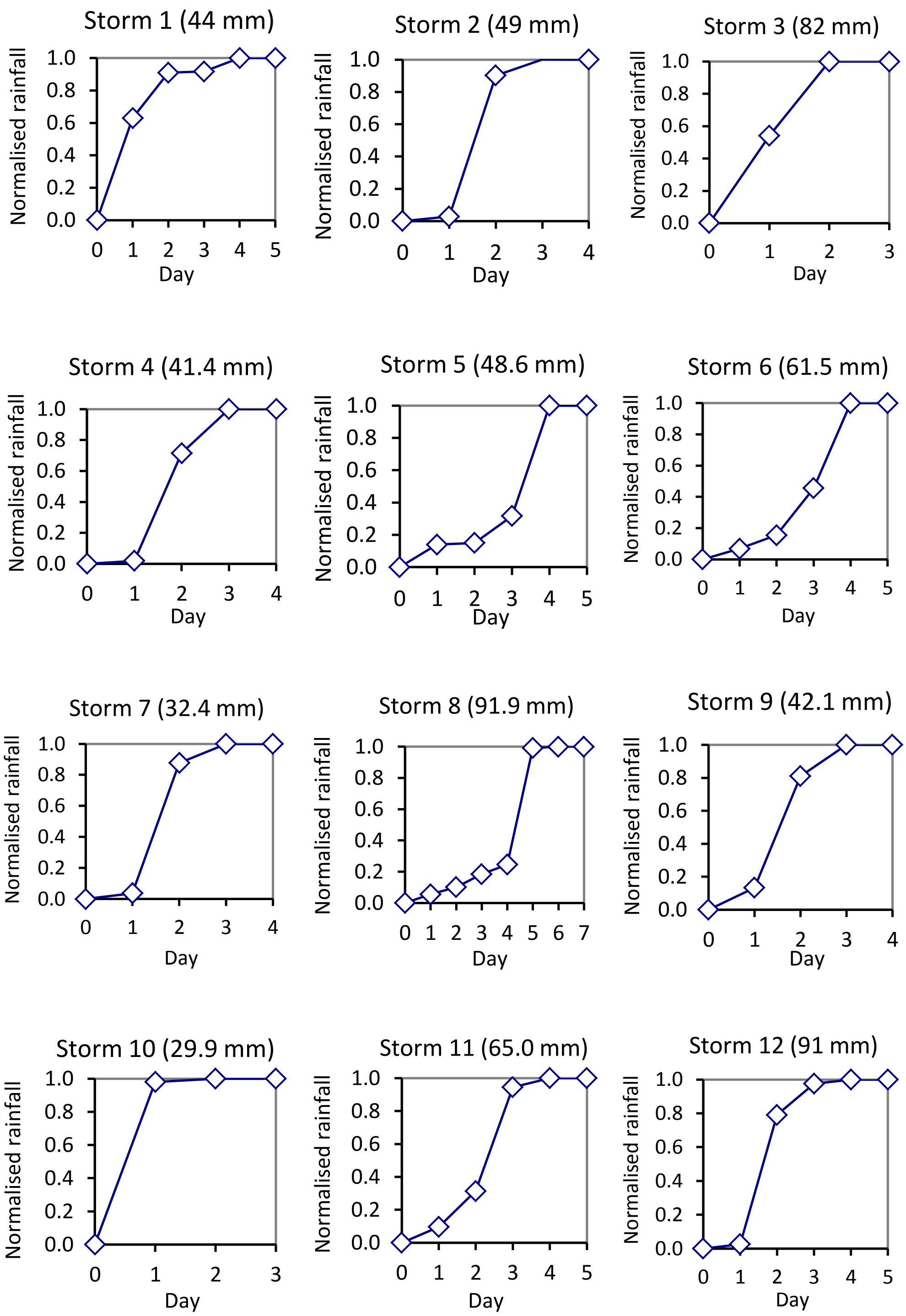


Figure 3.11

The 'storm' events in the numerical modelling shown as normalised rainfall profiles. Rainfall total values (in mm) are also shown for these events.

The SEEP/W models were configured using a regular mesh of rectangular and triangular elements, approximating a finite-difference mode. Three types of boundary condition were used in the analyses to assign the conditions at the edges of the mesh. A seepage face was created along the face of the cliff by setting a review boundary in the model (The left side of the mesh, the right side, and the base, were each assigned as a no-flow boundary. Daily rainfall total was input to the model as a flux boundary on the top surface with no evaporation. No modifying functions were applied or necessary. The maximum number of iterations allowed was set to 25 which produced model convergence with the minimum achievable water balance error. The tolerance was less than 0.1%. An element size of 10 cm was sufficient to produce a consistent mesh and to achieve model stability over the range of rainfall applied. This element size produced models with approximately 6800 elements and 7000 nodes (January 1999 model values). Once numerical issues were resolved, model runs took between 12 and 24hours to converge to a stable solution. Output pore-water pressure maps for each day modelled were visualised in the CONTOUR element of the SEEP/W software and nodal pore-water pressure and saturation data were exported into MS Excel for analysis.

<u>3.2.4.3 FS response to disturbing rainfall stress</u>

Ten case-study periods (see Table 3.8) were identified from the disaggregated retreat record at SWD4 for simulation of FS response to disturbing rainfall stress with time. Modelling the dynamic changes in FS over extended periods of time (i.e. thousands of days) had not previously been reported in the literature on soft rock cliff retreat. Inter-survey periods that showed little or no cliff recession (e.g. 0-1 m) at SWD4 were contrasted with periods where medium or high retreat was experienced (e.g. 5-10 m). A total of 1878 days were modelled in the simulation of FS response to disturbing rainfall stress (Table 3.8).

Start date to end date	*Survey*	*Rainfall total in period (mm)*	*Days*	*Retreat in period (m)*
11/08/1997 to 03/02/1998	S_97	334	183	0
28/01/2003 to 06/08/2003	W_03	213	194	0.4
13/09/2002 to 27/01/2003	S_02	369	138	0.7
17/01/1999 to 11/08/1999	W_99	360	211	1.2
22/01/2005 to 19/07/2005	W_05	320	185	1.5
23/07/1998 to 16/01/1999	S_98	400	187	2
12/08/1999 to 10/02/2000	S_99	277	216	2.6
23/08/2000 to 20/01/2001	S_00	424	153	3.5
06/01/1993 to 07/08/1993	W_93	301	211	5.7
21/07/2006 to 01/02/2007	S_06	479	200	10
		Total	1878	35.8

Table 3.8

Case study modelling periods, input SDMS survey information, rainfall input and days modelled shown with recorded retreat at Covehithe SWD4

The SLOPE/W models were configured to calculate the FS using Bishop's simplified method of slices (Bishop, 1955).

A further set of fifteen periods (Table 3.9) were taken from the disaggregated retreat record at SWD4 for simulation of correlation between FS response to rainfall stress and: a) 1-day rainfall total and, b) 2-day rainfall total. Periods between 1993 and 2008 that showed little or no cliff recession (e.g. 0-1 m) were contrasted with other periods where medium (1-4 m) or high retreat was experienced (e.g. 5-10 m). A total of 2840 days were included in this phase of the simulations.

Start date to end date	***Survey***	***Days***	***Retreat***	***Rainfall total in period mm***	***Maximum 1-day rainfall total mm***	***Maximum 2- day rainfall total mm***
21/08/1995 to 17/01/1996	S_95	152	0	194	14.9	25.6
11/08/1997 to 03/02/1998	S_97	183	0	334	28.8	40.6
04/02/1998 to 22/07/1998	W_98	151	0	272	21.6	28.5
28/01/2003 to 06/08/2003	W_03	194	0.4	213	28.5	37
02/02/2007 to 20/08/2007	W_07	203	0.6	496	70	86.9
13/09/2002 to 27/01/2003	S_02	138	0.7	369	68.5	74.1
10/01/1994 to 04/08/1994	W_94	213	0.8	320	22.8	30.3
17/01/1999 to 11/08/1999	W_99	211	1.2	360	33.5	52
22/01/2005 to 19/07/2005	W_05	185	1.5	320	27.4	37.6
23/07/1998 to 16/01/1999	S_98	187	2	400	33.2	41.3
12/08/1999 to 10/02/2000	S_99	216	2.6	277	13.9	16.1
23/08/2000 to 20/01/2001	S_00	153	3.5	424	32.6	43.9
06/01/1993 to 07/08/1993	W_93	211	5.7	301	27.7	40.1
18/01/1996 to 09/09/1996	W_96	243	7.6	238	44.6	82.4
21/07/2006 to 01/02/2007	S_06	200	10	479	46	55.2

Table 3.9

Case-study periods used in the simulations to investigate the sensitivity of FS response to short-term rainfall total at SWD4

3.2.5 Marine forcing of Cliff retreat

3.2.5.1 Introduction

Cliffs fronted by a low beach are more susceptible to marine energy inputs than those with higher beach levels (Sunamura, 1976; Ruggiero *et al*., 2001; Sallenger *et al*., 2002; Brunsden and Lee, 2004; Trenhaile, 2005; Walkden and Hall, 2005; Dornbusch *et al*., 2008; Lee, 2008). Specifically, when water is able to impact the cliff base increased toe erosion is expected (Everts, 1991; Komar and Shih, 1993; Ruggiero *et al*., 2001; Sallenger *et al*., 2002; Lee, 2008). Early analyses of water level in storms used a geometric approach to assess the contribution of storm energy to dune dynamics (Edelman, 1968, 1972 and van de Graaf, 1977). Kriebel and Dean (1985) used an equilibrium profile approach (Bruun, 1962) to develop models where the equilibrium shoreline profile was governed by sediment size and water level. These models could account for the beach response to non-equilibrium conditions, such as elevated water level. More recently, Kriebel *et al*. (1997) presented an alternative approach, again for the assessment of dune vulnerability to storm erosion, which built on earlier numerical modelling (Kriebel, 1991; Kriebel and Dean, 1993). This approach developed a measure of erosion potential due to severe storm events. Judge *et al*., (2003) used a similar Intensity Index to determine the likelihood of dune failure on storm surge on a North Carolina barrier island during Hurricane Fran in September 1996.The research in this thesis has revealed a number of significant surge events have taken place in the study area. The surge of 1993, and asignificant event which took place in 2007, both occurred within the study period. For these reasons, water level at the study was considered in the study in this thesis.Regardless of the cause and effect relationship between marine action and coastal erosion, basal attack is largely determined by the influence of local tidal regimes and surge levels. The combination of a high tide coinciding with a storm-related surge has the potential to lead to elevated water levels contacting the base of the cliff. Water contact with the base of the cliff could trigger failure by notching. Alternatively, contact with the cliff base might account for high retreat values in some other way. For example, rapid removal of debris from landslides might allow the redundant events (Brunsden and Lee, 2000) to be 'switched on' and rapid cycles of failure take place. For these reasons, cliff base elevation values have the potential to be used with the still water level information available from the tide gauge records to compare cliff base elevation and maximum still water level over time.

3.2.5.2 Obtaining water level data

Still water levels for Lowestoft, Suffolk (12km north of Covehithe) that had been recorded at 15 minute intervals for the period 1993 to 2008) were available from the British

Oceanographic Data Centre (www.bodc.ac.uk).The tide gauge at Lowestoft is a bubbler pressure system, one of approximately 40 such gauges in the UK national network (Woodworth *et al*., 1999). The advantages and disadvantages of bubblers have been widely reviewed (e.g. Pugh, 1972, 1987). Their main disadvantages are the need to know the density of the sea water above the pressure point and to identify any long-term drift (Woodworth and Smith, 2003). The Lowestoft tide gauge data were referenced to Admiralty Chart Datum (ACD). As Ordnance Datum (ODN) was used in this research it was necessary to this datum using the relationship ACD = ODN -1.40m.The data were converted from Chart Datum to ODN using a correction of 1.4m. The correction from Chart Datum to ODN varies along this coast from 1.5 m to1.3 m.

3.2.5.3 The record of water level at Lowestoft between 1993 and 2008

The tide gauge records were analysed to provide information on relative sea level change over the recent decades. The still water level information was then used with information on astronomical tide to obtain tidal residuals from which positive surges that took place during the study period could be identified.

3.2.5.4 The record of cliff base elevation at the study sites

Figure 3.12 shows the method for defining the position of the 'cliff edge' and the position of the 'cliff-beach junction' (Ecf) from the SDMS survey data, and provides definitions for the parameter Wr.

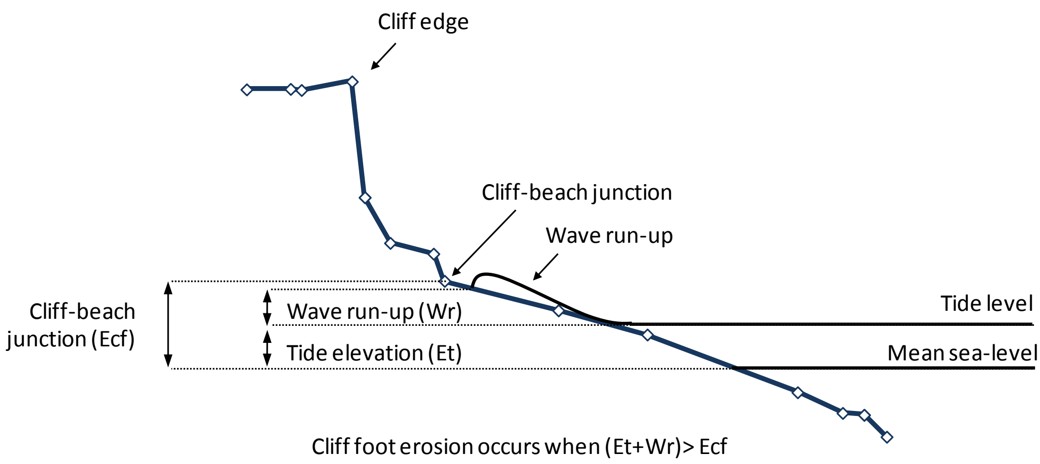


Figure 3.12

Schematic showing the method for defining the position of the 'cliff edge' and the position of the 'cliff-beach junction' from the SDMS survey data.

Cliff foot erosion occurs when the sum of the tidal elevation (Et) plus the wave run-up elevation (Wr) is greater than the elevation of the cliff-beach junction (Ecf) (Lee, 2008).

3.2.5.5 The association between water level and cliff retreat at the study sites

The association between water level and cliff retreat at the study sites was evaluated by comparing still water levels with the cliff-beach junction (e.g. Swenson *et al*. 2006; Collins and Sitar, 2008) and using the value obtained to assess vulnerability to marine action. The available shore-normal winter-winter profile information for the study cliffs in the period 1993 to 2008 is shown in Table 3.10. The winter profiles were chosen because Lee (2008) suggests that winter-winter beach profiles provide a good measure of the lower-bound beach conditions over a given year. This study has used information in the period 1993 to 2008 for the locations SWD3, SWD4, SWD5, SWD6 and SWD7 (Figure 2.3). The date for each of the surveys included in this study is shown in Table 3.1. The method for identifying the cliff-base junction is set out in Figure 3.12.

	Survey Availability				
	SWD3	SWD4	SWD5	SWD6	SWD7
06/01/1993	✓	✓	✓	✓	✓
09/01/1994					✓
10/01/1994	✓	✓			
15/01/1994				✓	
16/01/1994			✓		
12/01/1995	✓				✓
13/01/1995			✓		
27/01/1995				✓	
15/01/1996					✓
18/01/1996	✓	✓	✓	✓	
22/01/1997	✓	✓			
23/01/1997					✓
08/02/1997			✓	✓	
04/02/1998	✓	✓		✓	✓
16/01/1999					✓
17/01/1999	✓	✓		✓	
11/02/2000	✓	✓	✓	✓	✓
21/01/2001			✓	✓	✓
07/02/2001	✓	✓			
07/01/2002					✓
08/01/2002			✓	✓	
22/01/2002	✓	✓			
28/01/2003	✓		✓	✓	✓
29/01/2003		✓			
17/01/2004	✓		✓	✓	✓
21/01/2005	✓		✓	✓	✓
22/01/2005		✓			
06/02/2006			✓	✓	✓
08/02/2006	✓	✓			
02/02/2007		✓			
17/02/2007	✓		✓	✓	✓
30/01/2008			✓	✓	✓
31/01/2008	✓	✓			

Table 3.10

Shore-normal SDMS winter survey profile chronology

Chapter 4 Results

4.1 The history of retreat in the cliff line at Covehithe

The annual cliff edge retreat rates from analysis of the SDMS Surveys calculated for the period 1993 to 2008 at the SWD3, SWD4, SWD5, SWD6 and SWD7 locations are shown in Table 4.1.

	SWD3	SWD4	SWD5	SWD6	SWD7	SD	Mean	Total
1993-1994	15.8	6.1	8.7	9.7	6.1	4.0	9.28	46.4
1994-1995	8.2	2.4	6.8	6.1	1.5	2.9	5	25
1995-1996	0	0	9.8	0	0.2	4.4	2	10
1996-1997	7.9	10.3	10.5	16.4	1.4	5.4	9.3	46.5
1997-1998	1.5	13.7	0.1	0	0.7	5.9	3.2	16
1998-1999	4.3	4.3	2	0	3.4	1.8	2.8	14
1999-2000	4.1	3.8	0	0.1	2.6	2.0	2.12	10.6
2000-2001	4.4	6.1	3.9	0.1	11.9	4.3	5.28	26.4
SD	5.3	3.5	4.6	5.8	3.9			
Mean	7.3	3.9	5.0	4.8	3.5			
Total	58.4	30.8	39.7	38.2	27.8			

	SWD3	SWD4	SWD5	SWD6	SWD7	SD	Mean	Total
2001-2002	0.3	3.8	2.6	0.2	1.9	1.5	1.76	8.8
2002-2003	0.5	1.8	2.1	0	0.6	0.9	1	5
2003-2004	3.7	4.1	2.3	2.4	1.6	1.0	2.82	14.1
2004-2005	0.1	2.1	0.8	0.2	0.3	0.8	0.7	3.5
2005-2006	2.9	1.5	1.6	0.4	0	1.1	1.28	6.4
2006-2007	5.6	10	5.7	2.7	0.2	3.7	4.84	24.2
2007-2008	1.3	9.1	5.4	6.2	2.5	3.1	4.9	24.5
SD	2.1	3.5	1.9	2.3	1.0			
Mean	2.1	4.6	2.9	1.7	1.0			
Total	14.4	32.4	20.5	12.1	7.1			

Table 4.1

End Pont Method cliff edge retreat rates calculated from analysis of the SDMS Surveys

A paired t-Test (with a two-tailed distribution) for the mean retreat rates calculated using the EPR method at SWD3, SWD4, SWD5,SWD6 AND SWD7 in the period 1993-2001 and the period 2001-2008 showed a 93% confidence that the greater retreat rates observed in the period 2001-2008 compared with those for 1993-2001 at the study sites were significant.

Cumulative retreat at the study sites is shown in Figure 4.1.

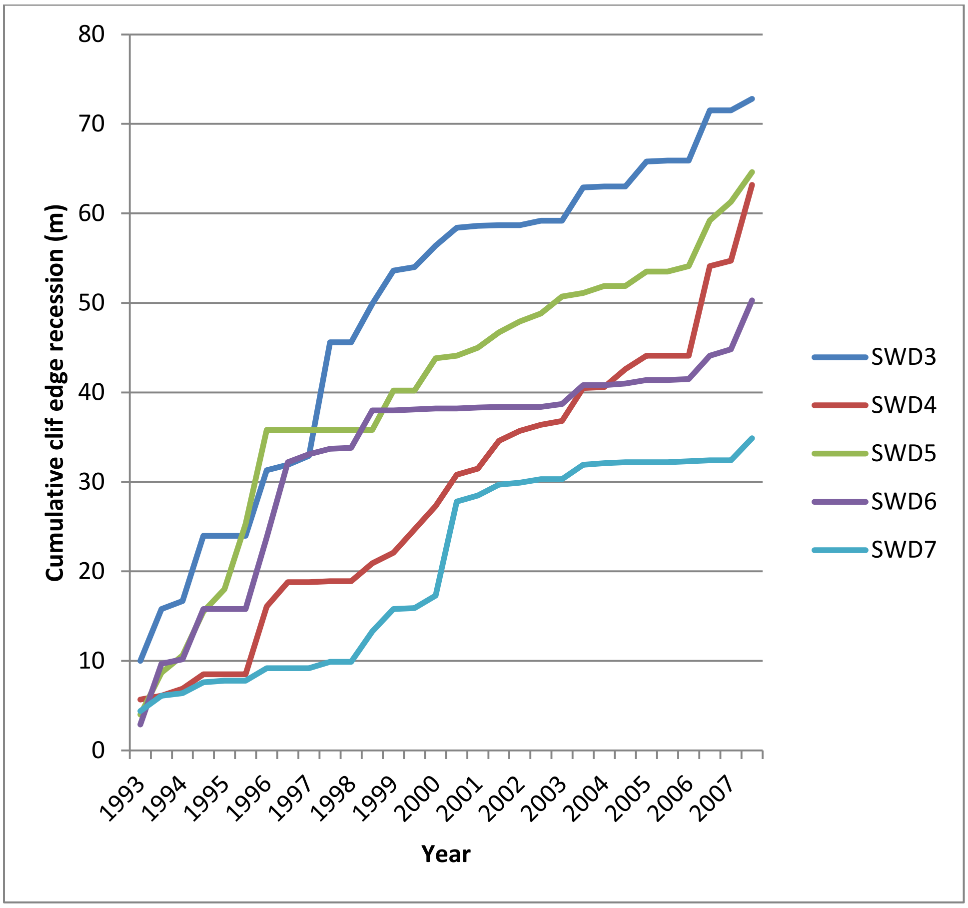
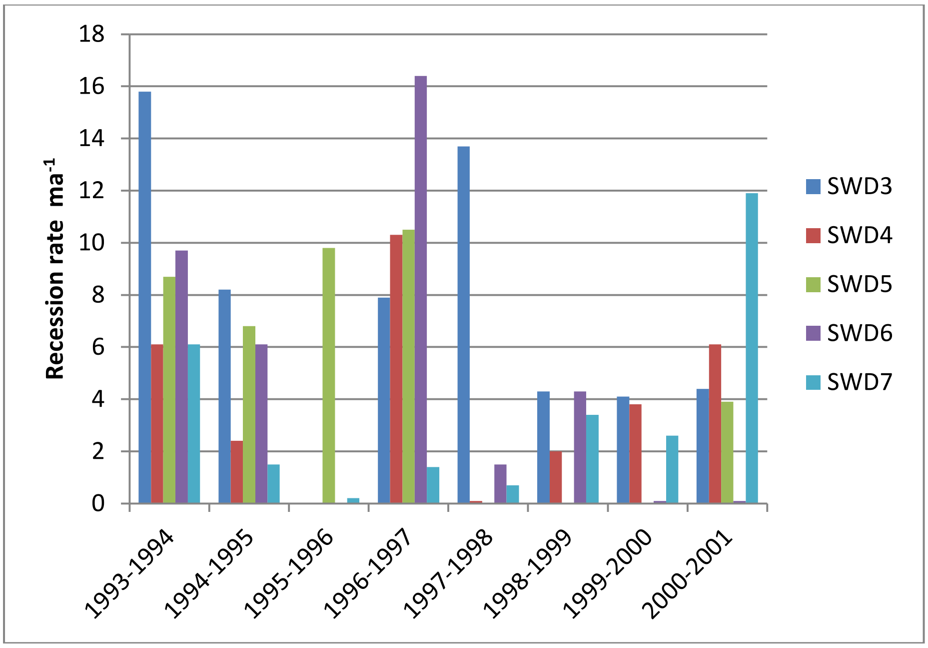


Figure 4.1

End Point Method cumulative cliff edge retreat from analysis of the SDMS Surveys at the study sites between 1993 and 2008

The cliff edge retreat rate (m a^{-1} winter-winter) between SWD3 (Covehithe) and SWD7 (Easton) for the period 1992-2008, and the sub-periods 1992-2001 and 2001-8 are shown in Figure 4.2. The key behaviour exhibited is a considerable change in retreat rates from higher rates in 1992-2001 compared with those in 2001-8.



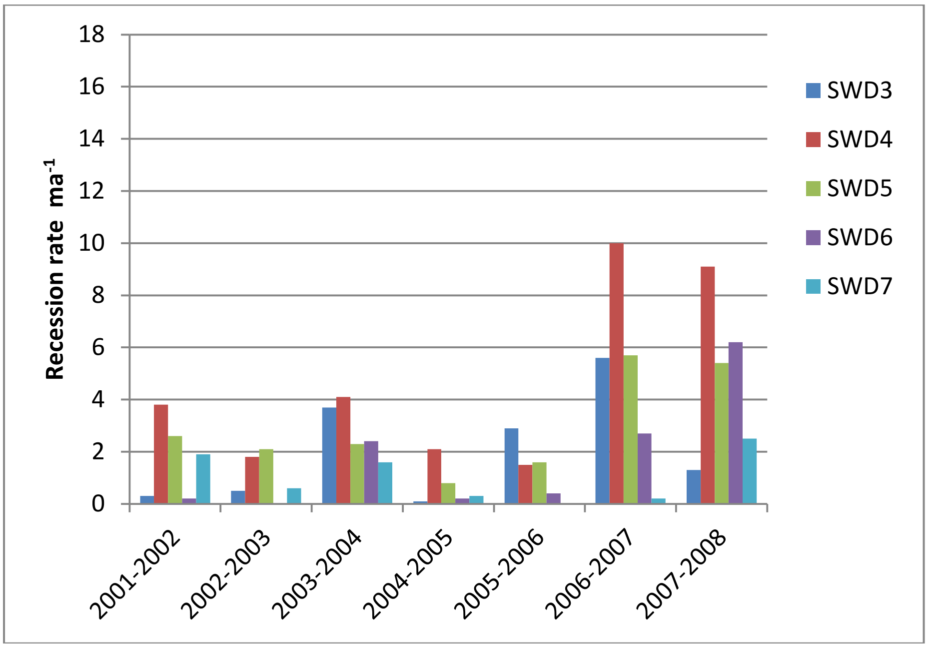


Figure 4.2

The cliff edge retreat rate (m a^{-1}) between SWD3 (Covehithe) and SWD7 (Easton) for the period 1992-2008, and the sub-periods 1992-2001 and 2001-8

4.2 The association between rainfall and cliff retreat

Annualised (between alternate biannual surveys)values for rainfall at Wrentham between 1993 and 2008 ranged from 465 mm (in 1996) to 799 mm (in 2001) (Table 4.2). The mean was 652 mm±105 mm.

Year	***Total rainfall (mm)***	***Year***	***Total rainfall (mm)***
1993-1994	860	2001-2002	778
1994-1995	658	2002-2003	691
1995-1996	578	2003-2004	494
1996-1997	457	2004-2005	610
1997-1998	584	2005-2006	646
1998-1999	672	2006-2007	628
1999-2000	637	2007-2008	761
2000-2001	731		

Table 4.2

Annual rainfall totals and winter period rainfall totals in the period January 1993 to January 2008 at Wrentham, Suffolk

Analysis of the intra-annual rainfall pattern at the study sites showed that there was considerable variability between summer period rainfall totals and winter period rainfall totals (Table 4.3).

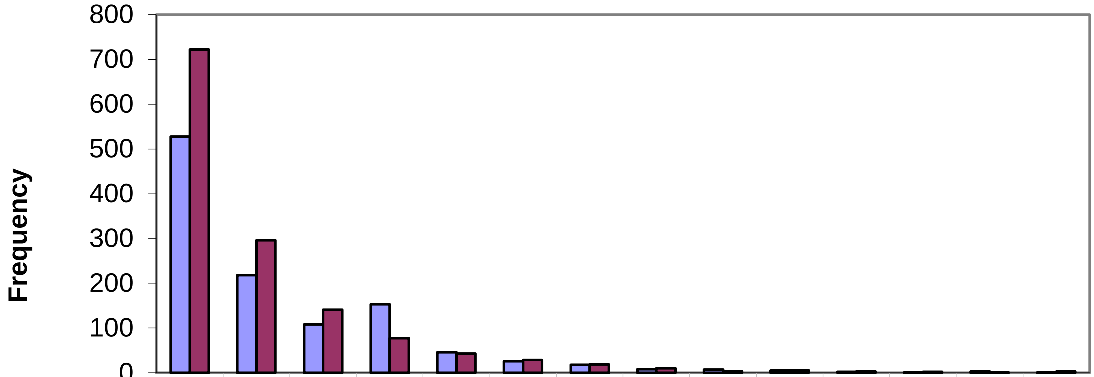
Summer	*Rainfall (mm)*	*Winter*	*Rainfall (mm)*	*Summer*	*Rainfall (mm)*	*Winter*	*Rainfall (mm)*
1993	278.6	1993-94	568.9	2001	393.7	2001-02	336.5
1994	332.4	1994-95	396.6	2002	212.4	2002-03	434.0
1995	246.4	1995-96	220.8	2003	183.4	2003-04	353.6
1996	247.2	1996-97	261.0	2004	366.4	2004-05	242.9
1997	242.7	1997-98	314.3	2005	313.6	2005-06	301.5
1998	356.2	1998-99	368.1	2006	354.0	2006-07	369.6
1999	324.4	1999-00	277.1	2007	433.8	2007-08	285.4
2000	286.6	2000-01	539.8	2008	364.1		

Table 4.3

Summer period rainfall totals and winter period rainfall totals in the period January 1993 to January 2008 at Wrentham.

Rainfall total was found to be highly variable. For example, the driest summer period was in 2003 (183.4 mm) and the wettest summer was in 2007 (433 mm). These values are comparable to those for the driest winter period in 1995-1996 (220.8 mm) and the wettest winter period 1993-1994 (568 mm). This situation means that the elucidation of seasonal relationships is not straightforward.

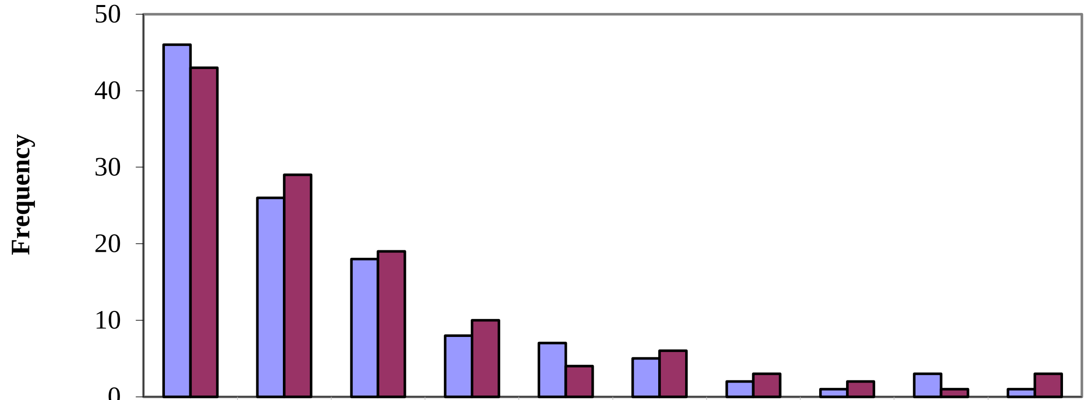
Daily rainfall total values were found to be dominated by days with rainfall totals in the classes <2.5 mm and 2.5 to 5mm. However, 237 days had rainfall totals of >10 mm and 38 days had rainfall totals > 20 mm (Figure 4.3). There were 18 days in summer with rainfall totals >20 mm and 18 days in winter. Out of the four days with rainfall totals that were >40 mm during the study period, 3 were in winter and 1 was in summer. The frequency of the daily rainfall totals >10 mm is shown in Figure 4.4. The maximum one-day and two-day rainfall totals in each inter-survey period are shown in Table 4.4.



	< 2.4	2.5 to 4.9	5.0 to 7.4	7.5 to 9.9	10.0 to 12.4	12.5 to 14.9	15.0 to 17.4	17.5 to 19.9	20.0 to 24.9	25.0 to 29.9	30.0 to 34.9	35.0 to 39.9	40.0 to 44.9	> 45
Summers	528	218	108	153	46	26	18	8	7	5	2	1	3	1
Winters	722	296	141	77	43	29	19	10	4	6	3	2	1	3

Figure 4.3

Frequency distribution of daily rainfall total (mm) at Wrentham (2.8 km inland from Covehithe) for the period 1993 to 2008 is shown with number of summer/winter events.



	10.0 to 12.4	12.5 to 14.9	15.0 to 17.4	17.5 to 19.9	20.0 to 24.9	25.0 to 29.9	30.0 to 34.9	35.0 to 39.9	40.0 to 44.9	> 45
Summers	46	26	18	8	7	5	2	1	3	1
Winters	43	29	19	10	4	6	3	2	1	3

Figure 4.4

Frequency distribution of daily rainfall totals (>10 mm) at Wrentham (2.8 km inland from Covehithe) for the period 1993 to 2008 is shown with number of summer/winter events.

Period	*Start date to end date*	*Survey*	*Rainfall total in period mm*	*Maximum 1-day rainfall total mm*	*Maximum 2- day rainfall total mm*
1	06/01/1993 to 07/08/1993	W_93	301	27.7	40.1
2	08/08/1993 to 09/01/1994	S_93	559	48.4	89.1
3	10/01/1994 to 04/08/1994	W_94	320	22.8	30.3
4	05/08/1994 to 12/01/1995	S_94	338	42.5	47.3
5	13/01/1995 to 20/08/1995	W_95	384	22.7	23.5
6	21/08/1995 to 17/01/1996	S_95	194	14.9	25.6
7	18/01/1996 to 09/09/1996	W_96	238	44.6	82.4
8	10/09/1996 to 21/01/1997	S_96	219	17.4	23.8
9	22/01/1997 to 10/08/1997	W_97	250	18	32.1
10	11/08/1997 to 03/02/1998	S_97	334	28.8	40.6
11	04/02/1998 to 22/07/1998	W_98	272	21.6	28.5
12	23/07/1998 to 16/01/1999	S_98	400	33.2	41.3
13	17/01/1999 to 11/08/1999	W_99	360	33.5	52
14	12/08/1999 to 10/02/2000	S_99	277	13.9	16.1
15	11/02/2000 to 22/08/2000	W_00	307	26.4	44.5
16	23/08/2000 to 20/01/2001	S_00	424	32.6	43.9
17	21/01/2001 to 29/08/2001	W_01	519	28	28.1
18	30/08/2001 to 07/01/2002	S_01	259	39	54.4
19	08/01/2002 to 12/09/2002	W_02	322	13.2	15.3
20	13/09/2002 to 27/01/2003	S_02	369	68.5	74.1
21	28/01/2003 to 06/08/2003	W_03	213	28.5	37
22	07/08/2003 to 16/01/2004	S_03	281	18	30.5
23	17/01/2004 to 26/07/2004	W_04	323	21	26.4
24	27/07/2004 to 21/01/2005	S_04	287	21.5	33.1
25	22/01/2005 to 19/07/2005	W_05	320	27.4	37.6
26	20/07/2005 to 07/02/2006	S_05	326	29.3	29.9
27	08/02/2006 to 20/07/2006	W_06	149	12.5	12.5
28	21/07/2006 to 01/02/2007	S_06	479	46	55.2
29	02/02/2007 to 20/08/2007	W_07	496	70	86.9
30	21/08/2007 to 30/01/2008	S_07	265	20.6	21.7

Table 4.4

The maximum one-day and two-day rainfall totals in each inter-survey period

The association between cliff edge retreat rate at SWD3, SWD4, SWD5, SWD6 and SWD7 and the value obtained for the ratio of 2-day rainfall total to the rainfall total in the period between surveys (from Table 4.4) is shown in Figure 4.5.

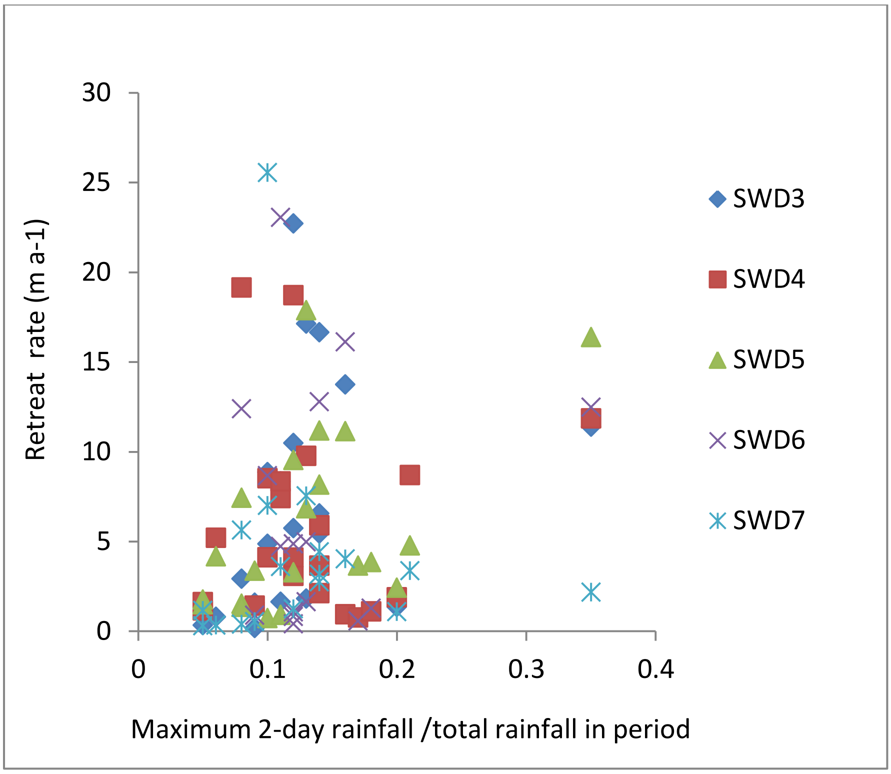


Figure 4.5

The association between cliff edge retreat rate at SWD3, SWD4, SWD5, SWD6 and SWD7 and the value obtained for the ratio of 2-day rainfall total to the rainfall total in the period between surveys (from Table 4.4)

Statistical analysis of the association between rainfall and retreat rate using a Pearson Correlation test produced a value for R of 0.2009. Although this is technically a positive correlation, the relationship between the variables is weak. The value of R^2, the coefficient of determination, was 0.0404. For a Pearson R value of 0.2009 (n=97) the P-Value is 0.048478. The result is significant at $p < 0.05$.

4.3 Terrestrial forcing of Cliff retreat

4.3.1 Coupled hydrology and stability model sensitivity analysis

The Factor of Safety (FS) results in the Sensitivity Study are shown in Figure 4.6 and Figure 4.7 as sensitivity plots. In these graphs, the strength parameters have been normalised to a sensitivity range value between zero and one, such that zero corresponds to the lowest parameter data point and one to the highest. Zero therefore represents a friction angle of 20 degrees or cohesion of 0 kPa, whilst a value of one represents a friction angle of 40 degrees or cohesion of 20 kPa. In this analysis, when the factor of safety is plotted against the sensitivity range the gradient of the line increases with sensitivity to the parameter under consideration.

Comparison of the gradient of the lines in Figure 4.6and Figure 4.7 shows that in all cases the modelled Factor of Safety (Bishop Method) is more sensitive to changes in the cohesion value than to changes in the friction angle of the material. Consequently, as either the value for friction angle or the cohesion chosen affect the initial slope stability; they will also affect the slope stability under a given set of rainfall conditions, despite not influencing the hydrology.

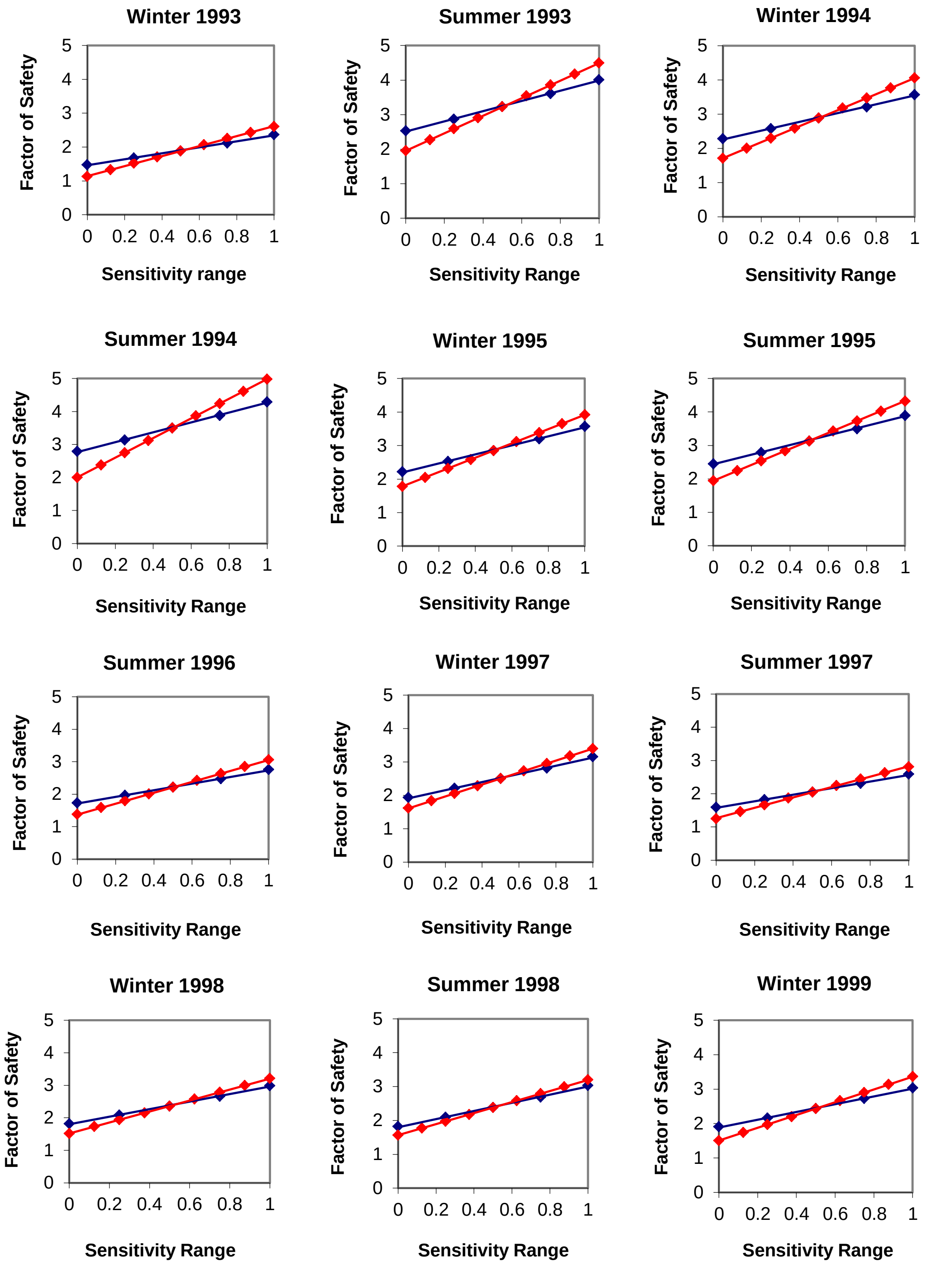


Figure 4.6

Factor of Safety shown with Sensitivity Range for the period from Winter 1993 to Winter 1999 in the Sensitivity Study at SWD4. Friction angle is shown in blue and cohesion is shown in red.

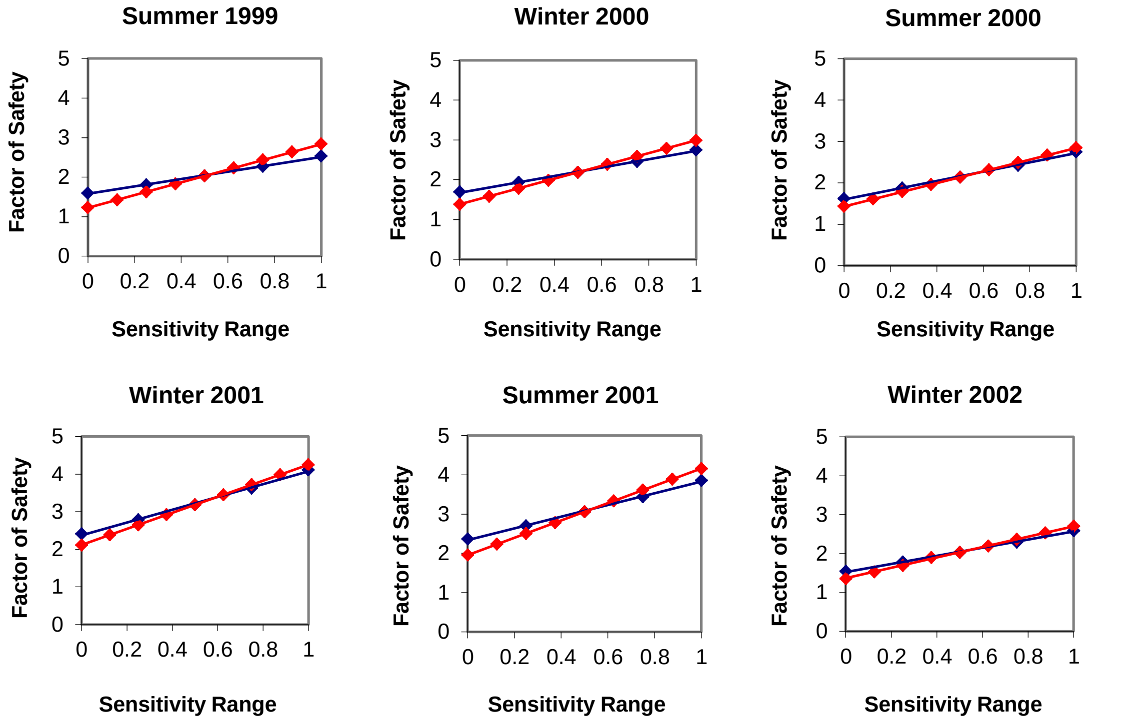


Figure 4.7

Factor of Safety shown with Sensitivity Range for the period from Summer 1999 to Winter 2002 in the Sensitivity Study at SWD4. Friction angle is shown in blue and cohesion is shown in red.

The results of hydrological sensitivity analyses are shown in Figure 4.8 to Figure 4.10 as graphs of the Factor of Safety results under each of the hydraulic conductivity and rainfall parameterisations used.

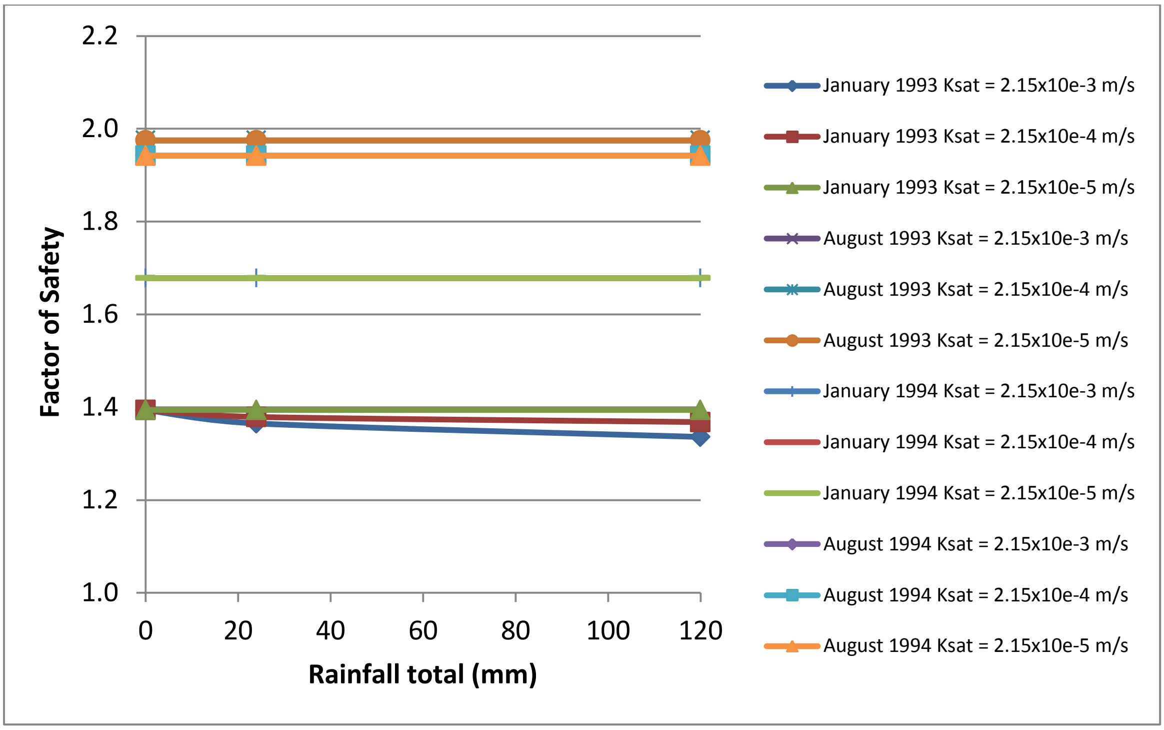
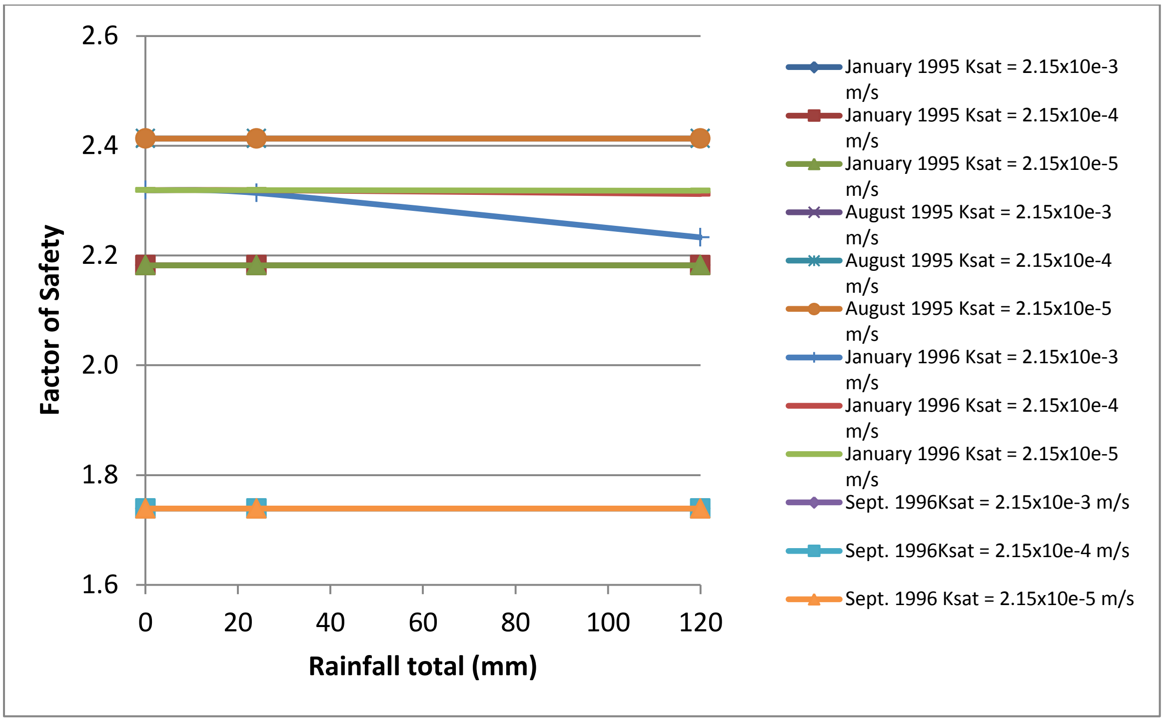


Figure 4.8

Factor of Safety responses in the hydrological sensitivity analysis for the periods; January 1993, August 1993, January 1994 and August 1994

A



B

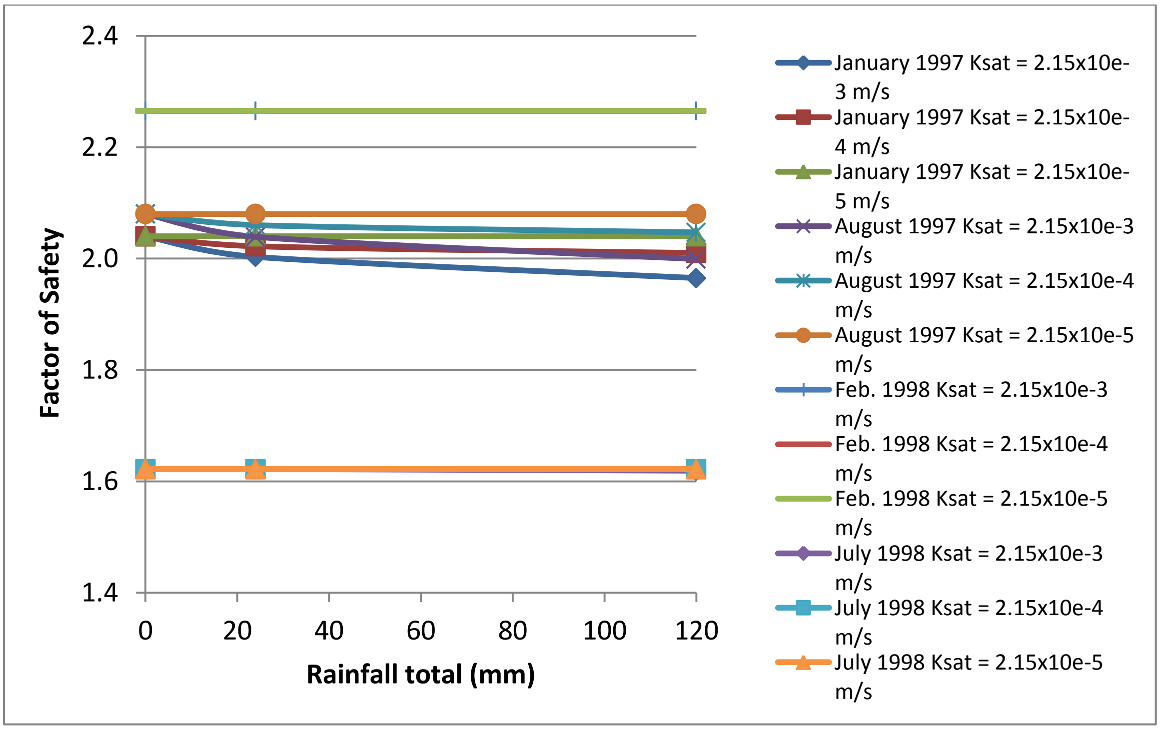
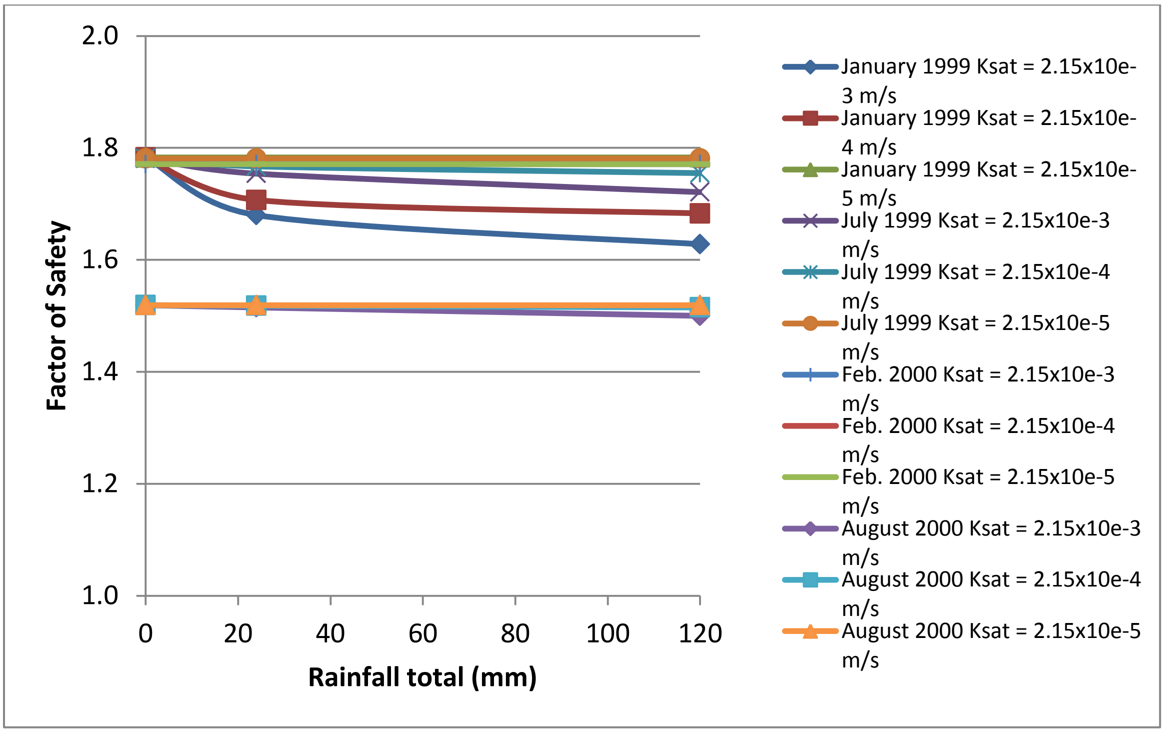


Figure 4.9

Factor of Safety responses in the hydrological sensitivity analysis for the periods; January 1995, August 1995, January 1996 and September 1996 (A) and January 1997, August 1997, February 1998 and July 1998 (B)

A



B

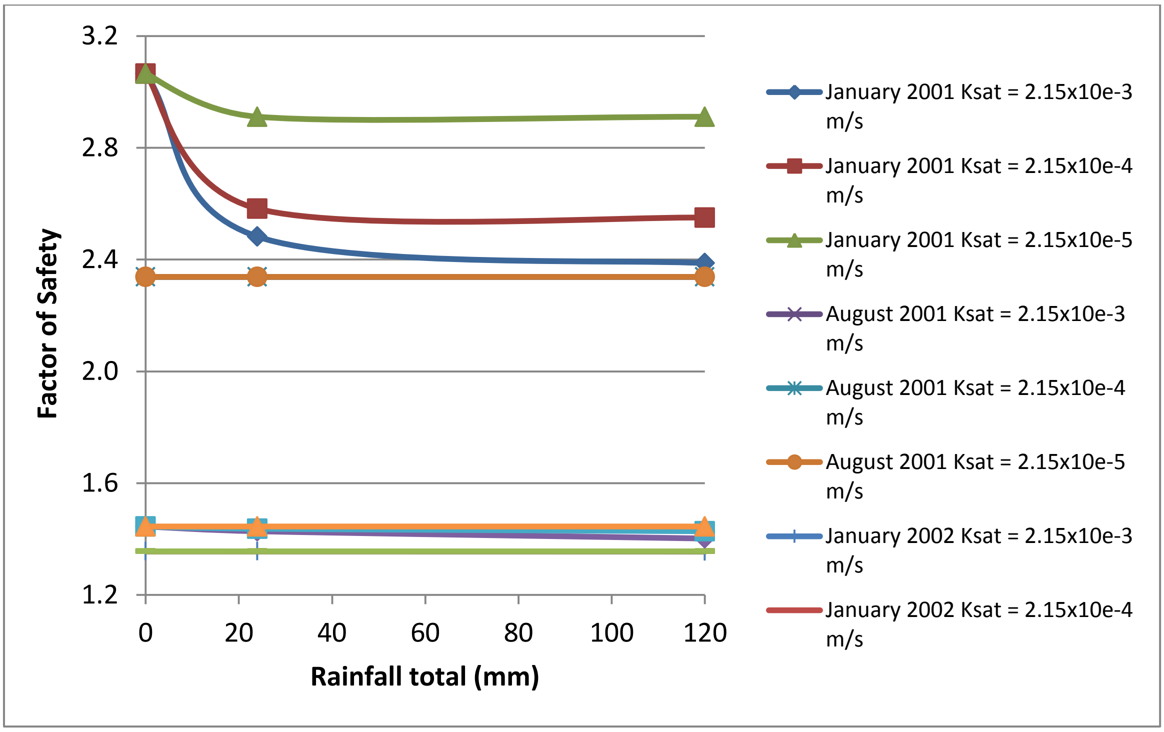


Figure 4.10

Factor of Safety responses in the hydrological sensitivity analysis for the periods; January 1999, July 1999, February 2000 and August 2000 (A) and January 2001, August 2001 and January 2002 (B)

4.3.2 Hydrological response to disturbing rainfall stress

This section sets out the pore-water pressure behaviour in response to disturbing rainfall stress. The relationship between the SEEP/W model output contours and finite element nodal pore-water pressure values used to interpret the behaviour is shown in Figure 4.11 (using the January 1993 SEEP/W analysis as illustration). The pore-water pressures vs. depth plots represent the pore-water pressure distribution in the cliff segment at 1-day intervals. Figure 4.11 illustrates that the rainfall stress modelled in this scenario produced a perched water table in the upper cliff segment, with pore-water pressures being greater than 0kPa.

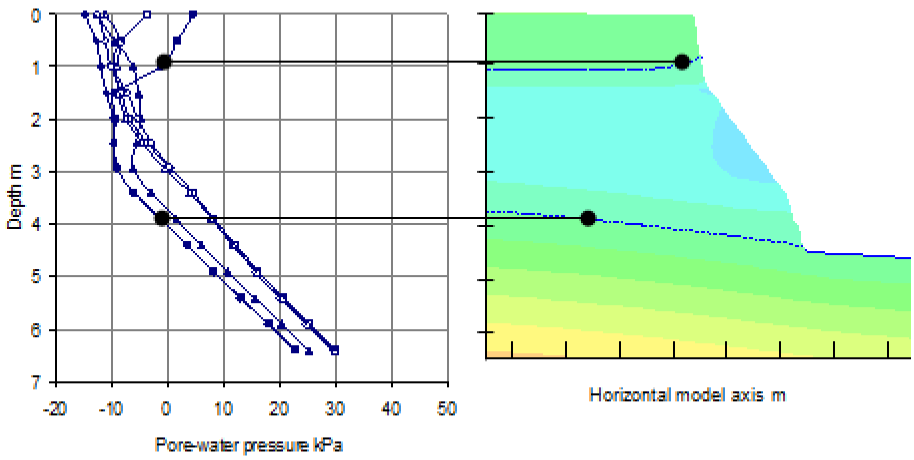
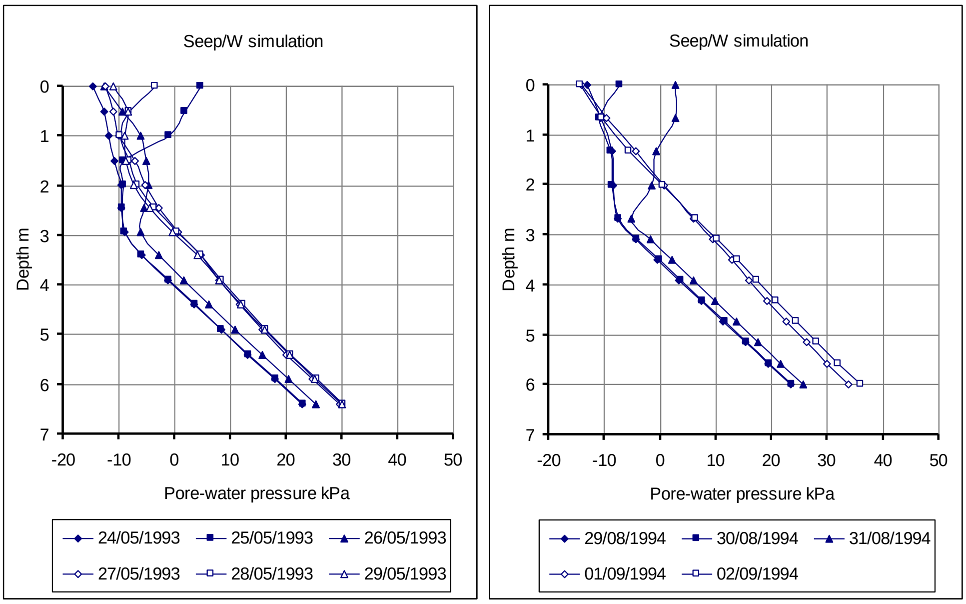


Figure 4.11

The relationship between the SEEP/W model output of pore-water pressure contour and water table surfaces (right) and the pore-water pressure response information (left)

Pore-water pressure responses from the hydrological analysis of Storm 1 to Storm 12 in the modelling at SWD4 are shown in: a) Figure 4.12 for Storm 1 to Storm 4 b) Figure 4.13 for Storm 5 to Storm8 and c) Figure 4.14 for Storm 9 to Storm 12.

A B



C D

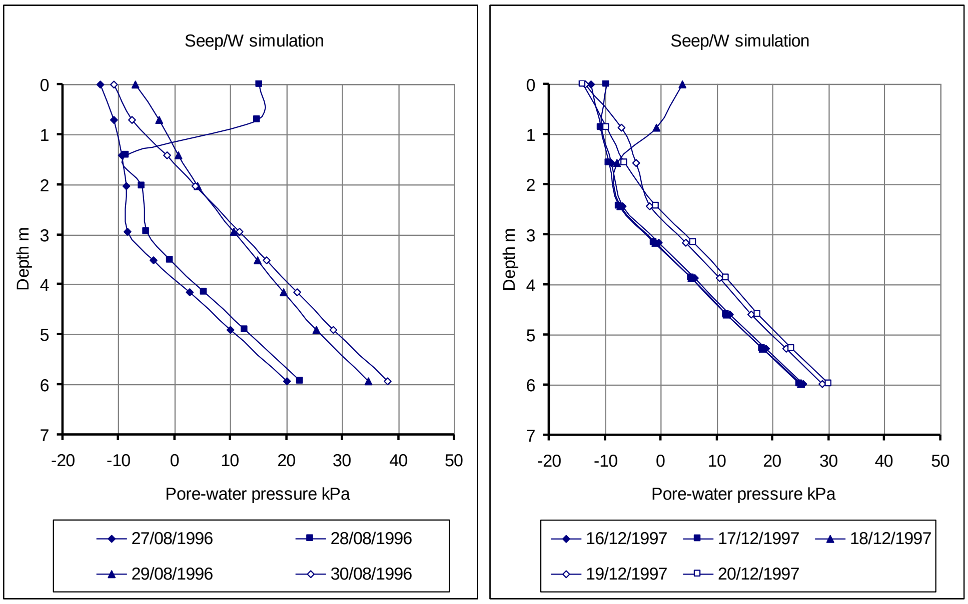


Figure 4.12

Pore-water pressure responses in the hydrological analysis for Storm 1 (A); Storm2(B); Storm 3 (C) and Storm 4 (D).Each line represents the pore water pressure (positive and negative)distribution in the cliff segment at 1-day intervals, showing the response from day 0 through to the end of the storm event.

A B

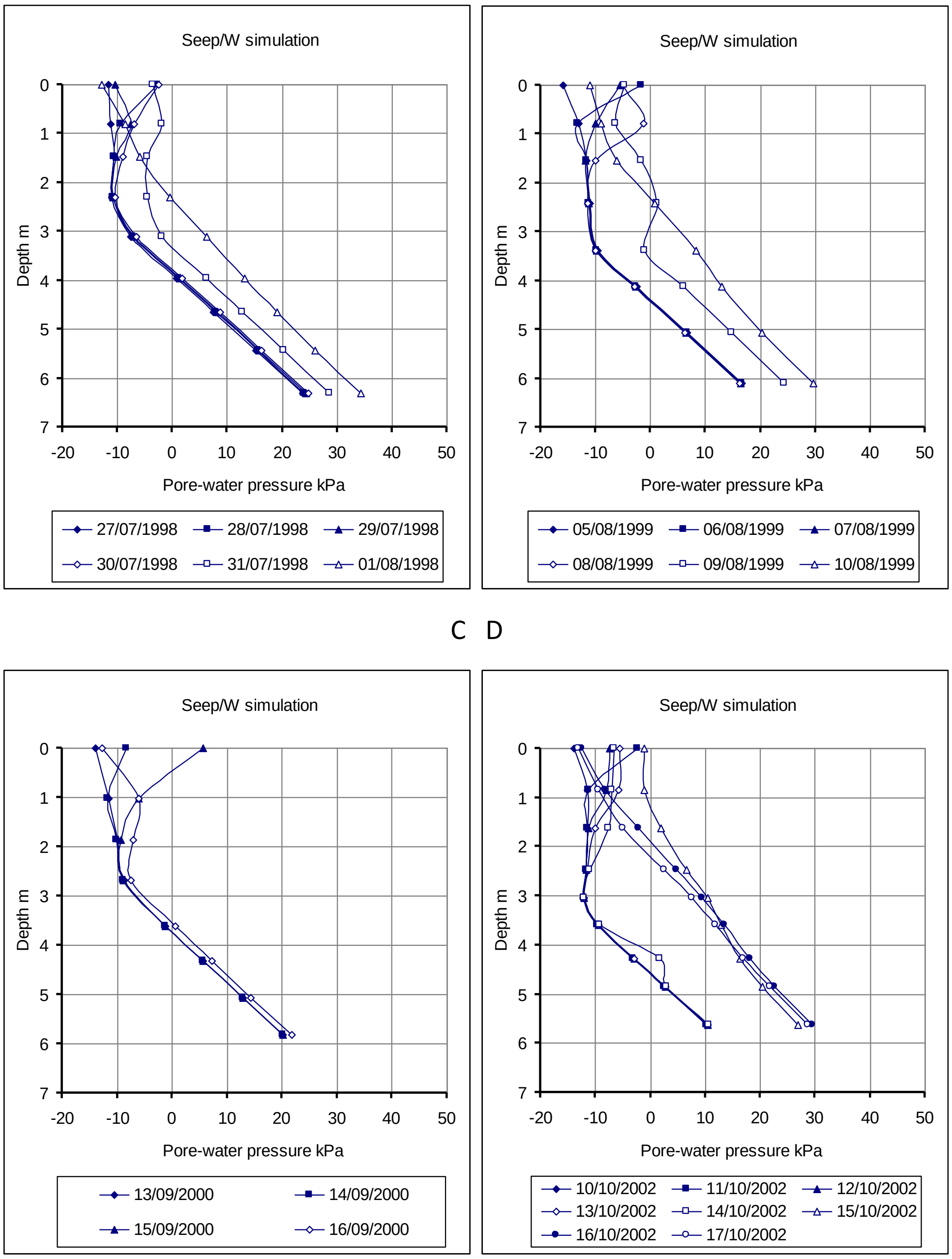


Figure 4.13

Pore-water pressure responses in the hydrological analysis for Storm 5 (A); Storm 6 (B); Storm 7 (C) and Storm 8 (D).Each line represents the pore water pressure (positive and negative) distribution in the cliff segment at 1-day intervals, showing the response from day 0 through to the end of the storm event.

A B

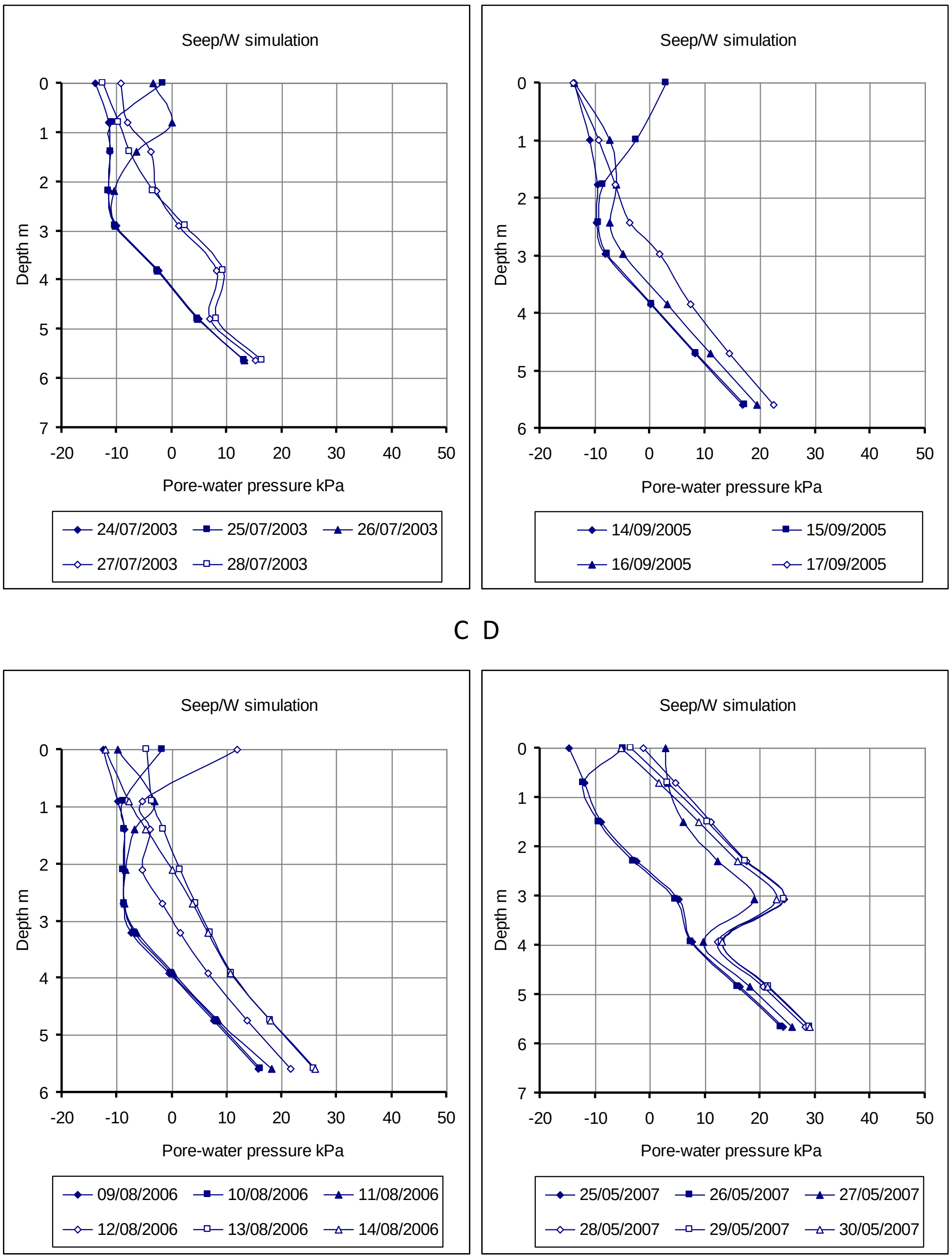


Figure 4.14

Pore-water pressure responses in the hydrological analysis for Storm 9 (A); Storm 10 (B); Storm 11 (C) and Storm 12 (D). Each line represents the pore water pressure (positive and negative) distribution in the cliff segment at 1-day intervals, showing the response from day 0 through to the end of the storm event.

4.3.3 FS response to disturbing rainfall stress

The FS responses in the simulations for the time periods modelled at Covehithe SWD4 (see Chapter 3) are shown (in order of increasing observed retreat in the field) with daily total rainfall (in mm) in Figure 4.15 to Figure 4.24. All simulations produced a consistent range for the location of the critical slip surface, although the FS varied according to rainfall conditions and profile geometry. In all cases the critical slip surface intersected the cliff top at around 1-3 m inland and outcropped at the cliff-beach junction.

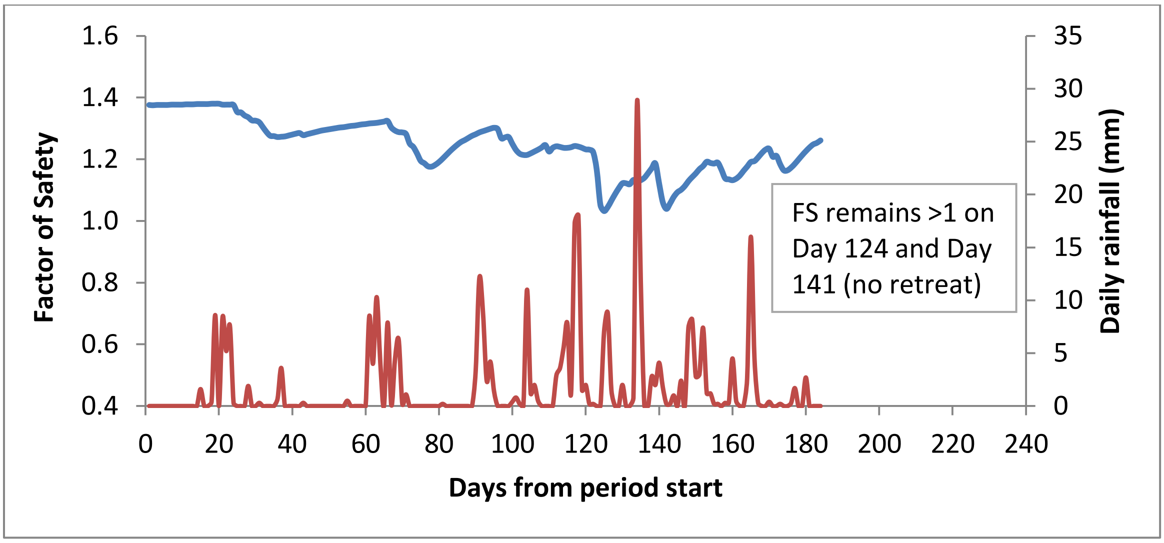


Figure 4.15

FS (Bishop Method) for simulation from 11/08/1997 to 03/02/1998 (no retreat)

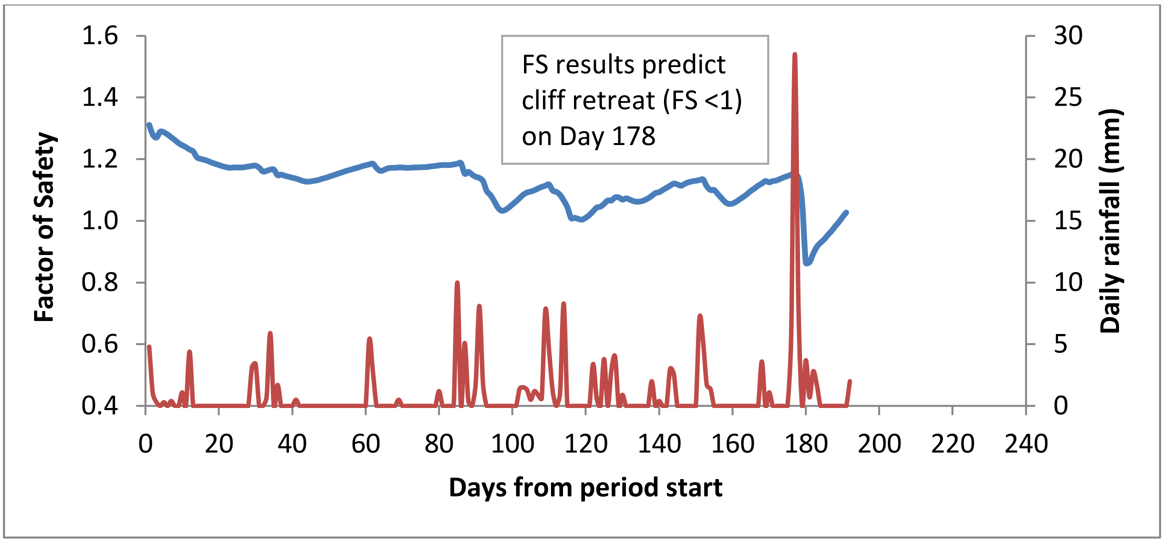


Figure 4.16

FS (Bishop Method) for simulation from* 28/01/2003 to 06/08/2003*(actual retreat = 0.4 m)

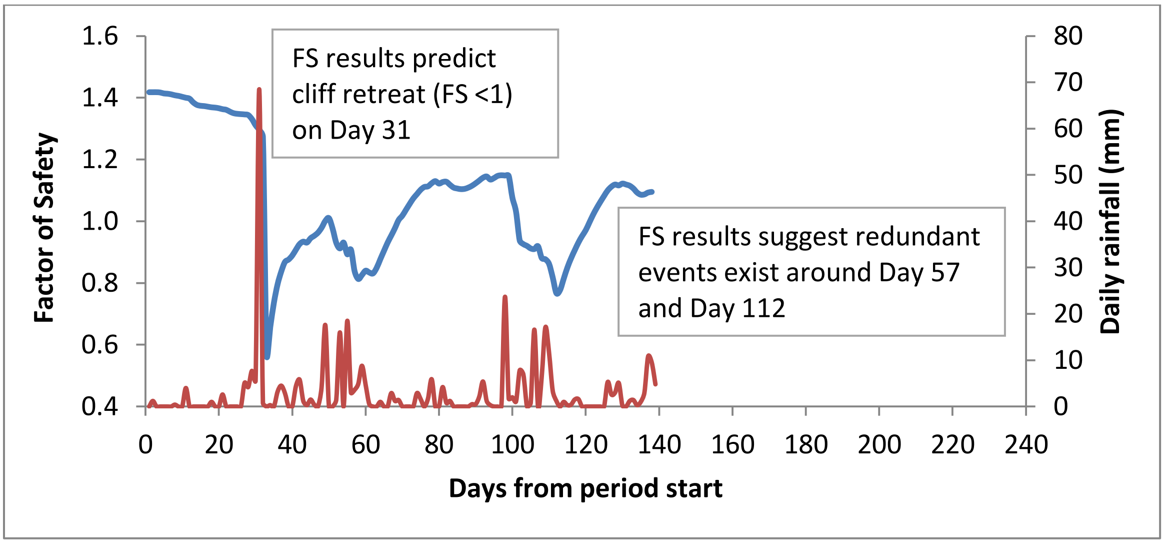


Figure 4.17

FS (Bishop Method) for simulation from 13/09/2002 to 27/01/2003 (actual retreat = 0.7 m)

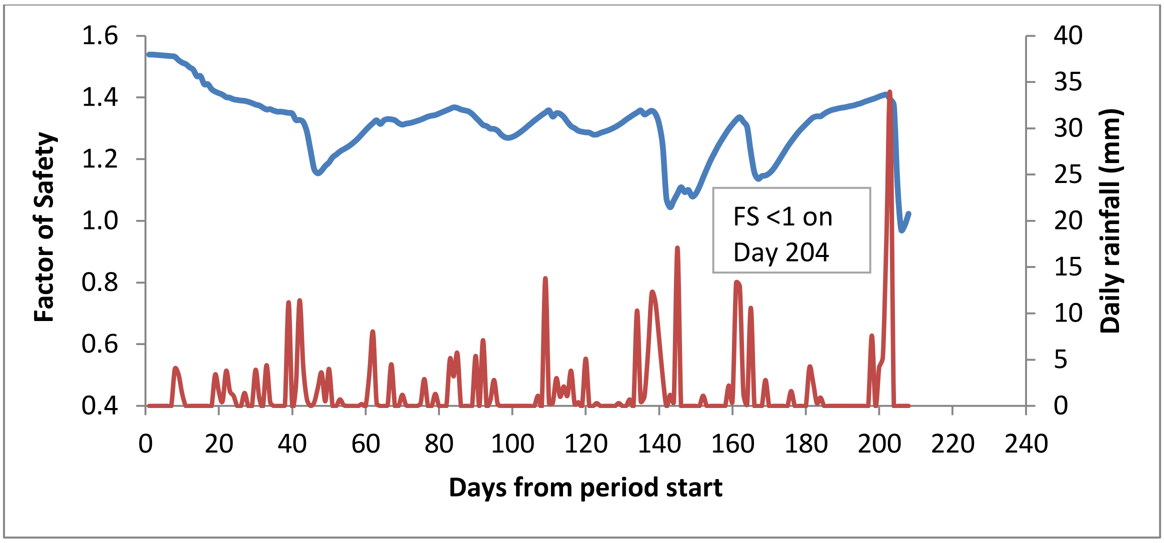


Figure 4.18

FS (Bishop Method) for simulation from 17/01/1999 to 11/08/1999(actual retreat = 1.2 m)

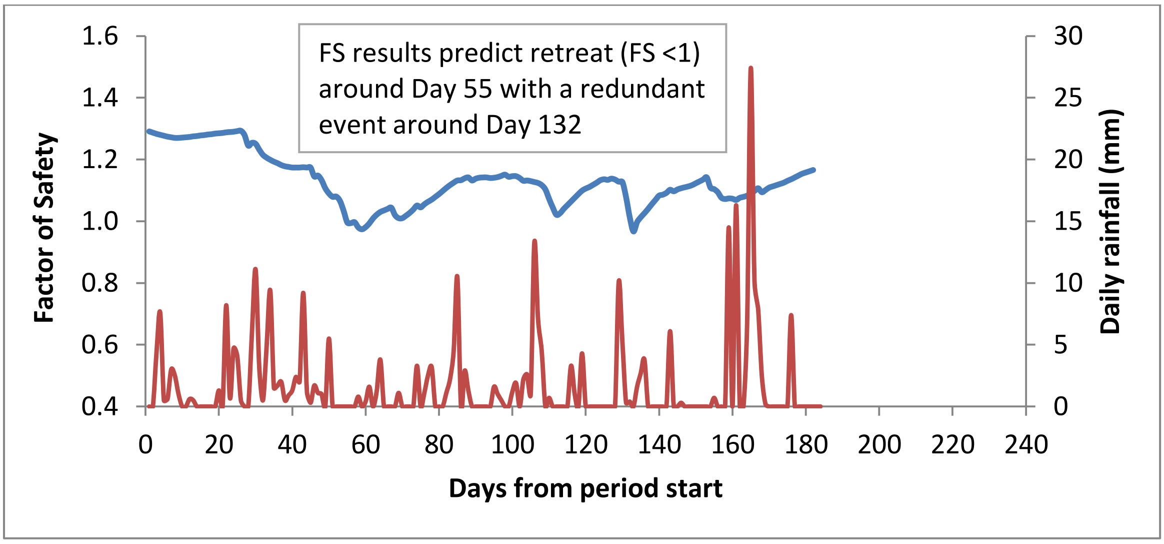


Figure 4.19

FS (Bishop Method) for simulation from 22/01/2005 to 19/07/2005 (actual retreat = 1.5 m)

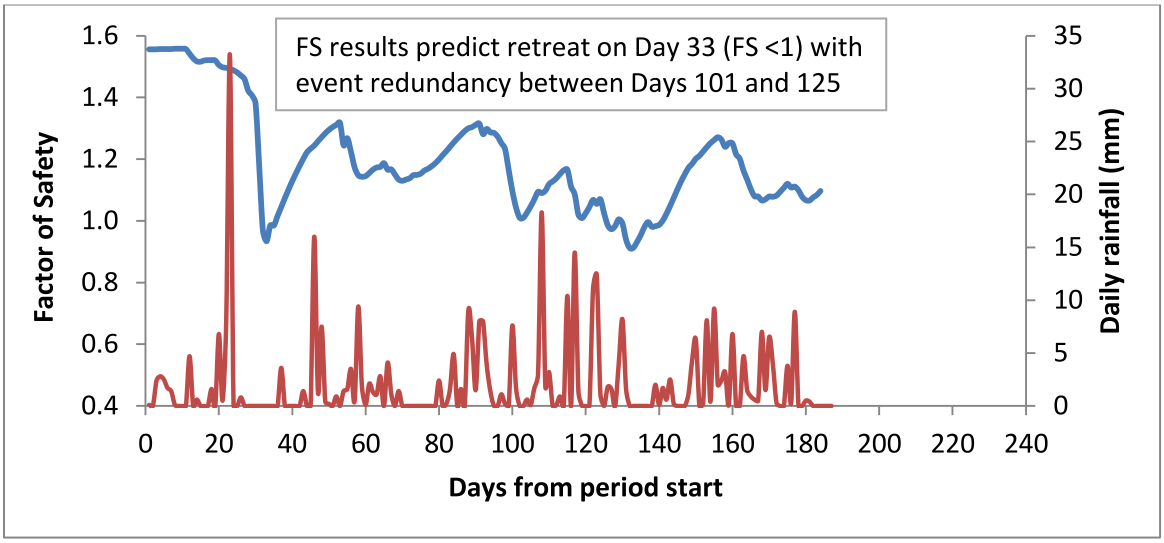


Figure 4.20

FS (Bishop Method) for simulation from 23/07/1998 to 16/01/1999(actual retreat = 2 m)

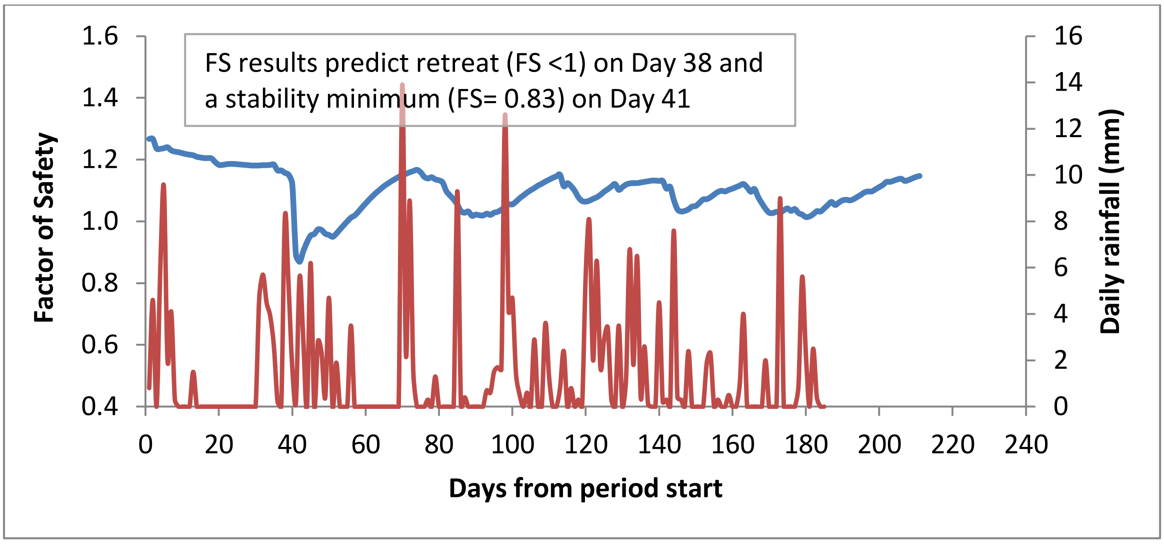


Figure 4.21

FS (Bishop Method) for simulation from 12/08/1999 to 10/02/2000 (actual retreat = 2.6 m)

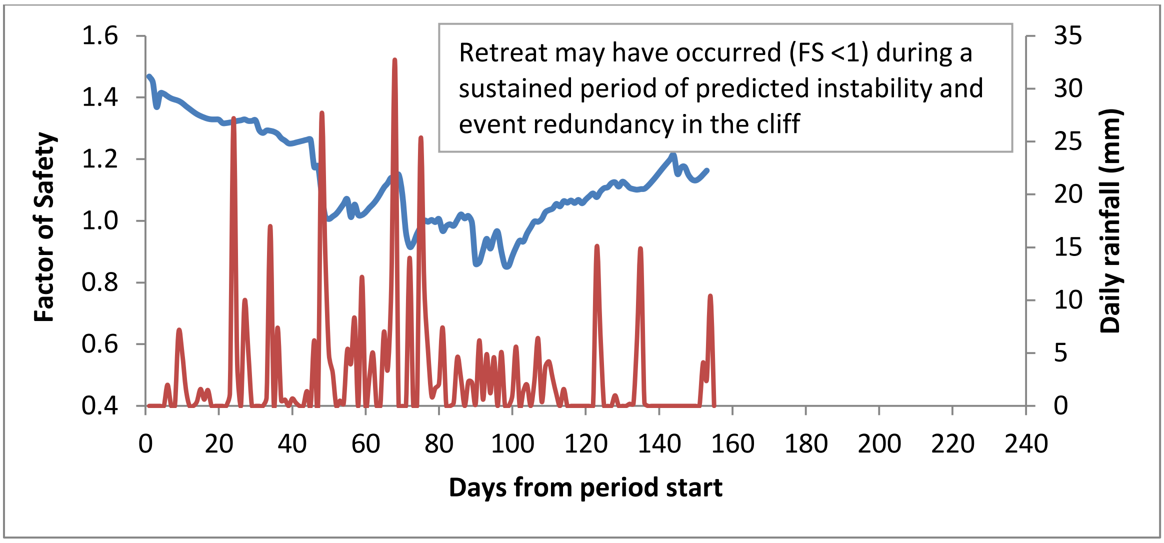


Figure 4.22

FS (Bishop Method) for simulation from 23/08/2000 to 20/01/2001 (actual retreat = 3.5 m)

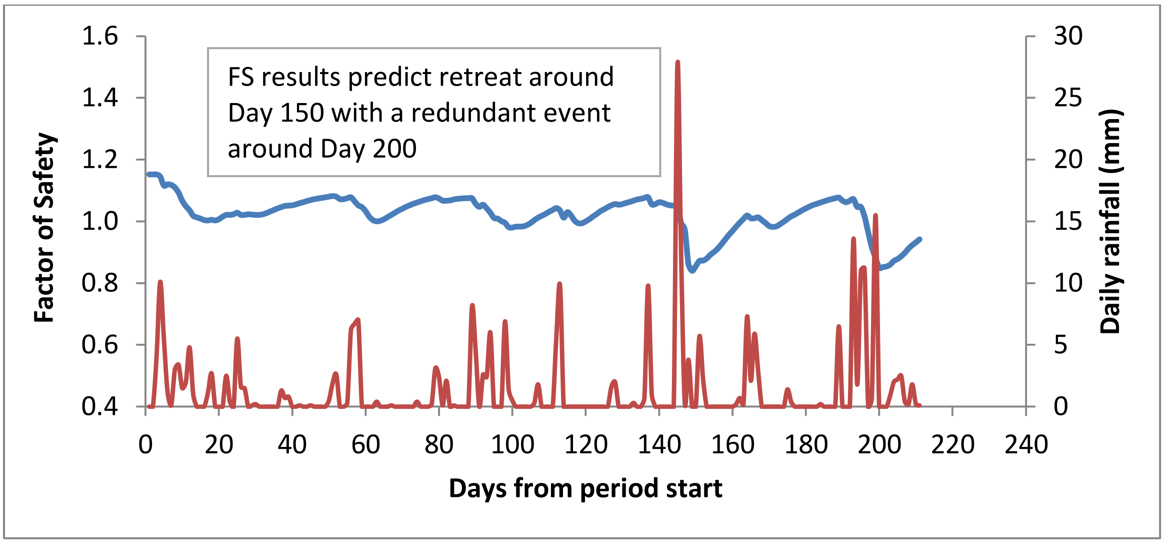


Figure 4.23

FS (Bishop Method) for simulation from 06/01/1993 to 07/08/1993(actual retreat = 5.7 m)

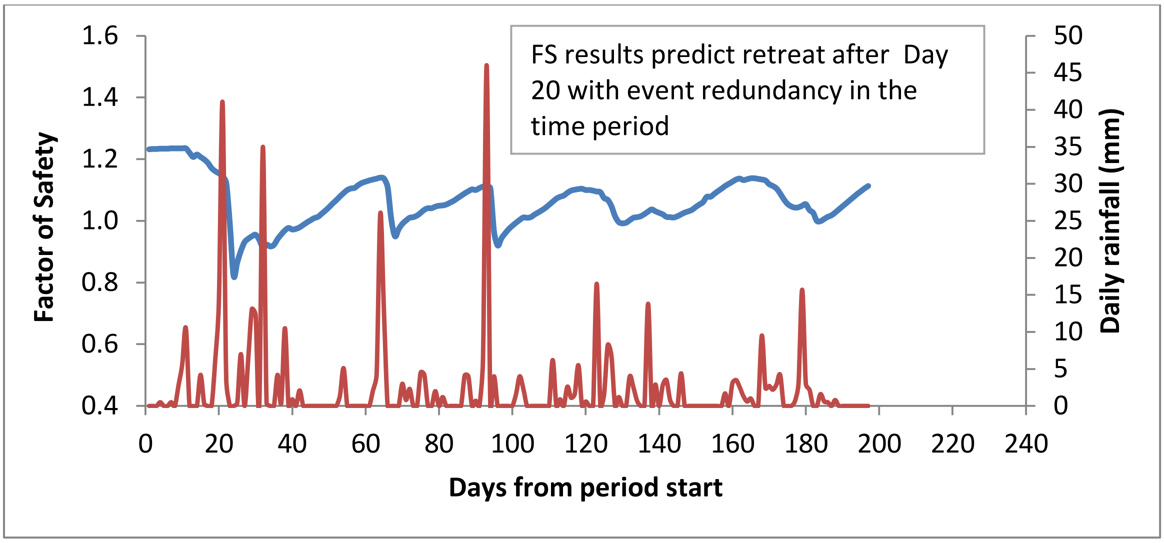


Figure 4.24

FS (Bishop Method) for simulation from 21/07/2006 to 01/02/2007 (actual retreat = 10 m)

Figure 4.25 shows regression analysis of the association between 2-day rainfall total and reduction in FS and the association between 1-day rainfall total and reduction in FS for the time series periods modelled (see Table 3.9).

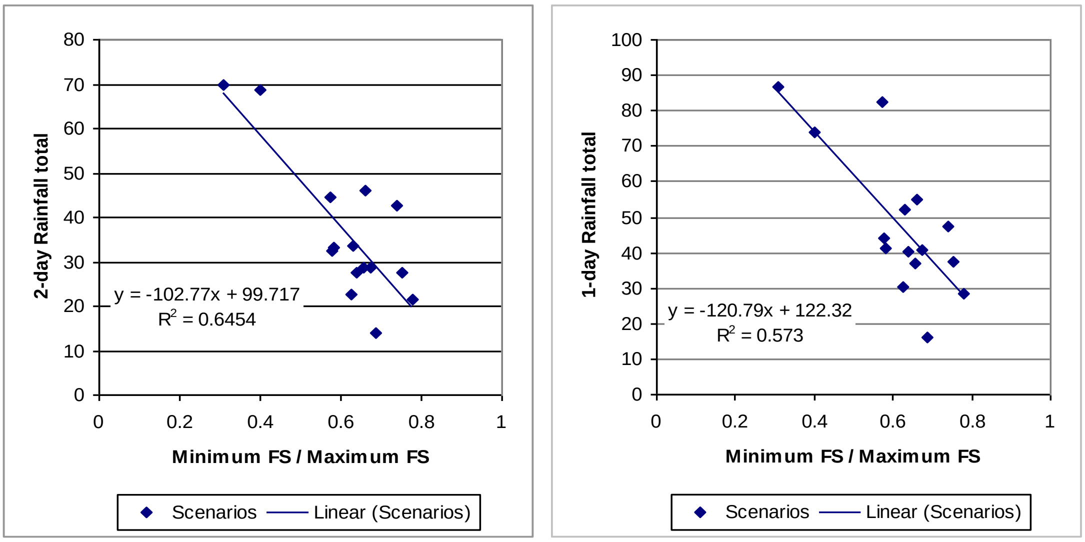


Figure 4.25

The relationship between 2-day rainfall total and reduction in Factor of Safety (FS) in the model shown with the relationship between 1-day rainfall total and reduction in Factor of Safety (FS)

4.4 Marine forcing of Cliff retreat

4.4.1 The record of water level at Lowestoft between 1993 and 2008

Analysis of the tide data for Lowestoft for the period 1993 to 2008 showed that there were 216 positive surge events. The frequency distribution of positive surges in the period 1993 to 2008 at Lowestoft is shown in Figure 4.26.

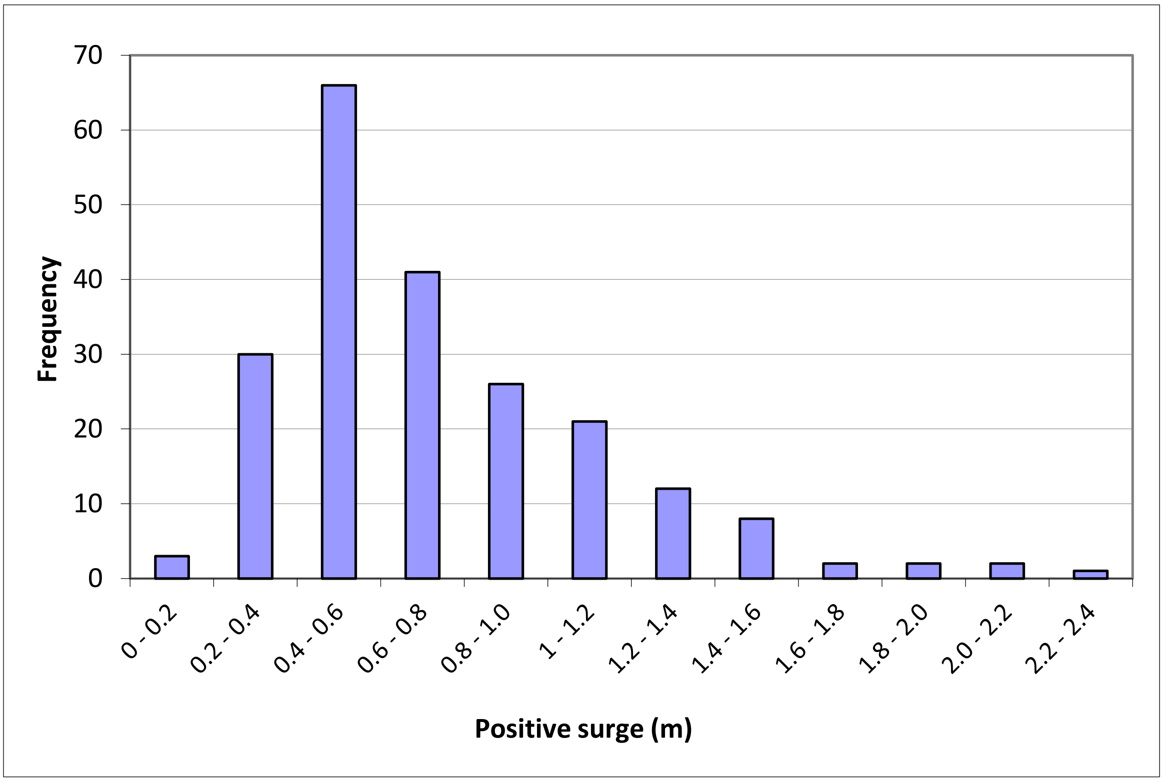


Figure 4.26

Positive surges at Lowestoft from tide gauge data in the period 1993 to 2008

During the study period 70 events were up to +0.5 m, a further 98 were between +0.5 m and +1.0 m and 38 were between +1.5 m and +2.0 m. There were 10 events greater than +2.0 m with the two largest values (+2.09 and +2.28) recorded in winter 2007. In situations where positive surges coincide with high astronomical tides there is potential for total water levels to reach extreme values. Tidal height (m) is shown with positive surge (m) for the periods 1993 to 1997 in Figure 4.27; the period 1998 to 2002 in Figure 4.28 and 2003 to 2007 in Figure 4.29.

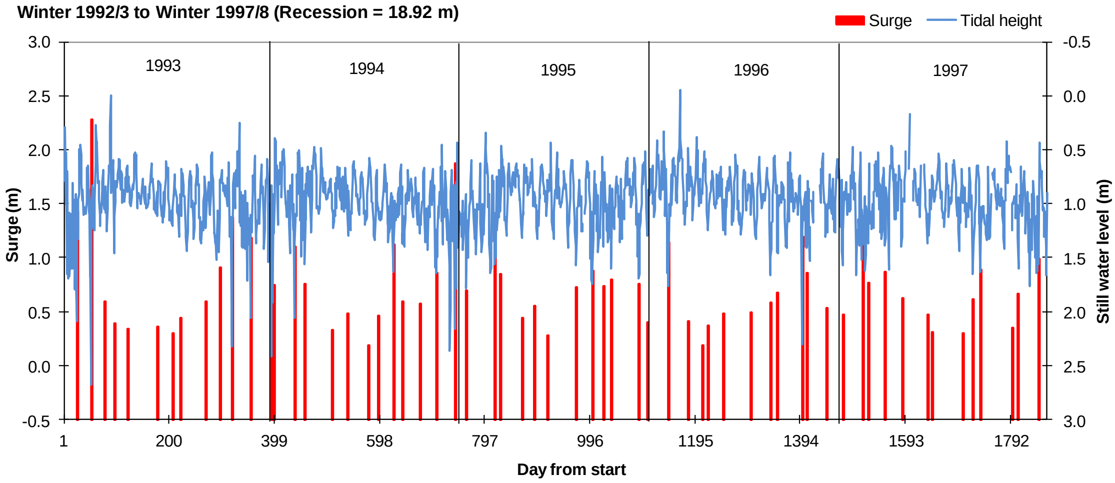


Figure 4.27

Frequency and temporal distribution of positive surges in the period 1993 to 1997 shown with tidal height (m)

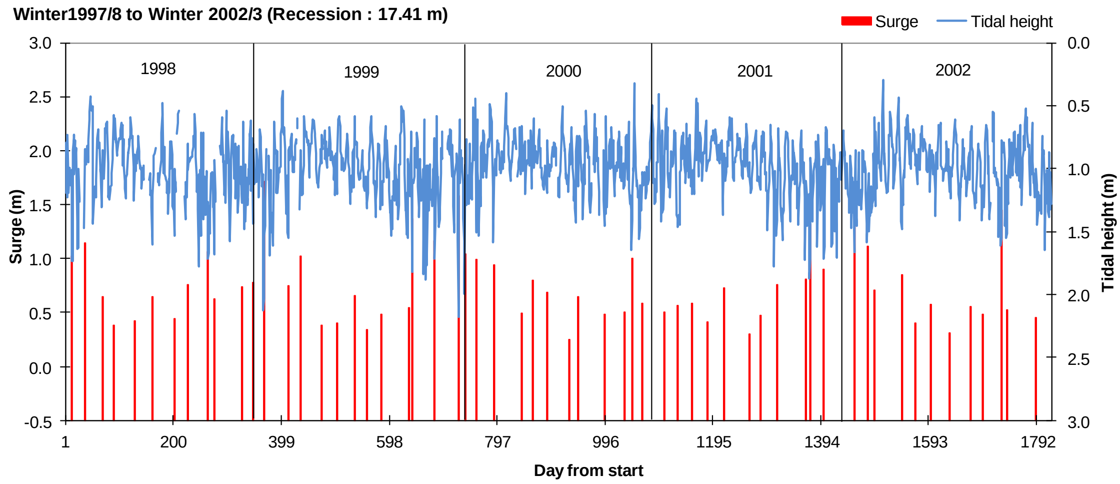


Figure 4.28

Frequency and temporal distribution of positive surges in the period 1998 to 2002 shown with tidal height (m)

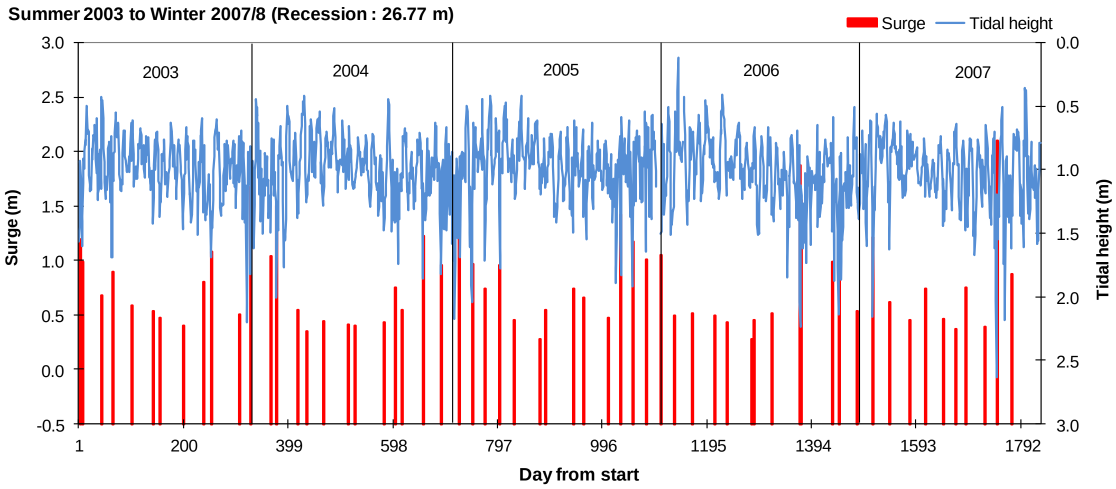
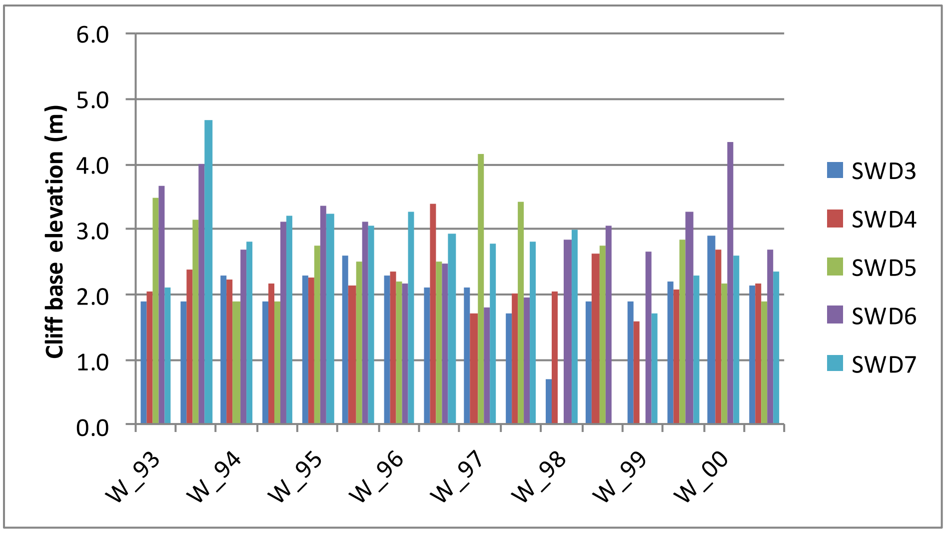


Figure 4.29

Frequency and temporal distribution of positive surges in the period 2003 to 2007 shown with tidal height (m)

4.4.2 The record of cliff base elevation at the study sites

The cliff base elevations identified from the analysis for the survey locations SWD3 to SWD7 are shown in Figure 4.30 for the period 1993 to 2001 (top) and the period 2001-2008 (bottom).



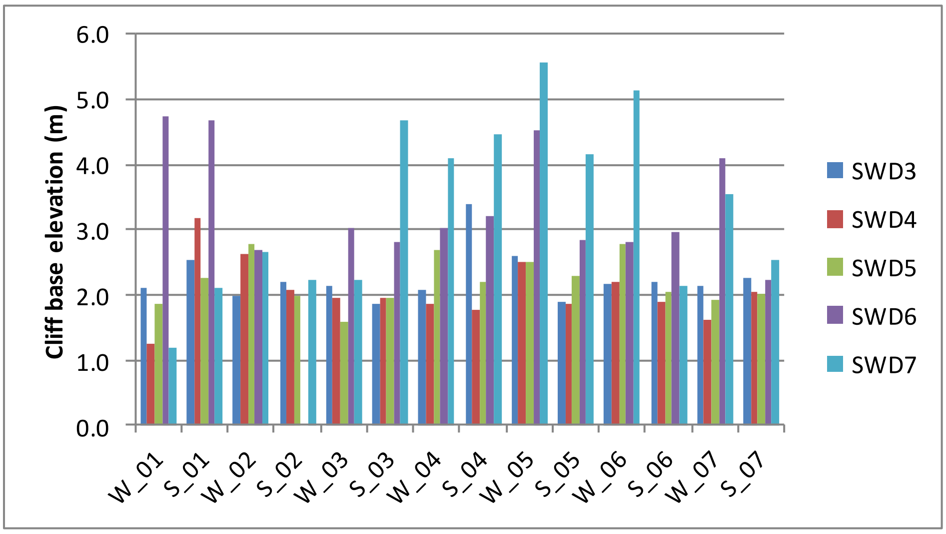


Figure 4.30

The cliff base elevations identified from the analysis for the survey locations SWD3 to SWD7 are shown for the period 1993 to 2001 (top) and the period 2001-2008 (bottom).

The variation in cliff base elevation at the at-a-point survey sites is apparent in Figure 4.30. This variability might be explained by small changes in aspect or surrounding cliffs offering shelter from prevailing waves that might occur over short periods of time. This may change the power of wave attack and induce local variability in beach behaviour.

A total of 66 periods were identified where co-incident information on retreat, cliff base elevation and still water level could be obtained from the SDMS surveys and the tide gauge records, respectively. Winter-winter surveys were used (after Lee, 2008).The cliff base elevation values derived in these analyses in the period 1993 to 2008 at SWD3, SWD4, SWD5, SWD6 and SWD7 are shown (in m OD) in Table 4.5 and Table 4.6.

Location (SDMS)	Period	Starting survey ref.	Cliff base elevation (m OD)	Relative water level
SWD3	06/01/1993 to 09/01/1994	W_93	1.9	0.8
SWD4	06/01/1993 to 09/01/1994	W_93	2	0.7
SWD5	06/01/1993 to 09/01/1994	W_93	3.5	-0.8
SWD6	06/01/1993 to 09/01/1994	W_93	3.4	-0.7
SWD7	06/01/1993 to 09/01/1994	W_93	2.1	0.6
SWD3	10/01/1994 to 12/01/1995	W_94	2.3	0.2
SWD4	10/01/1994 to 12/01/1995	W_94	2.2	0.2
SWD5	10/01/1994 to 12/01/1995	W_94	1.9	0.5
SWD6	10/01/1994 to 12/01/1995	W_94	3.6	-1.1
SWD7	10/01/1994 to 12/01/1995	W_94	2.8	-0.4
SWD3	13/01/1995 to 17/01/1996	W_95	2.34	-0.6
SWD5	13/01/1995 to 17/01/1996	W_95	2.8	-1
SWD6	13/01/1995 to 17/01/1996	W_95	3.38	-1.6
SWD7	13/01/1995 to 17/01/1996	W_95	3.2	-1.5
SWD3	18/01/1996 to 21/01/1997	W_96	2.3	0
SWD4	18/01/1996 to 21/01/1997	W_96	2.3	0
SWD5	18/01/1996 to 21/01/1997	W_96	2.2	0.1
SWD6	18/01/1996 to 21/01/1997	W_96	2.2	0.1
SWD7	18/01/1996 to 21/01/1997	W_96	3.3	-2.4
SWD3	22/01/1997 to 03/02/1998	W_97	2.1	0.9
SWD4	22/01/1997 to 03/02/1998	W_97	1.65	0.1
SWD6	22/01/1997 to 03/02/1998	W_97	1.8	-0.1
SWD7	22/01/1997 to 03/02/1998	W_97	2.8	0.1
SWD4	04/02/1998 to 16/01/1999	W_98	2.5	-0.8
SWD6	04/02/1998 to 16/01/1999	W_98	2.8	-1.1

Table 4.5

Cliff base elevation derived from winter SDMS survey data for the study sites for the period 1993 – 1998

Location (SDMS)	Period	Starting survey ref.	Cliff base elevation (m OD)	Relative water level
SWD3	17/01/1999 to 10/02/2000	W_99	1.9	0.3
SWD4	17/01/1999 to 10/02/2000	W_99	1.5	0.7
SWD6	17/01/1999 to 10/02/2000	W_99	3.86	-1.7
SWD3	11/02/2000 to 20/01/2001	W_00	2.9	-0.9
SWD4	11/02/2000 to 20/01/2001	W_00	2.6	-0.6
SWD5	11/02/2000 to 20/01/2001	W_00	2.2	-0.1
SWD6	11/02/2000 to 20/01/2001	W_00	4.35	-2.3
SWD3	21/01/2001 to 07/01/2002	W_01	2.1	-0.3
SWD4	21/01/2001 to 07/01/2002	W_01	1.2	0.6
SWD5	21/01/2001 to 07/01/2002	W_01	1.9	0
SWD6	21/01/2001 to 07/01/2002	W_01	4.7	-2.9
SWD3	08/01/2002 to 27/01/2003	W_02	2	-0.3
SWD4	08/01/2002 to 27/01/2003	W_02	2.6	-0.9
SWD5	08/01/2002 to 27/01/2003	W_02	2.8	-1.1
SWD6	08/01/2002 to 27/01/2003	W_02	2.68	-1
SWD3	28/01/2003 to 16/01/2004	W_03	2.2	0
SWD4	28/01/2003 to 16/01/2004	W_03	1.9	-0.4
SWD5	28/01/2003 to 16/01/2004	W_03	1.6	0.6
SWD6	28/01/2003 to 16/01/2004	W_03	3	-0.8
SWD3	17/01/2004 to 21/01/2005	W_04	2.1	0.1
SWD4	17/01/2004 to 21/01/2005	W_04	1.8	0.3
SWD5	17/01/2004 to 21/01/2005	W_04	2.7	-0.5
SWD6	17/01/2004 to 21/01/2005	W_04	3	-2.3
SWD3	22/01/2005 to 07/02/2006	W_05	2.6	-0.6
SWD4	22/01/2005 to 07/02/2006	W_05	2.5	-0.5
SWD5	22/01/2005 to 07/02/2006	W_05	2.5	-0.5
SWD6	22/01/2005 to 07/02/2006	W_05	4.5	-1
SWD3	08/02/2006 to 01/02/2007	W_06	2.2	0.1
SWD4	08/02/2006 to 01/02/2007	W_06	2.2	0
SWD5	08/02/2006 to 01/02/2007	W_06	2.8	-0.5
SWD6	08/02/2006 to 01/02/2007	W_06	3	-0.8
SWD3	02/02/2007 to 31/01/2008	W_07	2.1	0.5
SWD4	02/02/2007 to 31/01/2008	W_07	1.6	1
SWD5	02/02/2007 to 31/01/2008	W_07	1.9	0.7
SWD6	02/02/2007 to 31/01/2008	W_07	4.1	-1.5

Table 4.6

Cliff base elevation derived from winter SDMS survey data for the study sites for the period 1999 - 2008

4.4.3 The association between water level and cliff retreat at the study sites

The association between cliff base elevation from the SDMS surveys at Covehithe SWD4 and still water level from the Lowestoft dataset is shown in Figure 4.31.

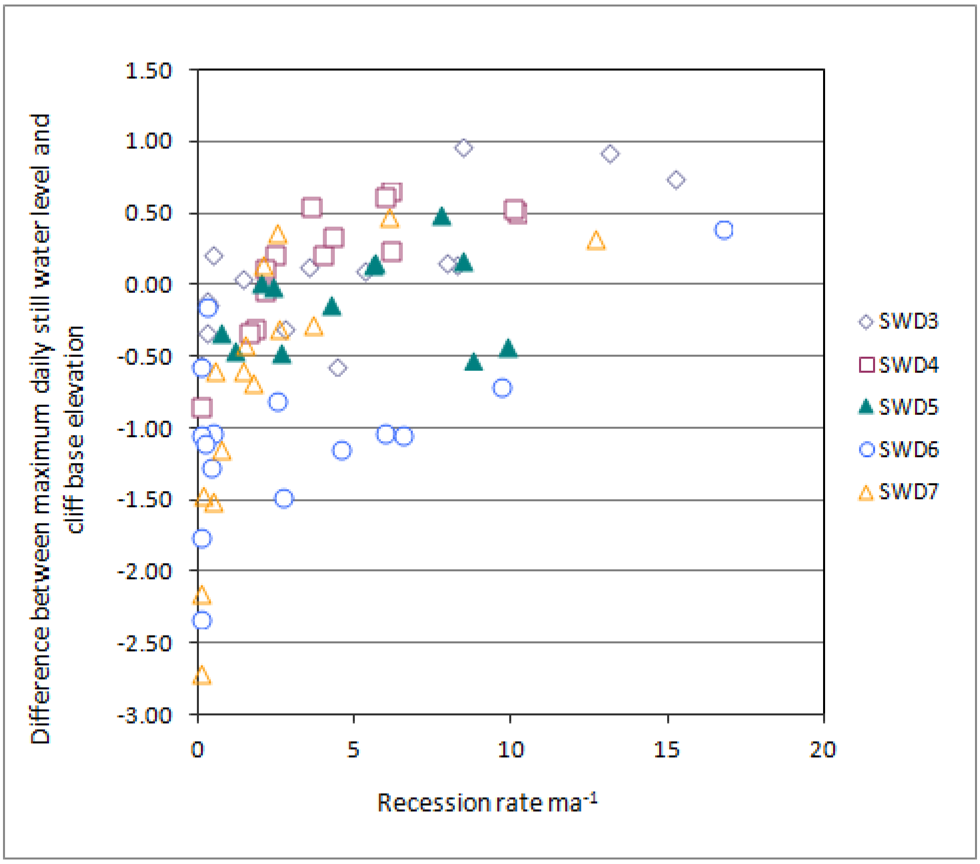


Figure 4.31

Results of the analyses of water level for stable and unstable phases at the study sites in the period 1993 to 2008

The value of R in the Pearson analysis was 0.3535. Although this is a positive correlation, the relationship between the variables is not strong. The value of R^2, the coefficient of determination, is 0.125.The P-Value (n=53) is 0.009. The result is significant at $p < 0.05$.

Chapter 5 Discussion

5.1 The history of retreat in the cliff line at Covehithe

The short-term (annual) retreat values obtained the study sites (Table 4.1) in general fall within with published values for this location between the 1880s and the 1950s (Carr, 1979; Cambers, 1976; McCave, 1978; Vincent 1979; Clayton et al., 1983). The median retreat rate of approximately 5m a^{-1} for the period between 1992 and 2008 obtained in the research in this thesis does not fit well with the published values. For example, Pontee (2005) gives retreat rates for the study site cliff line as a whole of between 0.16 and 0.24m a^{-1} from the 1880s to the present day. Pye and Blott (2006) also give lower retreat rates of 1.3m a^{-1} for the period 1903-1953 and 0.6m a^{-1} between 1953 and 2003. However, recent approaches propose rates of approximately 2.3 to 3.5 ma^{-1} are appropriate for the 105 year period from 1883 to 2008 (Brooks and Spencer, 2010). What is clear; however, is that calculating retreat over long periods masks the inter-annual variability in retreat (Table 4.1) and the decadal variability in retreat (compare the 1992-2001 and the 2001-8 rates) at these study sites.

5.2 The association between rainfall and cliff retreat

The annualised values for assumed rainfall at Covehithe between 1993 and 2008 ranged from 465 mm (in 1996) to 799 mm (in 2001) (Table 4.2). The mean was 652 mm±105 mm. Analysis of the intra-annual rainfall pattern at the study sites showed that there was considerable variability between summer period rainfall totals and winter period rainfall totals (Table 4.3). For example, there were 18 days in summer with rainfall totals >20 mm and 18 days in winter. Out of the four days with rainfall totals that were >40 mm during the study period, 3 were in winter and 1 was in summer. This meant that the identification of simple annual or seasonal relationships between rainfall and cliff retreat was not achievable. Testing the association between cliff edge retreat rate at SWD3, SWD4, SWD5, SWD6 and SWD7 and the value obtained for the ratio of 2-day rainfall total to the rainfall total in the period between relevant surveys (from Table 4.4) using a Pearson Correlation test produced a value for R of 0.2009. This is technically a positive correlation; however, the relationship between the variables is weak. For a Pearson R value of 0.2009 (n=97) the P-Value is 0.048478. The result is significant at $p < 0.05$. The value of R^2, the coefficient of determination was 0.0404. Taken together, these results do not support there being a direct relationship between the frequency of rainfall events and landslides at Covehithe. This situation is not unexpected. Ibsen and Brunsden (1996) were only able to demonstrate a broad association of retreat with wet years when they compared the frequency of recorded landslide activity on the south coast of England from 1840 with variations in the annual rainfall totals over the same period. In addition, the 1993 Holbeck Hall landslide at Scarborough, UK, followed a progressive decline in stability rather than responding to an identifiable trigger (Lee, 1999). The extensive 1994 landslide movements at Blackgang in Isle of Wight, UK, were also linked to almost continuous rainfall over the previous month, rather than the additional water contribution of a particular rainfall event. The poor association between rainfall and cliff retreat at Covehithe may be because rainfall and groundwater have acted as a preparatory factors working to make the slope increasingly susceptible to failure, but without actually initiating it.

5.3 Terrestrial forcing of Cliff retreat

5.3.1 Coupled hydrology and stability model sensitivity analysis

This sensitivity study was undertaken with the aim of numerically modelling the process by which a transition from stability to instability may take place in episodically eroding soft sea cliffs on rainfall infiltration. Specifically it was necessary to :

a) Identify a process based model that combines the geometrical characteristics of the study site with specific environmental parameters, such as rainfall and water table level, which may influence the processes of stability in soft sea-cliffs

b) To conduct a Sensitivity Study to establish the appropriate parameters for this model, using an in-depth study site, to demonstrate that it is an appropriate analytical tool to investigate and elucidate the processes that control episodic soft sea cliff erosion.

The following hypothesis could then be tested:

a) A process model can be identified that combines the geometrical characteristics of the study site with specific environmental parameters, such as rainfall and water table level, which may influence the processes of stability in soft sea-cliffs.

The sensitivity study revealed the implication of a three orders-of-magnitude change in the saturated hydraulic conductivity for the Factor of Safety was significant. Figure 4.8 to Figure 4.10 showed modelled FS responses for daily rainfall of 24, 48, 72, 96 and 120 mm. The FS values can be interpreted to indicate low rainfall produces no discernible response, while high magnitude events lead to clear reduction in the stability of some of the slopes. This suggested that topology may be linked to hydrology in the field. Specifically, the model results showed that for some of the cliff profiles modelled the onset of response in Factor of Safety was rapid (such as in January 1999, July 1999 and January 2001) and in some cases significant (such as January 2001). In others either the Factor of Safety did not drop so rapidly or so markedly (January 1993, January 1997, August 1997, August 2000 and September 2002). In some of the profiles analysed, the Factor of Safety calculated by the model did not respond during the modelled rainfall events at all. Consideration of the morphology of the cliff profiles as recorded in the SDMS surveys revealed that the most responsive profiles each appeared to have a lower base elevation and a less pronounced debris talus.

There were four key findings from the Sensitivity Study:

1. Comparison of the gradient of the lines in Figure 4.6 and 4.7 shows that the modelled Factor of Safety is more sensitive to changes in the cohesion value than to changes in the friction angle of the material.

2. As either the value for friction angle or the cohesion chosen affect the initial slope stability; they will also affect the slope stability under a given set of rainfall conditions, despite not influencing the hydrology.
3. The implication for the Factor of Safety of a three order-of-magnitude change in the saturated hydraulic conductivity was found to be less than varying the value for friction angle, or the cohesion between the minimum and maximum values.
4. The hydrological response to rainfall events was found to be sensitive to the value used for saturated hydraulic conductivity in the parameterisation.

The sensitivity study also suggested risks in applying a multi-parameter model where there has been no opportunity for data collection or well-founded model parameterisation. This finding is supported by Lloyd *et al.* (2004) who proposed that the suitability of a model for a given problem is dependent upon the specific environmental parameters that control the underlying processes. Ensuring an appropriate model domain space exists was therefore essential if the conclusions drawn about the processes operating are to reflect reality, and not be a function of the model used. Consequently, to create an appropriate domain space for the modelling in this thesis a rigorous assignment of the hydrological and geophysical properties of the cliff-forming materials was undertaken

5.3.2 Hydrological response to disturbing rainfall stress

Simulations revealed storm event rainfall infiltration can cause a rapid downward flux of water in the cliffs. During certain rainfall events (e.g. Figures 4.12C: 28/08/1998 and 4.13C: 15/09/2000) this downward flux can mean that there is a zone of positive pore-water pressure almost parallel with the top surface of the cliff. Under these conditions, the vectors of flow calculated by the model showed flow was extremely rapid and perpendicular to the surface, with very limited lateral movement of water. Under high- infiltration scenarios (e.g. Figure 4.14C and 4.14D) the water table rapidly rose to be less than 1m from the ground surface.

Simulation showed that values for matric suction near the ground surface could be reduced significantly (to between 1 and 10 kPa) and these losses persist for up to three days after a high intensity rainfall event. After a pore-water pressure peak, the water in general percolated down the profiles. Input water typically reached the contact between the iron-cemented sand and the silty-clays that form the base of the cliff after 3-7 days. During high rainfall-total events there was frequently inversion of pore water pressure with areas higher up in the cliff being wetter (if not actually saturated) than those immediately below. In these situations downward migration of the wetting front meets was sometimes able to meet an upward moving permanent water table to allow saturation of the cliff profile below 2 m from the cliff-top surface.

5.3.3 FS response to disturbing rainfall stress

The retreat history of the cliffs at SWD4 was disaggregated into 6-month intervals and a carefully parameterised numerical model was applied to elucidate the transition from stability to cliff failure in response to disturbing rainfall stress. The simulations revealed that FS reduction in the cliff system was greater overall, and that suction loss was experienced to a greater depth below the ground and occurred for longer with a sequence of high daily totals. The FS changes modelled consequent to high rainfall events in the study periods are reported in Figures 4.15 to 4.24. Predicted failures and candidate redundant events are shown. Simulations suggested that it is downward migration of the wetting front in the upper cliff section, rather than the upward migration of the permanent water table, which was the initiator of failure in these situations. For example, in the simulation of the period from 17/01/1999 to 11/08/1999 stability analysis suggested that the FS was less than 1 on day 204in the simulation. At this time the hydrological modelling revealed that the permanent water table was under 3m elevation. Soil suctions values in the upper segment of the cliff 0-4 m below the surface were, however, significantly reduced. The findings suggest that it is the downward movement of the wetter conditions from the surface creating rapid changes in the water table that is likely to have triggered retreat, rather than the existence of a high water table over a sustained period.

The linear relationship between 2-day rainfall total (after Collins and Sitar, 2008) was interpreted as suggesting sub-aerial processes principally drive low to intermediate retreat in the low height (*ca.*6-7m) cliffs at south Covehithe (SWD4). The hydrological response to rainfall in the cliffs at SWD4 has been modelled as a rapid downward flux of water, which in turn creates a defined wetting front. Under certain antecedent rainfall conditions, this wetting front can develop into a perched water table with consequent significant reduction in slope stability

5.4 Marine forcing of Cliff retreat

5.4.1 The record of water level at Lowestoft between 1993 and 2008

Surges appeared to be reasonably evenly distributed through the study period, with no particular period associated with a higher incidence of surges. This is in contrast to the decadal and sub-decadal variation in retreat rate established for the cliffs along this coast in this research. The even distribution of surges has been interpreted to mean that storm surges have been comparatively unimportant in explaining low to intermediate annual cliff retreat rates along this coast. However, the highest annual cliff retreat rates have been largely associated with years that include a storm surge with high water levels. Of the largest surge events, in the 1990s the years 1993–1994 and 1994-1995 were particularly noteworthy. In particular, events occurred in the 1990s on 14 October 1993, 16-17 December 1997 and 8 October 1998 (Figure 6.3).In the 2000s there a major surge event on the night of 8-9th November 2007 exceeded 2.3 m OD (see Figure 6.5). For comparison, the storm surge of 31st January to 1st February 1953 reached a height of 3.1 m OD at Lowestoft, which was 1.62 m above the Highest Astronomical tide of 2.98 m above sea level (Horsbaugh *et al.*, 2008). The 2007 event was associated with high retreat rates alongshore at Covehithe. The magnitude of this surge (although not the destructive consequences) was comparable to others that have occurred during the late twentieth Century; notably the disater of 1953 and other events in 1971, 1973, 1976, 1978 and 1993 (Cambers, 1975; HR Wallingford; Flather and Davies, 1976; Horsburgh *et al*., 2008).

The surge event that took place on the 21st February 1993 was an example of an internal surge generated by a combination of strong winds produced by low pressure over the continent and an area of high pressure to the west of Ireland. The surge affected much of the east coast of England (McRobie, 2005, Baxter, 2005) and in addition to the extreme water levels; waves on the east coast reached heights of 5m (HR Wallington). The surge event on 9th November 2007 (Figure 6.5) was caused by the atmospheric conditions surrounding the British Isles during the days leading up to and including the 8-9th November 2007 (Parker and Foden, 2009). An Atlantic low-pressure system moved from Iceland towards southern Norway during and on 9 November 2007, there were exceptionally strong northerly winds over the entire North Sea (Horsburgh *et al*., 2008). The maximum surge around Lowestoft on the 9th November reached 2.63 mOD (Horsburgh *et al*., 2008). The storm surge event that occurred during the 8th-9th November 2007 was one of only two events with residual surge heights exceeding 2.0 m and the only event exceeding 2.3 m (Parker and Foden, 2009) in the study period. Each were associated with cliff retreat.

5.4.2 The association between water level and cliff retreat at the study sites

The SDMS surveys were used to provide information on the rates of region-wide cliff erosion that occurred during the study period. The analysis found that the maximum erosion occurred during the periods of still water elevation associated with surge events. Furthermore, cliff retreat rates above $10ma^{-1}$ (7 values; 10.0 $ma^{-1}$to 16.7 ma^{-1}) were not observed at any study site in periods when the still water level remained below the elevation of the cliff base. Lower retreat rates are clustered with low still water levels in the analyses. In periods where the maximum daily still water height did not reach the base of the cliff, the erosion rate was zero or low. The modelling discussed in Section 5.3.3 suggested cliff retreat values greater than

$10ma^{-1}$ are poorly accounted for by single mass-movements. It was not possible to investigate the timing of failure events using the available at-a-point information. Multiple small failures between surveys (with removal of material from the beach but no cliff undercutting) could explain the high 'annual' retreat rates in those periods where the still water elevations were low in relation to the elevation of the cliff base. However, the at-a-point surveys do not pin-point smaller events (such as localised crest failures) that have been shown to play a role in coastal cliff erosion (Rosser *et al*., 2005; Young *et al*., (2009).

Chapter 6 General Discussion and Conclusions

Shoreline retreat is an important issue in the United Kingdom, where regional coastal retreat rates are among the highest found globally (Brooks, 2010; Brooks *et al*., 2012). A significant proportion of the coastal cliffs that form the dominant coastal features along many parts of the north-eastern, East Anglian and the south-eastern coasts of the United Kingdom (DEFRA, 2002) are retreating. Cliffs developed in soft rock lithologies such as those on the coast of eastern England, are at particularly high risk. When formulating Shoreline Management Plans it is necessary to provide an assessment of the potential for landward movement of these cliff lines, or to forecast cliff position at some future time. Providing the information to do this is a challenge, as the response of coastal cliffs to environmental inputs can be complex and non-linear (DEFRA, 2002; Dronkers, 2005). Rainfall, particularly storm rainfall, is acknowledged as playing a significant role in cliff stability and is one of the 'preparatory processes' that reduce the strength of soft-rock cliff materials (Greenwood and Orford, 2008). The aims of this thesis were to address the incomplete understanding of the role of rainfall infiltration in the transition from stability to failure in soft rock cliffs. Specifically, elucidating the dynamic pore-water pressure behaviour which recent major advances in computational modelling technology has made possible. The mechanistic study in this research was centred on the low (<7m) soft-rock cliffs on Suffolk coast of the United Kingdom between Covehithe and Easton, where no research has investigated annual (winter-winter) retreat rates. Covehithe is important relative to other cliffs of the region. In addition, the fact that these cliffs are not (nor have ever been) protected is a major issue as it allows study of cliff processes in their natural setting. The research in this thesis has:

a) used available coastal morphology survey data to refine estimates of cliff, retreat rate and establish their temporal variability over the period from 1993 to 2008 at detailed case-study sites,

b) used the information obtained in a) with estimates of retreat from the literature such as maps, aerial photographs and archival records to determine whether erosion is speeding up or not at the study sites,

c) identified a suitable numerical model to investigate the hydrology and stability of soft-rock cliffs and to parameterise this using literature values applicable to the study sites,

d) parameterised and applied the numerical model identified in c) to elucidate the hydrological processes that may contribute to failure in soft-rock cliffs,

e) used available coastal morphology survey data to determine the temporal variation in cliff base elevation over the period from 1993 to 2008 at the case-study sites, and

f) to use the information obtained in e) to examine whether the temporal variability established in a) can be correlated with historic still water level and surge data for the study site obtained from the literature.

The originality of the approach lay in the application of recent coupled hydrology-stability models to low soft-rock cliffs of complex geology, as set out in the main objective. The assessment of marine forcing was useful in context setting and ways forward, rather than giving rise to new techniques in its own right. The goal of the research in this thesis was to address the lack of understanding of the mechanisms controlling the retreat processes acting in some soft-rock cliffs, by numerically modelling some of the processes by which a transition from stability to instability may take place. This would provide geotechnical engineers and coastal planners with novel techniques for assessing the potential for cliff failure, and also give new interpretation and understanding to the role of thresholds in determining the transition from stability to instability in soft sea-rock cliffs. In particular the research:

a) Identified an appropriate combined hydrology and slope stability computer model that combines the geometrical characteristics of the study site with specific environmental parameters, such as rainfall and water table level, which may influence the processes of stability in soft-rock cliffs;

b) Conducted a Sensitivity Study to establish the appropriate parameters for this model, using an in-depth study site, to demonstrate that it is an appropriate analytical tool to investigate and elucidate the processes that control episodic soft-rock cliff failure, and

c) Conducted a detailed event-based hydrological analysis using appropriate input parameters to investigate the relationship between daily rainfall total and the stability of soft-rock cliffs, comparing these findings with detailed actual instability events at a study site.

6.1 Sensitivity study

The sensitivity study supported the following conclusions:

a) The modelled Factor of Safety was more sensitive to changes in the cohesion value than to changes in the friction angle of the material; however both were important,

b) as either the value for friction angle or the cohesion chosen affected the initial slope stability; they would also affect the slope stability under a given set of rainfall conditions despite not influencing the hydrology,

c) careful geotechnical and hydrological parameterisation was essential to ensure that the conclusions drawn about the processes operating were not a function of the way that the model was being operated, and

d) GEO-SLOPE was an appropriate tool for the modelling in the context of this research.

6.2 Hydrological response to disturbing rainfall stress

The simulation of the hydrological response to disturbing rainfall stress suggested that:

a) Geometry in the model (and by extension topography in the field) controlled the localised head pressure gradients as a result of seepage,

b) High intensity rainfall resulted in a rapid downward flux of water in the cliff with the creation of a defined wetting front which could develop into a perched water table,

c) After the initial infiltration phase, water then moved down the cliff profile more slowly (over3-5 days for each discrete daily rainfall event) until reaching the contact between the iron-cemented sand and the basal silty-clay. Permeability contrast between these soils then resulted in water being held up in the iron-cemented sand. Soil suctions were consequently reduced significantly, to the extent that zones of positive pore water pressure were able to merge with each other and temporarily raise the local water table.

6.3 FS response to disturbing rainfall stress

The simulations of FS response to disturbing rainfall stress suggested that:

a) The FS was highly dynamic over a fine temporal scale and a variable interaction between potential triggering events and eventual landslides (i.e. redundant events; Brunsden and Lee, 2000) was suggested in the time-series data,

b) The most extreme rainfall totals were sufficient to trigger failure in the cliffs and in these situations, suction loss or pore-water pressure inversion were the primary controls on cliff dynamics,

c) By extrapolation, in situations where low permeability soils are overlain by higher permeability material, rapid flow of water, with consequent destruction of soil suction would be a plausible candidate triggering mechanism for rotational failure,

d) Rotational failures explain retreat events of 1-3m magnitude over the time period studied at SWD4.

The simulations of the sensitivity of FS response to 1-day rainfall total and 2-day rainfall totals suggested that:

a) There was a linear relationship between 1-day rainfall total and 2-day rainfall total and FS response in the model which could be interpreted to suggest that sub-aerial triggering could explain low to intermediate retreat rates at the study site.

6.4 Marine forcing of cliff retreat

The frequency at which the cliff base could be affected by marine action was found to be critical to the occurrence of high magnitude retreat at the study sites. Individual high-retreat events in the record were explained by the occurrence of surge events, particularly the events in 1993 and 2007. This finding was consistent with observations of increased erosion at other sites when water was able to impact the cliff base (Everts, 1991; Komar and Shih, 1993; Ruggiero *et al*., 2001; Sallenger *et al*., 2002). The research provided insight into the plausibility of marine initiation of failure in the cliff at the study site. This has no bearing on the process whereby marine action removes and redistributes material on the beach. It must be assumed that this process is in operation at Covehithe, otherwise the cliffs would tend towards a stable geometry over time, as is the case for inland slopes. It is possible that although some storms at Covehithe have coincided with high tide and are onshore directed, these storms have not had erosional impacts at the shoreline. This is almost certainly linked to dynamic thresholds at each site and requires further research to identify the combination of storm attributes necessary to produce an erosional response. The beach elevations were highly dynamic, probably as offshore sediment losses during storms are replaced by fair-weather swell conditions. Thus, the impacts of individual storms are impossible to detect in the winter-winter record of morphological change in the profiles used. The analyses of marine forcing of cliff retreat at the study sites suggested:

a) There may be periods where retreat is controlled primarily by marine forcing. In these time intervals failures were observed and the maximum daily still water elevation was above the cliff base. This means that direct water contact with the cliff toe had occurred, and in general, these periods were associated with the highest retreat rates. Intermediate-high retreat rates may have been promoted by rapid cycling of failure-debris removal-failure although the nature of the available at-a-point data did not permit this aspect to be investigated.

b) There is possibly a threshold around 8m retreat. For retreat to be above this threshold, still water level must exceed the elevation of the cliff base making the cliff vulnerable to the force of wave attack. This is consistent with the Sunamura (1983) model being applicable at the study site.

6.5 Implications of the findings

Soft rock coasts are erosional coasts, which retreat even under stable sea-level conditions (Foresight Flood and Coastal Defence, 2004). Sea defence planners face the prospect of rising sea levels (Woodworth *et al*, 2006) and changing storm surge behaviour due to anthropogenic climate change (Woth *et al*, 2006). Increased sea level (Miller and Douglas, 2004; IPCC, 2007) will lead to greater wave attack on sea-cliffs (Wang *et al*., 2008) while predicted changes in storminess and precipitation under climate change are also widely expected to affect the future stability of soft rock cliffs (Pierre and Lahousse; 2006, Nicholls *et al*., 2007). The UKCP09 Climate Projections provide a worst case estimate of sea level rise in the UK of up to 190cm by 2095 (UKCP09). Climate change might also result in increased storm surge heights around the UK by 2100 and higher sea level will lead to higher extreme water levels (Lowe and Gregory, 2005; Tsimplis *et al*., 2005). As sea levels rise tidal regimes will change. Over the short term, meteorological effects can also distort the astronomical tide. The combined effect at the coast is a storm surge. British soft-rock cliffs are subjected to surges that are common on the east coast of the UK in the southern North Sea (Wolf and Flather, 2005). The combined effect of the projected increases in storm surges and extreme water levels and changing precipitation and storminess on climate change is that coastal erosion around the UK is likely to be increased.

6.6 Further work

To improve the coupled hydrology and stability analyses and to take into account, for example, the effects of dip angle in the strata present at the study site (Hey, 1967) a better definition of the geological structure is necessary. Better description of the hydrological functions (volumetric water content and hydraulic conductivity) for the unsaturated zone is desirable, although these have never been measured in the field. Closer definition of the geological basement is also required and this could be achieved with Ground Penetrating Radar. The at-a-point SDMS survey data are imperfect and further work is required here. For example, to avoid uncertainties regarding the relationships between data values (particularly the problems associated with elevation) field based levelling could be used to check and refine the elevation data relative to Ordnance Survey benchmarks. A finer temporal basis for the surveys would allow modelling to be improved as the redundant events could be investigated. More detailed assessment of the three-dimensional nature of the erosion processes would also be beneficial. This is possibly achievable by drawing a series of two-dimensional profiles at closely spaced intervals if better at-a-point information were available. It may be also be valuable to run some analyses in light of: a) sea level change (the Environment Agency currently allow for 6mm/year in planning and 2mm/year as an estimate of actual change) which would affect water level in relation to beach height, and b) increased storminess and more high rainfall total events, which would affect the dynamic hydrology. Further general research to improve understanding of the causes and impacts of cliff retreat is also needed if the threats of climate change are to be mitigated. This is particularly relevant to soft-rock cliffs as climate change is expected to affect the frequency, trajectory and strength of storms (IPCC, 2007) and to intensify the occurrence of extreme water levels (Wang *et al.,* 2008; Esteves *et al.,* 2011).

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